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THE GOWGANDA FORMATION IN THE SOUTHERN PART OF THE HURONIAN OUTCROP BELT, ONTARIO, CANADA: STRATIGRAPHY, DEPOSITIONAL ENVIRONMENTS AND REGIONAL TECTONIC SIGNIFICANCE

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ABSTRACT

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The early Proterozoic Huronian Supergroup of the north shore of Lake Huron comprises a lower part that is largely of continental origin and a more widespread, dominantly marine, upper succession. The Gowganda is the lowest formation of the upper Huronian. In the southern part of the Huronian outcrop belt it is in conformable, but commonly erosional, contact with the underlying Serpent Formation. The basal part of the Gowganda Formation, Unit 1, is stratified diamictites, boulder and cobble orthoconglomerates and subordinate thin turbiditic sandstones. These rocks are largely resedimented but glaciogenic. The basal diamictite complex is overlain by Unit 2, a thick argillite formed in deep water during a period of glacial retreat. Unit 3 begins with a discontinuous glaciomarinite. This is overlain by resedimented boulder and cobble conglomerates that pass up into sandy turbidites. Down-to-basin movements on syn-sedimentary north-trending normal faults led to deposition of coarsening upward wedges of eastward-transported debris. There is a thick stratified diamictite complex at the top of Unit 3. In the eastern part of the study area it includes a 50 m-thick argillite. The diamictite complex is overlain by a series of coarsening upward sequences formed by prograding deltas. These comprise Unit 4 of the Gowganda Formation. The lowest deltaic sequence includes a thick diamictite in the east and a more widespread thin diamictite in its upper part.

The glaciogenic and resedimented nature of the rocks at the base of the Gowganda Formation suggests that basin deepening was tectonic, rather than due to eustatic sea level rise. Glaciation in the Huronian Supergroup may have been initiated by uplift of rift shoulders and propagated by influx of marine waters into the interior of the continent. The regional extent of the Gowganda Formation, its unconformable relationship with older Huronian rocks in the north, and its largely resedimented nature all indicate an episode of regional subsidence, possibly after continental separation. Similar tectonic and climatic events have been postulated for early Proterozoic rocks of southeastern Wyoming, and possibly elsewhere, lending support to earlier correlations based mainly on stratigraphic similarities.

Glaciogenic diamictites are present above the breakup unconformity in many early and late Proterozoic successions, suggesting a possible causative relationship.

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INTRODUCTION

The Gowganda Formation has been the subject of many investigations since the 1840's when these rocks were among the first studied by the fledgling Geological Survey of Canada. It forms part of the early Proterozoic or Aphebian succession known as the Huronian Supergroup and outcrops on the north shore of Lake Huron in Ontario. The Huronian Supergroup is commonly cited as the "type" succession of the early Proterozoic but its age is rather poorly constrained. The Huronian succession unconformably overlies Archaean rocks and is cut by mafic intrusives of the Nipissing diabase suite. These mafic rocks have yielded radiometric ages of about 2.1 Ga by a variety of techniques, so that the limits on Huronian deposition are commonly cited as between about 2.5—2.6 Ga and 2.1 Ga. A recent zircon age of about 2.3 Ga from the Creighton granite (Frarey et al., 1982) has been interpreted as a minimum age for deposition of the Huronian Supergroup but the

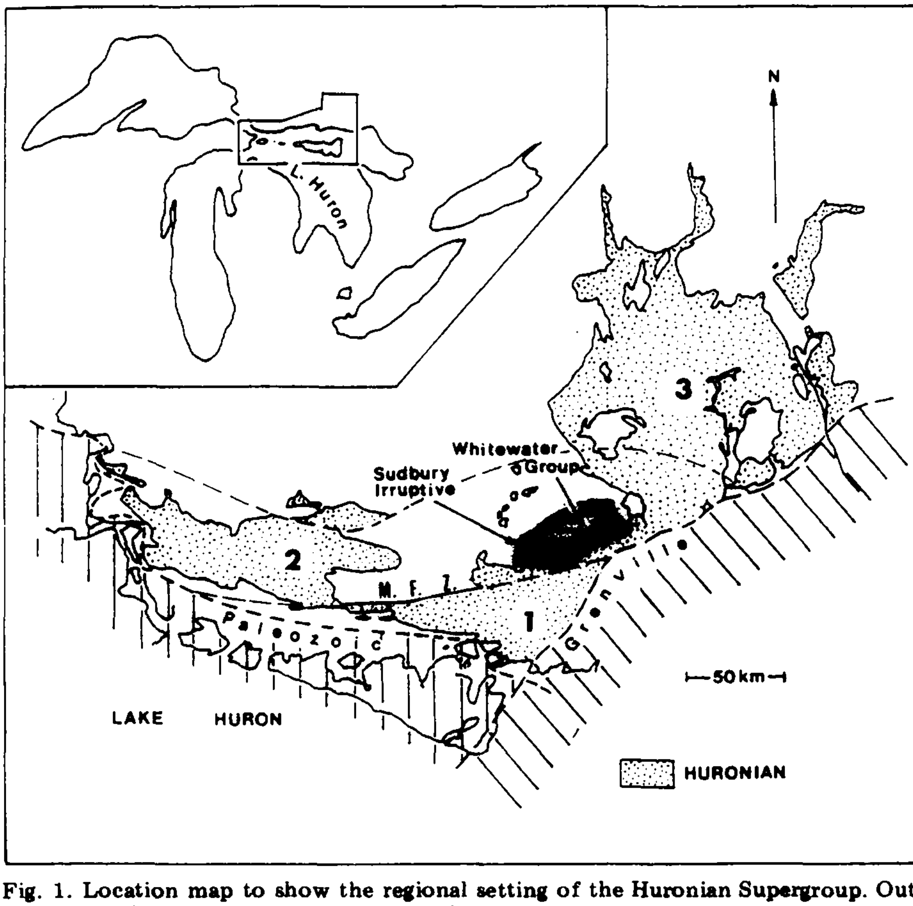


Fig. 1. Location map to show the regional setting of the Huronian Supergroup. Outcrop area is divided into Zones 1, 2 and 3. See text for discussion. M.F.Z. is Murray Fault Zone.

precise timing of this intrusion in relation to the depositional and tectonic history of the Huronian succession is not clear (Card, 1978, 1979; Dutch, 1979; Zolnai et al., 1984). Fairbairn et al. (1969) obtained a Rb—Sr isochron of about 2.3 Ga from 10 samples of the Gowganda Formation. The Huronian succession and the Gowganda Formation are therefore older than 2.1 Ga and younger than the Archaean basement, but precise limits cannot currently be placed on the time of deposition.

The Gowganda Formation is much more extensive than the underlying Huronian formations. Because of the glaciogenic interpretation by many authors, it has been of special interest to palaeoclimatologists and stratigraphers. Young (1973) proposed that it may be a remnant of a very extensive early Proterozoic glaciation in North America. In the northern part of the Huronian outcrop belt (Zone 3 of Fig. 1) the Gowganda Formation lies on Archaean rocks; to the south (Zone 2) it lies unconformably on older Huronian rocks and farther south (Zone 1) it is in conformable but commonly erosional contact with these rocks.

This report is concerned with the stratigraphy and depositional environments of the Gowganda Formation in the southern part of the Huronian outcrop belt. In this region the Huronian rocks are disposed in a series of east-trending, commonly doubly plunging folds (Fig. 2). Efforts were concentrated on an area on the north limb of the McGregor Bay anticline (Fig. 2) where exposure is exceptionally good, but some sections were also measured in the Bass Lake syncline and in the vicinity of Deacon Lake near the Grenville front (Fig. 2).

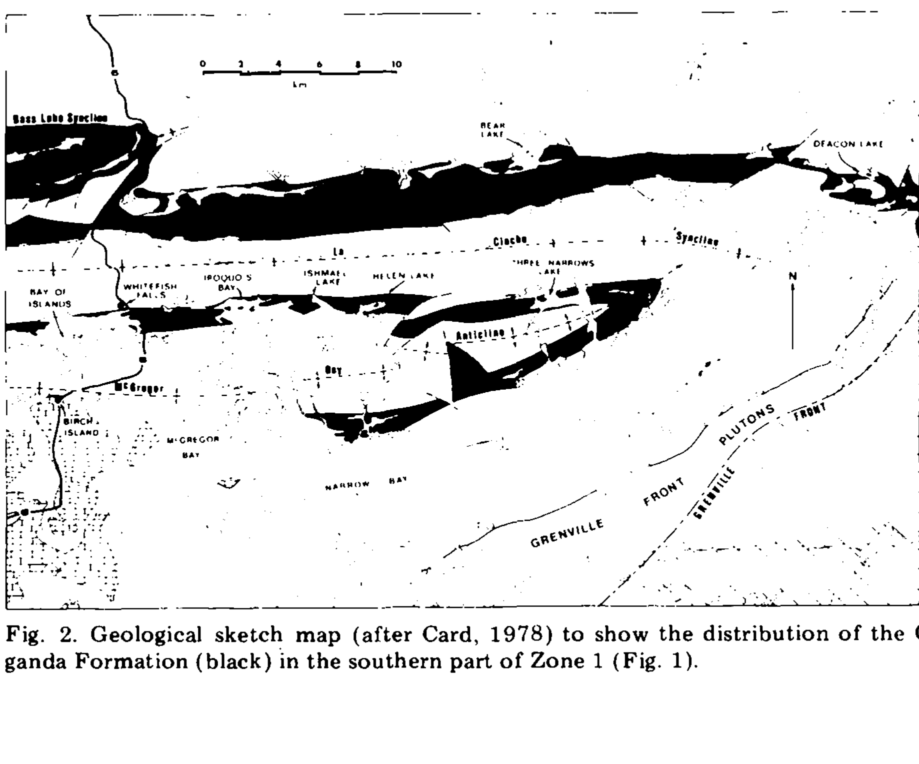


Fig. 2. Geological sketch map (after Card, 1978) to show the distribution of the Gowganda Formation (black) in the southern part of Zone 1 (Fig. 1).

OVERVIEW OF THE STRATIGRAPHY OF THE GOWGANDA FORMATION

The stratigraphic unit mapped by previous workers in the area (e.g., Card, 1976) at the Gowganda Formation is about 1000 m thick. A simplified representation of the Huronian succession to show the stratigraphic position of the rocks described in this report is shown in Fig. 3. As pointed out by Lindsey (1969) the Gowganda can be subdivided into two stratigraphic units; a lower diamictite-bearing unit and an upper succession that is generally devoid of large basement clasts. Lindsey (1971) proposed different formation names for these two units, restricting the name Gowganda Formation to the lower subdivision and introducing the name La Cloche Formation for the upper rocks. This suggestion has not been widely followed in the subsequent literature and in this report we use the name Gowganda Formation for the entire unit and call the two subdivisions "lower" and "upper" Gowganda Formation. This study focusses on the lower Gowganda Formation. The upper part is currently under study by R. Junnila at the University of Western Ontario and will be described elsewhere.

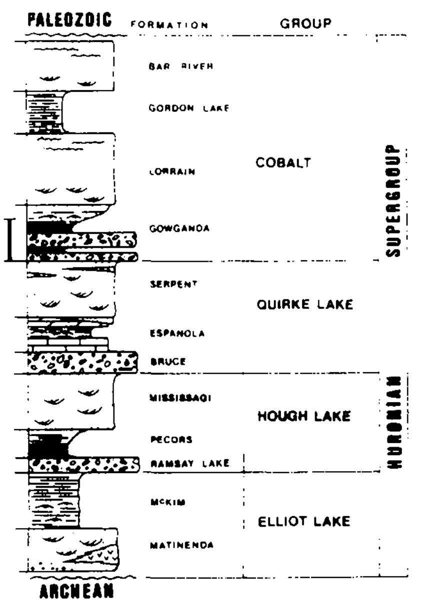


Fig. 3. Generalized stratigraphic column of the Huronian Supergroup. Ramsay Lake, Bruce and Gowganda Formations include diamictites. Dotted symbol—sandstone; dashes —siltstone; black—mudstone. Bar at left shows the stratigraphic position of the rocks discussed in this report.

The lower Gowganda Formation can be divided, in ascending sequence, into three major units or members as follows: Unit 1 (40—240 m thick) which is dominated by diamictites, Unit 2, an argillite (100—240 m thick) that is almost devoid of extra-basinal clasts and Unit 3, which consists of 80—400 m of diamictites, orthoconglomerates, sandstones and argillites, all

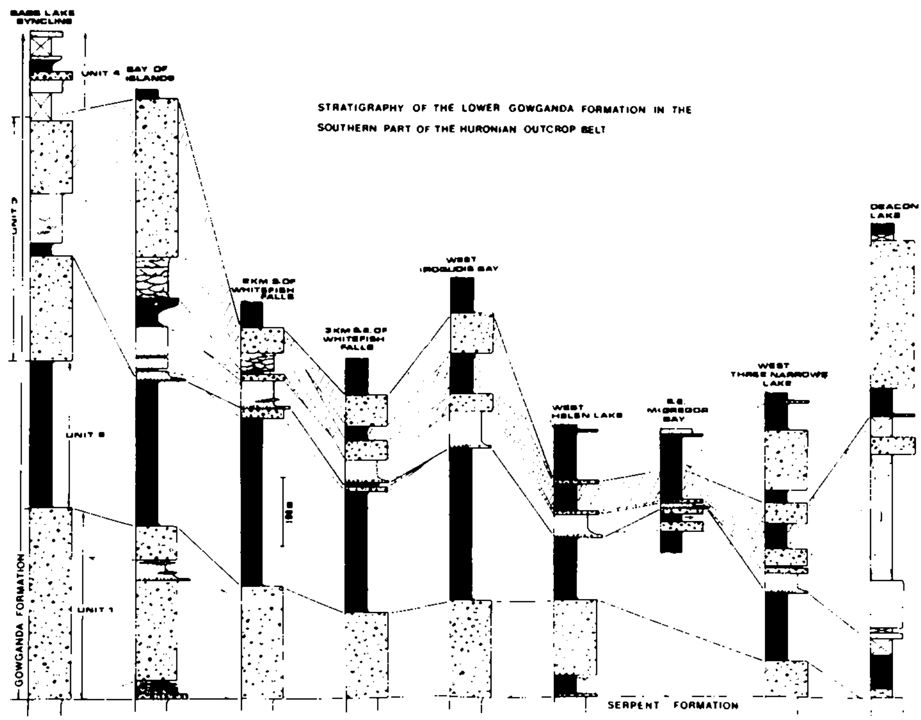


Fig. 4. Generalized sections of the Gowganda Formation in the southern part of the Huronian outcrop belt. Figure 2 shows the location of the columns, which are displayed in a generally west-to-east order. Coarse spotted symbol represents diamictite; black—mudstones; fine dots—sandstone. Dotted area between columns identifies largely resedimented sand-dominated facies in Unit 3. Diagonal ornament between columns represents the upper diamictite complex (Unit 3). Stratigraphic subdivisions used in the text are numbered on the left column. Note the eastward-thickening argillite unit that is present in the upper diamictite complex about 3 km southeast of Whitefish Falls. Roman numerals above the columns are keyed to descriptions of Unit 3 in the text.

containing basement clasts. These subdivisions are shown in Fig. 4. In the study area the thickness of the lower Gowganda Formation ranges from about 200 to 900 m. These estimates exclude the argillite unit that forms the base of the first coarsening upward sequence of the upper Gowganda Formation. This unit is highly varied in lithology and thickness and is discussed separately as Unit 4. In the study area the lower Gowganda Formation generally becomes thinner from west to east but a relatively thick succession is present in areas near the Grenville front (Fig. 4). Regionally the thickness of the Gowganda Formation is highly variable (Lindsey, 1969).

UNIT 1: THE BASAL DIAMICTITE COMPLEX

Throughout the study area the Gowganda Formation has a generally conformable contact with underlying sandstones of the Serpent Formation. In

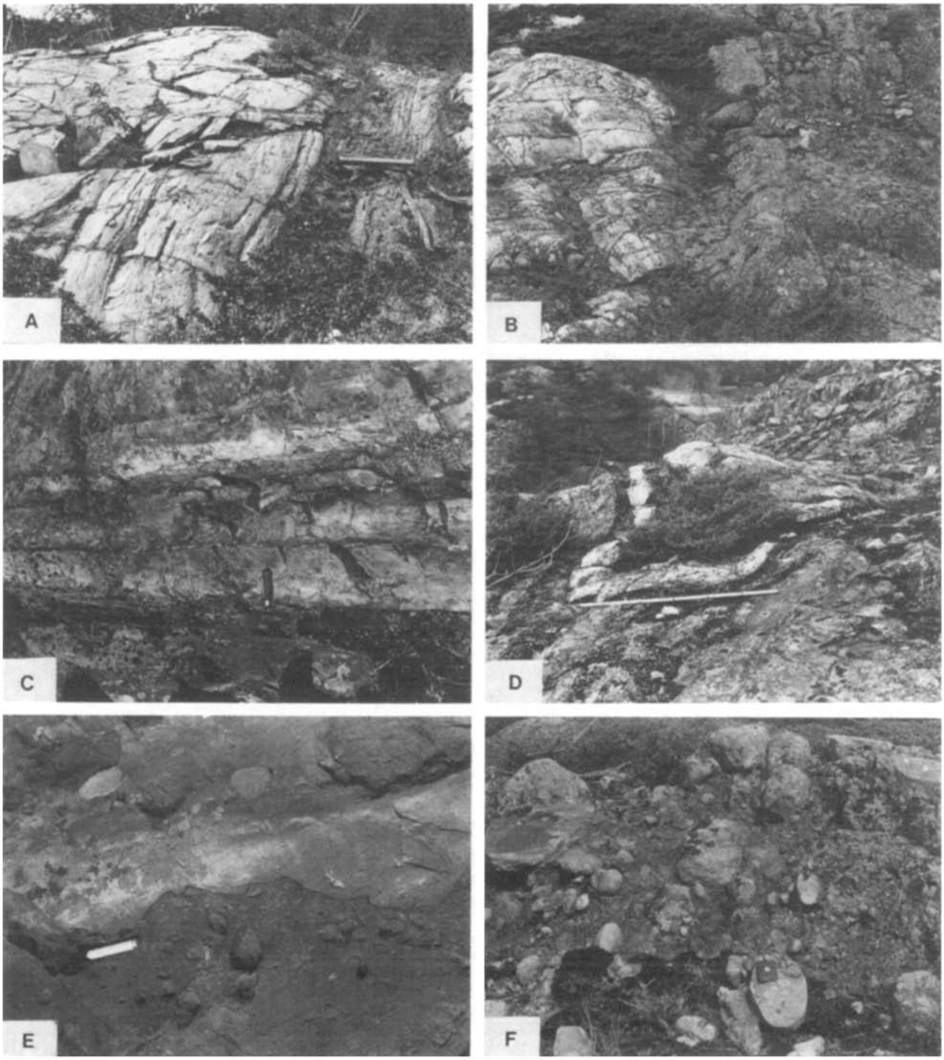


Fig. 5. (A) Fining upward sequence in the upper part of the Serpent Formation south of Whitefish Falls. Hammer (about 35 cm long) lies on silty mudstones in the upper part of the sequence. Light portion at left is cross bedded and laminated sandstone. (B) Sharp contact between cross bedded sandstone (left) and stratified diamictite of the basal Gowganda Formation. Photo represents about 4 m of stratigraphic section. (C) Fine grained sandstones (turbidites) in the lower part of the lower diamictite complex (Unit 1) south of Whitefish Falls. Knife is about 10 cm long. (D) Thin sandstone layers in the lower part of the Gowganda Formation south of Whitefish Falls. The beds are chaotically folded and disrupted, suggesting contemporaneous slumping. Scale bar is marked in 20 cm intervals and has a length of 1.2 m.(E) Graded and load casted sandstone beds in the lower diamictite complex (Unit 1) of the Gowganda Formation in the Bay of Islands (see Fig. 2 for location). Marker pen is about 12 cm long. (F) Boulder-bearing orthoconglomerate at the base of the Gowganda Formation in the Bay of Islands (see col. II, Fig. 4).

detail, however, the contact is quite varied from place to place. The Serpent Formation is mostly felspathic sandstones with abundant large scale cross beds (Fig. 5A). It also includes mudstone beds and lenses some of which are carbonate-bearing. Long (1977) interpreted the Serpent Formation as a fluvial complex with possible eolian influence. The mudstones were tentatively interpreted as lake deposits. The abrupt transition from arkosic sandstones of the Serpent Formation to diamictites of the Gowganda Formation signifies a dramatic change in depositional environment.

The contact between the two formations is generally quite sharp (Fig. 5B) and is marked by the first appearance of diamictites. On the north limb of the McGregor anticline there is local development of boulder- and cobble-bearing conglomerates that occupy channels (up to 10 m deep) in the Serpent Formation. Sandstones of the Serpent Formation are in places interbedded with graded lenticular conglomerate over a thickness of a few metres below the first diamictite of the Gowganda Formation. On the south limb of the anticline some thin (c. 1m) lenticular orthoconglomerates are present, up to 35 m below the base of the Gowganda Formation. In some areas the contact has been modified by secondary processes. In the Bay of Islands diamictites of the lower Gowganda Formation have been intruded downwards into the Serpent Formation as clastic dykes (Chandler, 1973). In other areas apparent interbedding of sandstones and diamictites can be shown to be due to post-depositional tectonic "wedging" of one formation into the other (Fig. 6a). Diffuse boundaries between diamictite and sandstone suggest that these structures formed prior to complete consolidation of the sediments. Thus the boundary between the two formations is highly varied, ranging from unconformable in the north to essentially conformable and erosive in the south with local evidence of secondary, early tectonic (?), modification.

The basal unit of the Gowganda Formation consists largely of grey-green, grey-weathering diamictite with clasts up to 2 m in diameter. The clasts are mostly granitic but other less conspicuous varieties include diabase, metavolcanics, schist and vein quartz. It ranges in thickness from about 40 to 240 m and displays a general decrease in thickness from west to east.

In some places the diamictite appears to be massive but commonly there is subtle evidence of stratification in the form of variations in the amount of clasts and in variable susceptibility of the matrix material to erosion. These differences give rise to a crude stratification on a scale of metres. Stratified diamictites make up most of this member but it also includes pebbly orthoconglomerates, granule conglomerates and sandstones. Thin (10–35 cm) sandstone beds are common in the lower part of the member in the area south of Whitefish Falls (Fig. 5C, D, E). Some of the white-weathering sandstones are subtly graded and many display partial Bouma sequences. Some sandy beds have irregular erosive bases with concentrations of granules and pebbles. Thin sandstone beds have been traced discontinuously along a strike length (east—west) of several kilometres. In some places they are severely contorted in a manner suggesting "soft sediment" deformation (Fig. 5A).

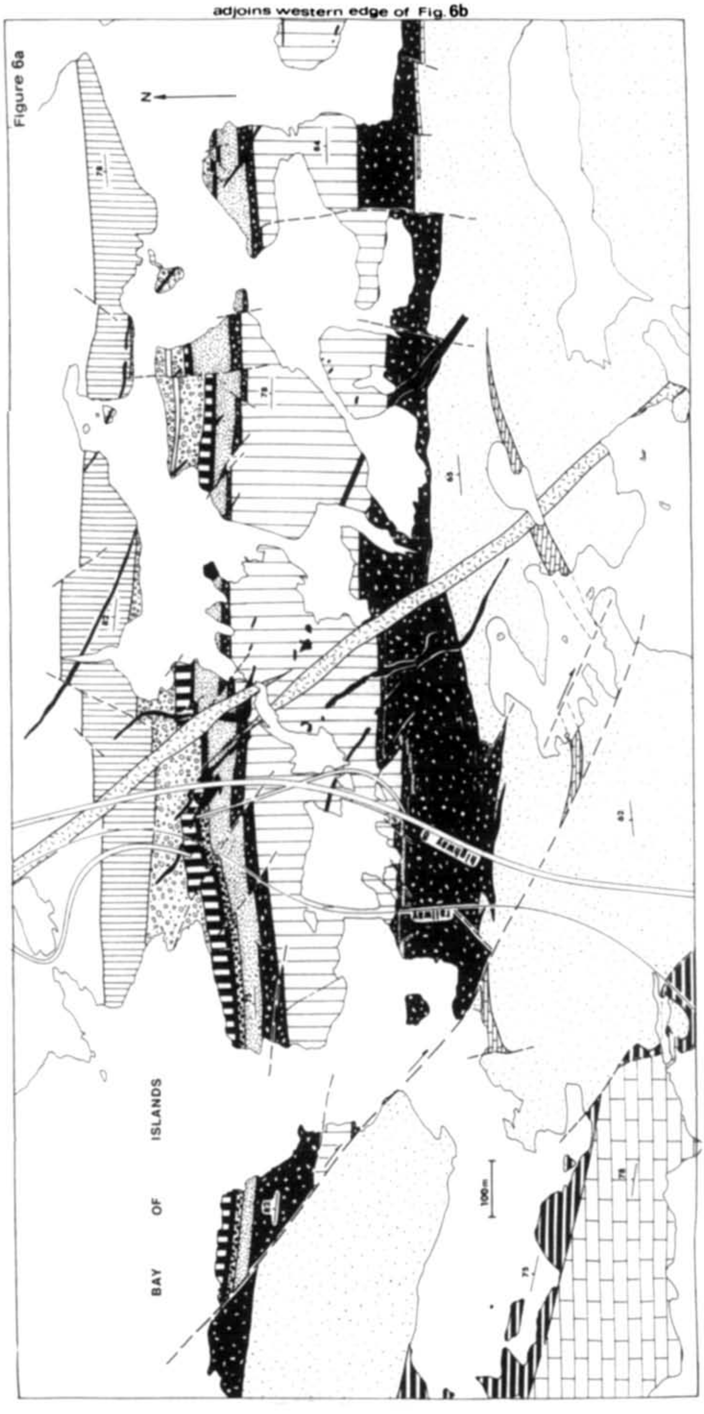


Figure 6a

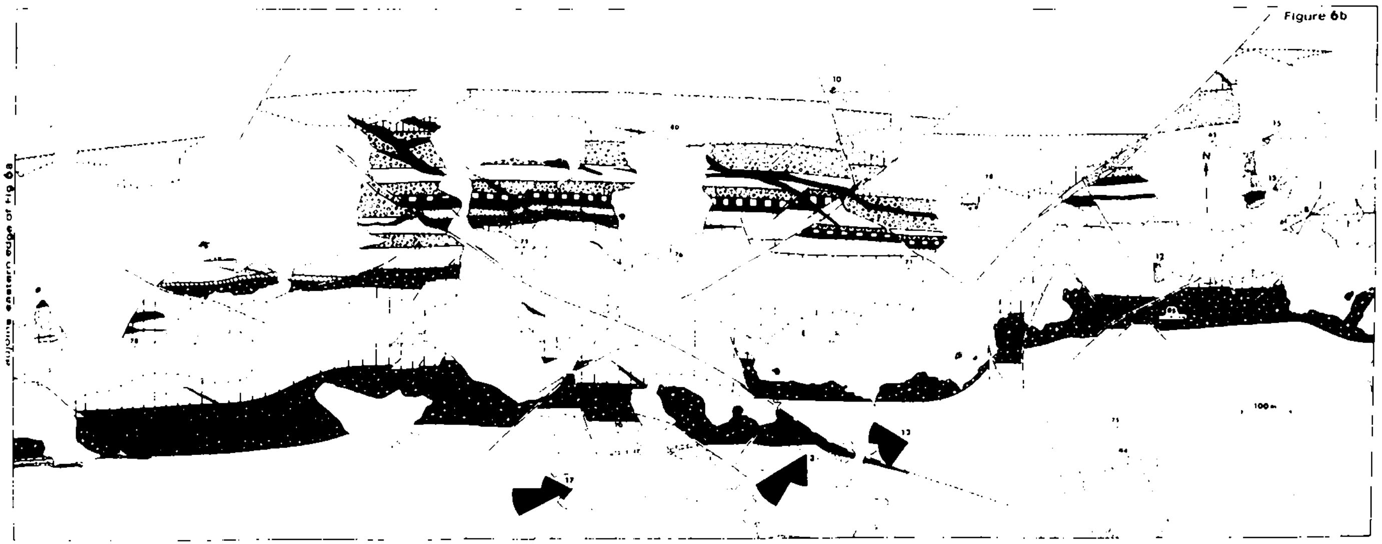
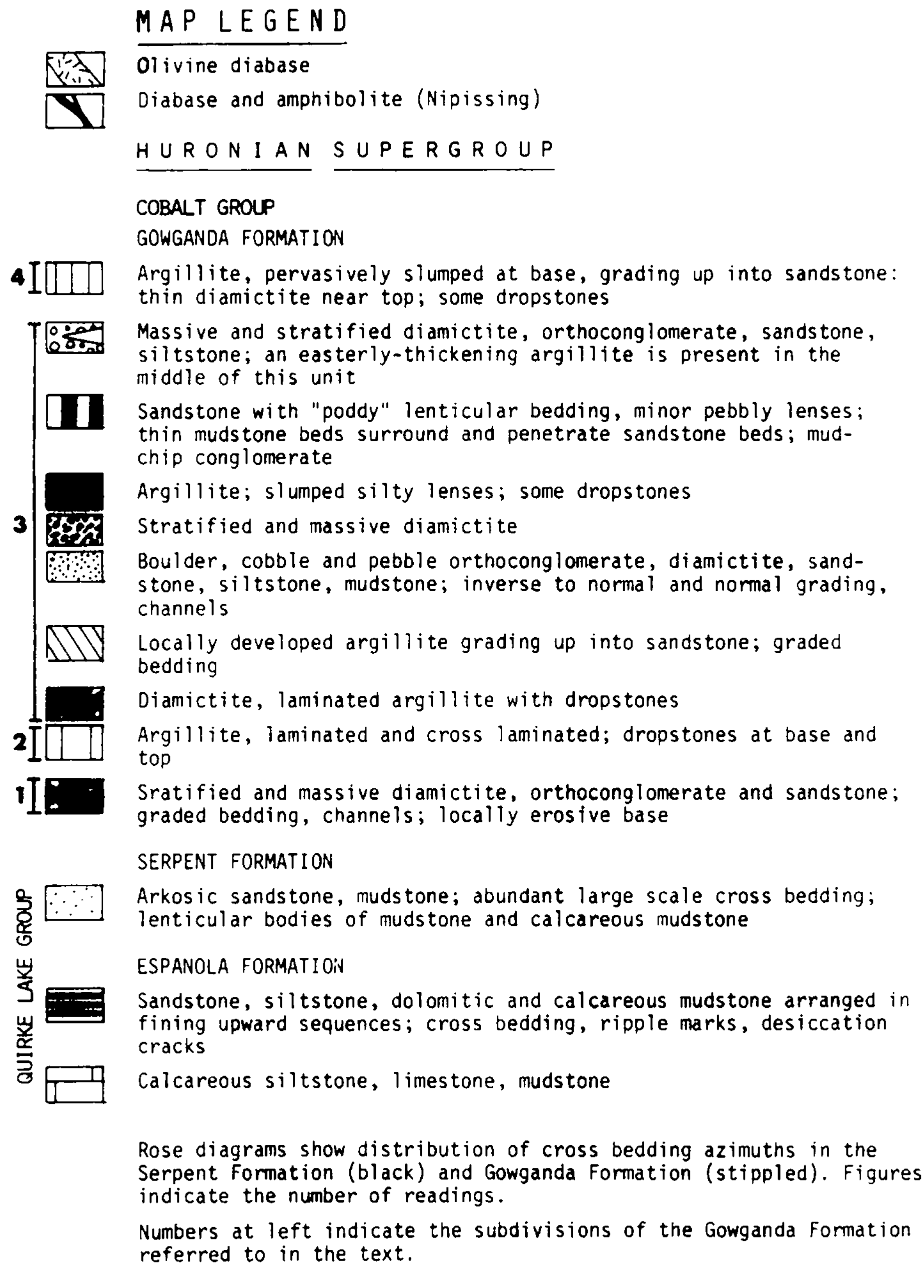


Fig. 6. (a and b) Geological Sketch map of part of the Gowganda Formation in the area south of Whitefish Falls. Note the discontinuous nature of some units, particularly those in the upper part of Unit 3. In the western half of Fig. 6b several stratigraphic units are introduced on the east side of a NW-trending fault. These units thin and disappear to the east. The highly irregular contact between the Serpent and Gowganda Formations shown in Fig. 6a near Highway 6 is thought to be due to early tectonic disturbance (see also Fig. 5D). Rose diagrams represent the distribution of palaeocurrent directions from cross beds. Black current roses are from the Serpent Formation. Those with dotted ornament are from the Gowganda Formation. Numbers of readings are also shown.



Map legend for Fig. 6.

Some beds of siltstone have ragged wispy boundaries and contain diffuse and irregular-shaped lenticular sandstone inclusions.

In the western part of the study area, at the north end of Ireson Island (Fig. 4, col.2) the Gowganda Formation begins with interbedded orthocon-

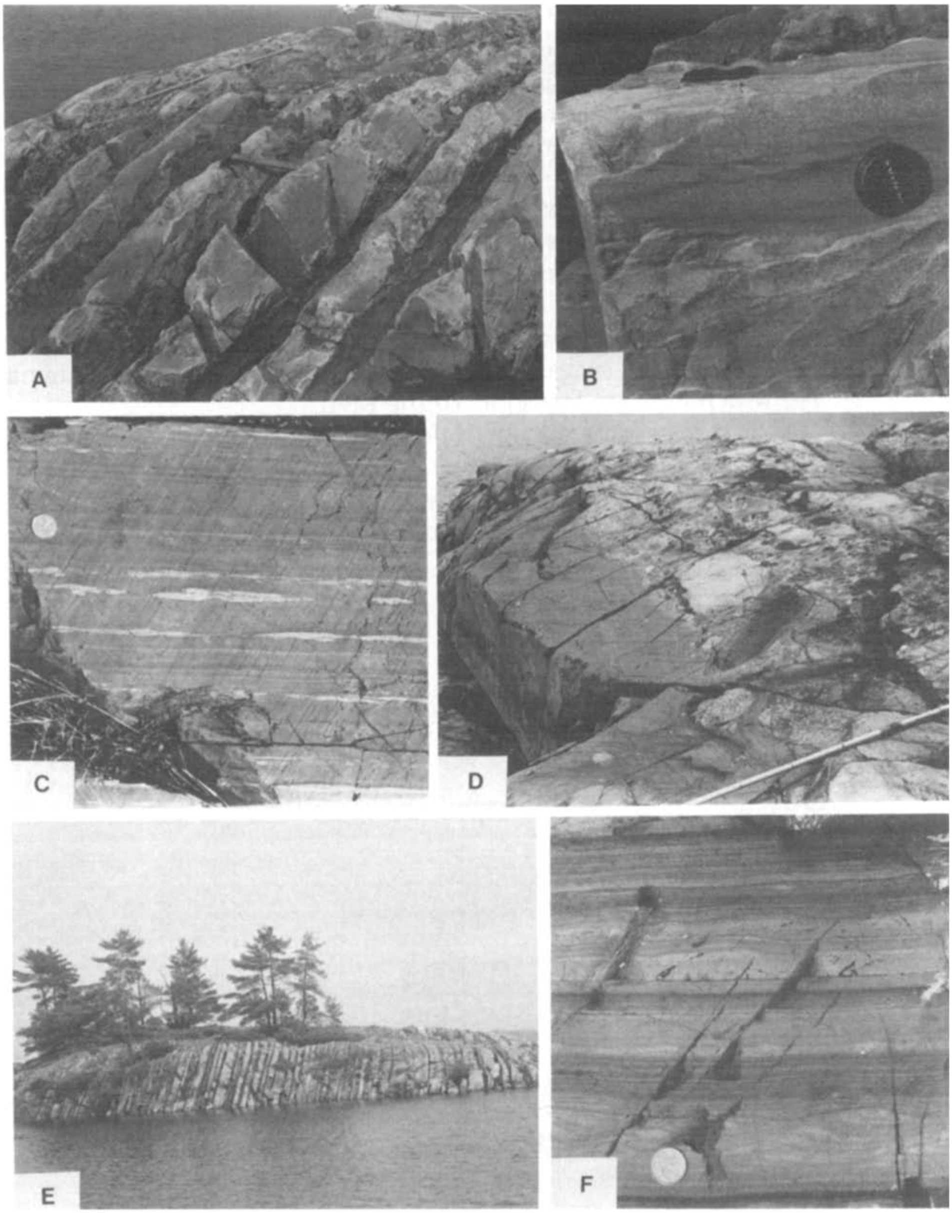


Fig. 7. (A) Alternating beds of sandstone and mudstone in the upper part of the lower diamictite complex (Unit 1) in the Bay of Islands. These resedimented beds are also shown in Fig. 4 (col. II) and in more detail in the upper part of the succession shown in Fig. 8. Hammer is about 35 cm long. (B) Detail of ripple cross lamination in sandstone beds shown in Fig. 7A. Lens cap is about 7 cm across. (C) Parallel laminations, wavy and lenticular beds in argillite of Unit 2. Coin is about 2.5 cm across. (D) Erosional contact between boulder conglomerate and basal diamictite of Unit 3, south of Whitefish Falls. See Fig. 4 (col. I) and near the base of Fig. 10 for stratigraphic position of this unit. (E) Turbidites in Unit 3 of the Gowganda Formation in the Bay of Islands. These beds are shown by horizontal striping in columns 1, 2, 3 and 4 of Fig. 11. (F) Detail of turbidites shown in Fig. 7E. Most of the turbidite sequences begin with the B portion of the Bouma sequence. Some small granite clasts are present. Coin is about 2.5 cm across. See Fig. 15 for a detailed measured section.

glomerates, sandstones and lenticular diamictites (Fig. 4). At a higher level in the same section (Fig. 4) there is a 30 m-thick unit of lenticular boulder (up to 1 m) and finer conglomerates (Fig. 5F), diamictite and associated sandstones, siltstones and mudstones (Figs. 7A,8). The section comprises a fining and thinning upward succession followed by two coarsening and thickening upward sequences. This complex extends about 500 m to the east where it passes laterally into diamictites; its westerly extent is not known due to water cover. Lenticular orthoconglomerates commonly display inverse-to-normal grading. Some sandstone layers are graded and ripple cross laminated; other beds are amalgamated graded layers with pebbles and granules at the base. The upper part of the succession contains abundant ripple cross laminations (Fig. 7b) which indicate transport to the ENE.

Farther east in the western part of Helen Lake (Figs. 2,4) the base of the Gowganda Formation is a cryptically laminated and highly disturbed 2 m-thick unit of silty argillite with scattered granite clasts. This is followed by about 28 m of clast-free laminated argillite, then 3 m of laminated ar-

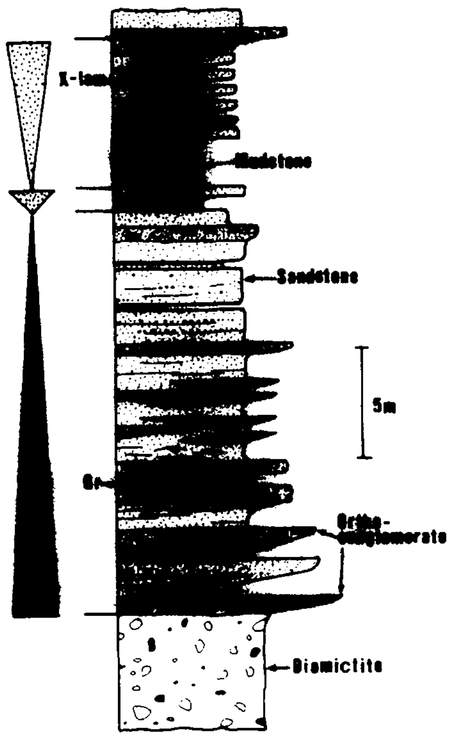


Fig. 8. Measured section in the upper part of the lower diamictite complex (Unit 1) of the Gowganda Formation in the Bay of Islands. Stratigraphic position is shown in column II of Fig. 4. Cross laminated turbiditic sandstones are shown in Figs. 7A and B. See text for discussion.

gillite with scattered clasts up to about 18 cm across. This argillite unit is known only from the Helen Lake area; in most areas the base of the Gowganda Formation is conglomeratic.

At Deacon Lake, about 3 km west of the Grenville front (Figs. 2,4) the basal diamictite is missing and the formation begins with a thick argillite correlated with the argillites of Unit 2. The possibility of faulting in this area cannot be ruled out because the contact between the argillite and the Serpent Formation is not exposed.

The upper part of the lower diamictite complex contains lenticular bodies of pebbly orthoconglomerate and white-weathering, grey, graded sandstones with load casted bases. Some more continuous metre-thick structureless medium—fine sandstone layers are present near the top of the diamictite complex.

The contact between the lower diamictite complex and the overlying argillite is conformable and gradational. About 30–50 cm of faintly laminated argillite with small scattered clasts separates diamictite from clast-free argillite.

Interpretation of the Basal Diamictite Complex

The thick and extensive development of diamictite with abundant basement clasts suggests that glacial processes were at least in part responsible for deposition of Unit 1. It also contains clear evidence of resedimentation in the form of normal and inverse-to-normal graded orthoconglomerates and sandstones. These are commonly lenticular and have erosive bases, suggesting that they are channel fillings. Thin sandstone beds near the base contain partial Bouma sequences. These thin beds are well sorted and lack large clasts, in marked contrast to the enclosing diamictites. Similar mature sands noted by Wright and Anderson (1982) from the eastern Weddell Sea in Antarctica were interpreted as products of resedimentation of poorly sorted glacial debris. Wright and Anderson (1982) explained this as a transition from sliding or mass movement to a debris flow from which finer material was extracted at the debris—water interface. Eventually the debris flow "freezes" but the upper portion moves on to deposit a relatively well sorted turbidite. This process takes place over distances of < 10 km.

Thick bedded and massive coarse orthoconglomerates which have erosional contacts with sandstones of the underlying Serpent Formation are interpreted as resedimented deposits in submarine channels. At a higher level in the diamictite complex a large lenticular(?) body of stratified sandy rocks in the Bay of Islands area has many of the attributes of submarine fan complexes (Walker, 1978). A basal thinning and fining upward succession is comparable to deposits of a channeled suprafan; the overlying thickening upward sequences are similar to those of prograding depositional lobes on the suprafan. Palaeocurrents suggest that these lobes were growing in an eastward direction.

The Gowganda Formation ushered in a period characterised by relatively steep depositional slopes and with water sufficiently deep to allow accumulation of a thick resedimented succession without significant reworking. Such a change in depositional environment could be explained either by a rise in sea level or by tectonic subsidence of the basin. If the glacial origin of the diamictites is accepted then it is more likely that locking up of water in glacial ice would have led to a drop in sea level making the inferred deepening all the more remarkable and strongly suggesting subsidence of the depositional basin.

This interpretation is also given support by the change in palaeoslope direction inferred from palaeocurrents measured in the Serpent Formation and the lower diamictite complex. Deposition of the upper Serpent Formation took place subaerially or in very shallow water conditions with a local palaeoslope to the WSW (Fig. 6b). The resedimented units of the diamictite complex were transported to the ENE (Fig. 6b) and probably indicate a submarine slope in that direction. Such a sudden change in depositional regime and palaeoslope direction suggests significant tectonic movements causing foundering of the basin and concomitant regional tilting towards the east. This depositional phase was accompanied by regional faulting and subsidence as shown by the unconformable relationships between the Gowganda Formation and underlying Huronian formations in the northern part of the Huronian outcrop belt (Zone 2, Fig. 1) and by overstep of the Gowganda Formation onto the Archaean basement. This regional subsidence was compared by Young (1983) to that which occurs at newly formed continental margins after rifting and fragmentation. The lower diamictite complex is comparable to sediments described by Powell (1984) as forming where outlet glaciers with melting/freezing bases enter the sea as an ice shelf or floating glacier tongue. He stated (p. 34) that "while the grounding line is at the continental shelf edge, large volumes of debris may be dumped down the continental slope to create a submarine wedge (rather than fan)..... of sediment gravity flow sequences and glaciomarine diamictons".

UNIT 2: MIDDLE ARGILLITE MEMBER

This unit ranges in thickness from about 100 to 240 m. The rocks are mostly dark grey-to-blue, green-weathering argillites with thin buff-coloured silty layers. The basal 50 cm contains small scattered clasts in faintly laminated mudstone. Throughout the remainder of the unit no exotic clasts were noted and it consists almost exclusively of mud grade material. In areas of good exposure the argillite can be subdivided according to the bedding characteristics. The thin clast-bearing basal unit is followed by a very fine grained mudstone with parallel laminations and some cross laminated siltstones. This is overlain by argillite containing thicker light-weathering silty laminae. Some portions of Unit 2 have thin load casted lenticular silty lenses with ripple cross laminations (Fig. 7C). Some silty beds are subtly graded. These different facies are interbedded on a scale of tens of metres. A few thicker (up to 30 cm) homogeneous mudstone layers are present. Some of these contain contorted fragments of the enclosing laminated argillite. The fragments have diffuse boundaries. Cross laminated siltstones are more common in the upper part of Unit 2.

Interpretation of the Middle Argillite Member

The transition from diamictite to argillite with scattered clasts suggests a recession of the ice that was the ultimate source of the diamictites. Small clasts in the basal part of the argillite were probably emplaced by ice rafting. The remainder of the argillite contains no field evidence of glacial influence. The fine grain size and ubiquitous fine laminations suggest deposition below wave base. Thin graded silty layers are interpreted as deposits of distal turbidity currents. Isolated lenses of cross laminated siltstone are traction current deposits laid under conditions of limited sediment supply (starved ripples).

Turbidites of proximal aspect are reported from Deep Sea Drilling Project Site 325 by Tucholke et al. (1976) from the continental rise in water depths of about 3700 m in an area off Antarctica. Piper and Brisco (1975) reported laminated and ripple cross laminated lenticular muddy sediments from similar water depths at D.S.D.P. Site 268. They ascribed sedimentation at such depths to a variety of processes but emphasized the role of bottom (contour) currents. The argillites of Unit 2 are very similar to those described from these deep water environments. Coarse silty beds in the upper part of Unit 2 suggest a more proximal and/or prolific source of slightly coarser detritus. Rare beds of homogeneous (i.e., non-laminated) siltstone could have been produced as storm deposits or by remobilization related to slope instability. Highly contorted rafts of laminated argillite with diffuse boundaries indicate the "secondary" nature of these beds.

Most of Unit 2 was probably deposited in relatively quiet and probably deep water. Accumulation of mudstones above the coarse grained, largely resedimented diamictites of Unit 1 suggests that the basin remained relatively deep but the absence of coarse grained resedimented materials may indicate that contemporaneous fault activity was much less prevalent than during deposition of the underlying diamictites. Basin depth was maintained either by regional subsidence or by rising sea level. Because the argillites were probably deposited during a period of glacial retreat a eustatic sea level rise is possible. The grounding line moved back from the edge of the continental shelf causing sediment starvation in more distal areas (Powell, 1984, p. 34).

Dropstones in the basal part of the argillite indicate that floating ice was present during recession of the glaciers. Scattered clasts in the topmost part of the argillite likewise attest to a readvance of the ice from which the upper diamictite complex was deposited.

UNIT 3: THE UPPER DIAMICTITE COMPLEX

This member is stratigraphically complex and includes several discontinuous units. For descriptive purposes it is divided into stratigraphic units designated "A", "B", "C" etc.

Unit 3A

On the north limb of the McGregor anticline the lowest unit of the Upper Diamictite Complex is discontinuous and up to 30 m in maximum thickness. In the Bass Lake syncline (Figs. 2,4) it is about 150 m thick and is composed of dark grey, grey-green-weathering argillite with scattered clasts, together with diamictite and buff coloured sandstones. In some places it shows a transitional boundary with the underlying argillite; the top 75 cm of the argillite is massive and shows a gradual upward increase in abundance of small clasts and silty and sandy lenses. This grades up into finely laminated mudstones, siltstones and sandstones with some scattered dropstones.

Interpretation of Unit 3A

The near-ubiquitous presence of bedding and the gradational contact with the underlying basinal argillites suggest that the "diamictite" of Unit 3A is waterlaid. Scattered clasts were probably dropped from floating ice of the second glacial advance.

Unit 3B

This unit consists mainly of sandstones and orthoconglomerates. It is up to 90 m thick in the western part of the study area but to the east it is < 20 m. In some areas it comprises a large scale fining upward sequence from boulder conglomerate to sandstones and finer grained rocks.

Throughout much of the study area the base of Unit 3B is marked by an erosional surface above which there is a series of boulder-bearing and finer grained conglomerates. The discontinuous nature of the underlying glaciomarinites suggests that erosion took place at the base of Unit 3B. At the outcrop level erosion is also indicated by the irregular basal contact which truncates underlying beds and by incorporation of large clasts of these beds in the basal conglomerate.

Locally (Fig. 6b) the basal part of Unit 3B can be differentiated into a thin laminated argillite (1—2 m thick) which grades upward into about 6 m of sandstones (commonly with contorted bedding) and thinner interbedded argillites. These two units comprise a thickening and coarsening upward sequence. Unit 3A is commonly preserved beneath these beds but is missing in many areas where the base of Unit 3A is conglomeratic.

The succession in Unit 3B varies greatly from place to place as can be seen

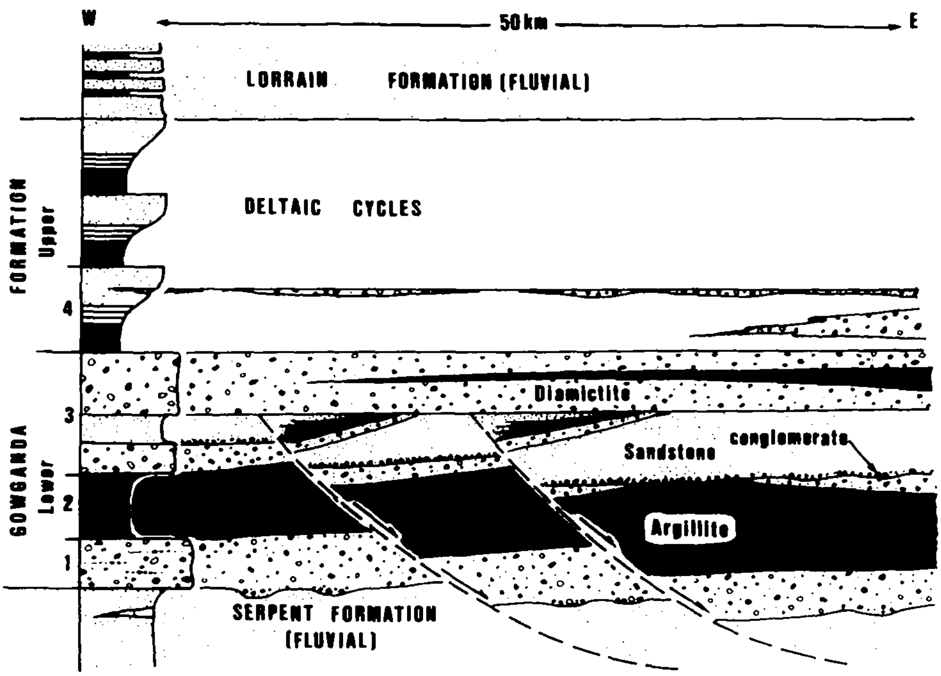


Fig. 9. Schematic representation of stratigraphic relationships among members of the Gowganda Formation along the north limb of the McGregor Bay anticline (Fig. 2). Note the fault-related sedimentary wedges in the middle part of Unit 3. Note also the easterly-thickening argillite unit in the upper diamictites of Unit 3. Diamictites are also present in Unit 4. Because of the great difference in horizontal and vertical scales (lower Gowganda Formation is about 1 km-thick), the faults are greatly magnified.

in the generalised sections of Figs. 4 and 9. Some details of the succession from selected areas are described below. Location of these sections is shown in Fig. 4.

Section I

At Section I (Fig. 4) Unit 3B is about 25 m thick and consists of three thinning and fining upward sequences (Fig. 10). It begins with a boulder orthoconglomerate with basement clasts up to 1 m across (Fig. 7D). It also contains large clasts of contorted argillite. The basal contact is erosive. The orthoconglomerate has an irregular upper surface with clasts protruding upward into the overlying beds.

The conglomerate is succeeded by sandstones and interbedded thin diamictite layers. A weakly graded sandstone at the top of this conglomeratic interval is erosively truncated by a second, thicker orthoconglomerate layer with inverse-to-normal grading and some pebbly layers. The upper 1–2 m of the conglomerate has a disrupted framework and is capped by a discontinuous layer of cobble and boulder orthoconglomerate.

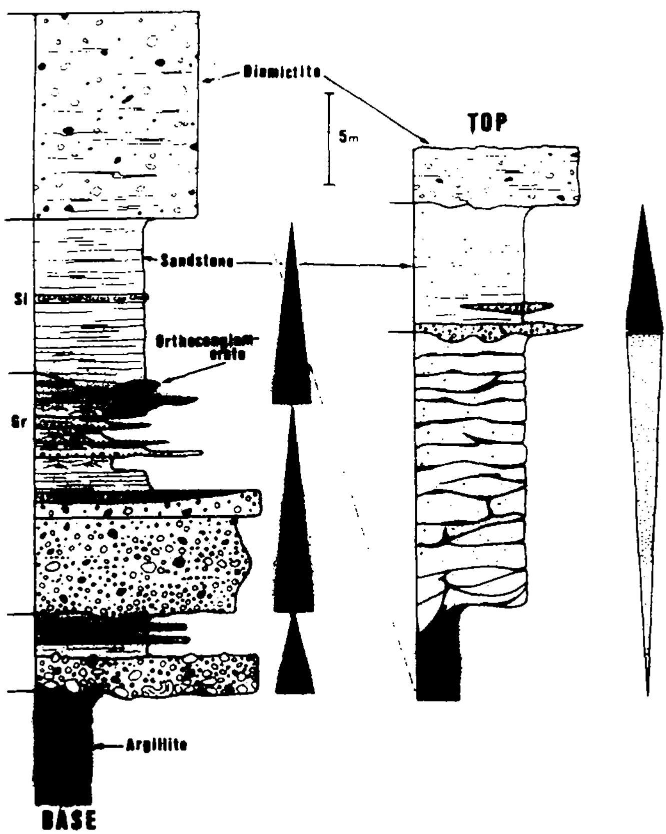


Fig. 10. Measured section of Unit 3 south of Whitefish Falls. This section is also shown in Fig. 4 (column I). It begins with an erosional-based boulder conglomerate (also shown in Fig. 7D) and consists of a series of thin resedimented sequences followed by a stratified diamictite, an argillite unit and a succession of lenticular sandstones. See text (Unit 3B, Section I) for discussion.

The overlying more finely stratified succession is a series of graded units each consisting of a thin pebble conglomerate above which are laminated and cross laminated sandstones, followed by silty contorted mudstones.

The next fining upward sequence begins at an erosive surface where at least 2 m of the underlying beds have been removed (Fig. 10). Near the base there are several thin (10—40 cm) lenticular pebble conglomerates with erosive bases and inverse grading. These are interbedded with, and overlain by, massive sandstone beds 40—50 cm thick and contorted sandy and silty beds. The contact with the overlying diamictite is conformable and sharp.

Section II

Section II was pieced together from excellent exposures on islands in the Bay of Islands (Fig. 4) about 8 km west of Section I. In this area Unit 3 has a maximum thickness of about 110 m and can be subdivided into five or six subunits (Fig. 11). The lowest is a series of boulder-to-pebble conglomerates

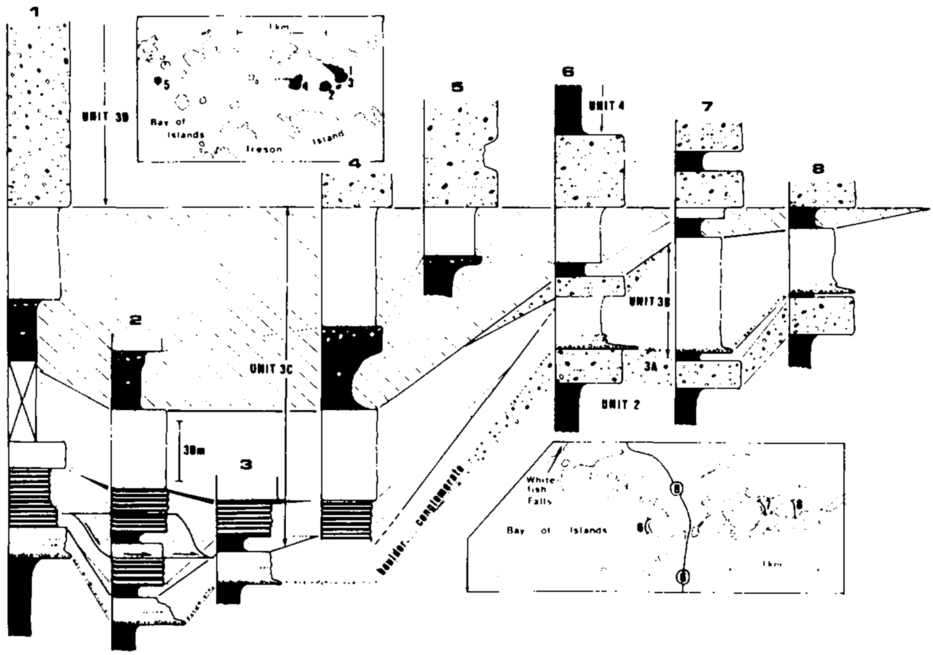


Fig. 11. Measured section of Unit 3 in the Bay of Islands and south of Whitefish Falls (insets) to show stratigraphic complexity. Symbols as in Fig. 4 except that horizontal stripes represent turbidites (see Figs. 7E, F and Fig. 15). The figure represents a strike length of about 8 km. Note that Unit 3C comprises two wedge-shaped, eastward-thinning, coarsening upward sequences. The lower one is indicated by dotted ornament between columns and the upper one by diagonal lines. Note also the continuous nature of the boulder conglomerate near the base of the illustrated sections.

with inverse-to-normal grading, interbedded with massive and graded sandstones. The succeeding units are considered later as part of Unit 3C.

Section III

In a section on the west side of Iroquois Bay (Fig. 4) about 4 km east of Highway 6, the base of Unit 3B is a boulder conglomerate that directly overlies argillites of Unit 2. Most of the measured section in this area consists of medium grained sandstones with small scale cross beds and ripple cross laminations, graded beds (commonly amalgamated) and some slumped beds. Some sandy beds have erosive bases and some have load and flame structures. There is a gradual upward decrease in the thickness of sandstone beds and an increase in the percentage of the section that is mudstone beds. Silty mudstone layers commonly exhibit ripple cross laminations and some are slumped. At the top of this rhythmic succession there is a 10 cm-thick bed of dark green mudstone followed by 40 cm of siltstone and mudstone with laminations and streaky irregular bedding. This is succeeded by Unit 3D which is a thick diamictite with poorly defined stratification.

Section IV

Section IV is located at the west end of Three Narrows Lake (Fig. 2) about 11 km east of Section III (Fig. 4). A pebbly orthoconglomerate overlies argillite of Unit 2 and is succeeded by about 28 m of sandstones with ripple cross laminations. The lower part of the sandstone succession includes pebble conglomerates but the upper part is massive medium sandstone beds with thin mudstones and thin diamictites. The sand-dominated unit is succeeded by diamictite.

Section V

About 16 km northeast of Three Narrows Lake an 80 m-thick section was measured on an island in Deacon Lake (Figs. 2,4,12). Neither the top nor the base of Unit 3B is exposed in this area. It consists mainly of sandstones with a variety of sedimentary structures. Many thicker beds are amalgamated graded beds; grading is weakly expressed due to the small range in grain size. Some sandstones contain rip-up clasts of mudstone (Fig. 13A). Ripple cross lamination is abundant in fine sandstones/siltstones and some cross bedding is present in coarse sandstone units. Contorted bedding is common. There is an upward increase in the proportion and thickness of sandstone beds. There are some weakly expressed fining and thinning upward sequences (Fig. 12).

Interpretation of Unit 3B

Resedimentation played an important role in the deposition of Unit 3B. The thickest succession occurs in the west at Section II (Fig. 4). To the east Unit 3B is generally between 20 and 60 m in thickness but a thicker section is preserved at Deacon Lake near the Grenville front. The basal contact is erosive and channeled on both a regional and local scale. Regional erosion is suggested by the discontinuous nature of the underlying glaciomarinite.

The lower part of Unit 3B tends to become finer grained upwards. Lateral continuity of such a coarse grained deposit throughout 50 km of strike length suggests derivation from a wide northern(?) source, rather than lateral transport in a direction parallel to the strike. The basal coarse grained portion of the succession is comparable to deposits of the proximal part of submarine fan complexes (Walker, 1975, 1977) or possibly a faulted basin margin (van de Kamp et al., 1974). Large clasts of varied composition were probably derived from contemporaneously deposited glacial debris on the basin margin. The coarse nature of these conglomerates, their channeled bases and the common occurrence of inverse-to-normal grading all suggest that the material is not far travelled. Argillites and sandstones that are locally preserved in the basal part of Unit B may be more distal facies that were subsequently overridden by the coarser grained proximal deposits.

Above the conglomerates, thinner bedded and finer grained units are commonly arranged in fining and thinning upward sequences like those developed on a channeled suprafan complex. Many of these sequences have

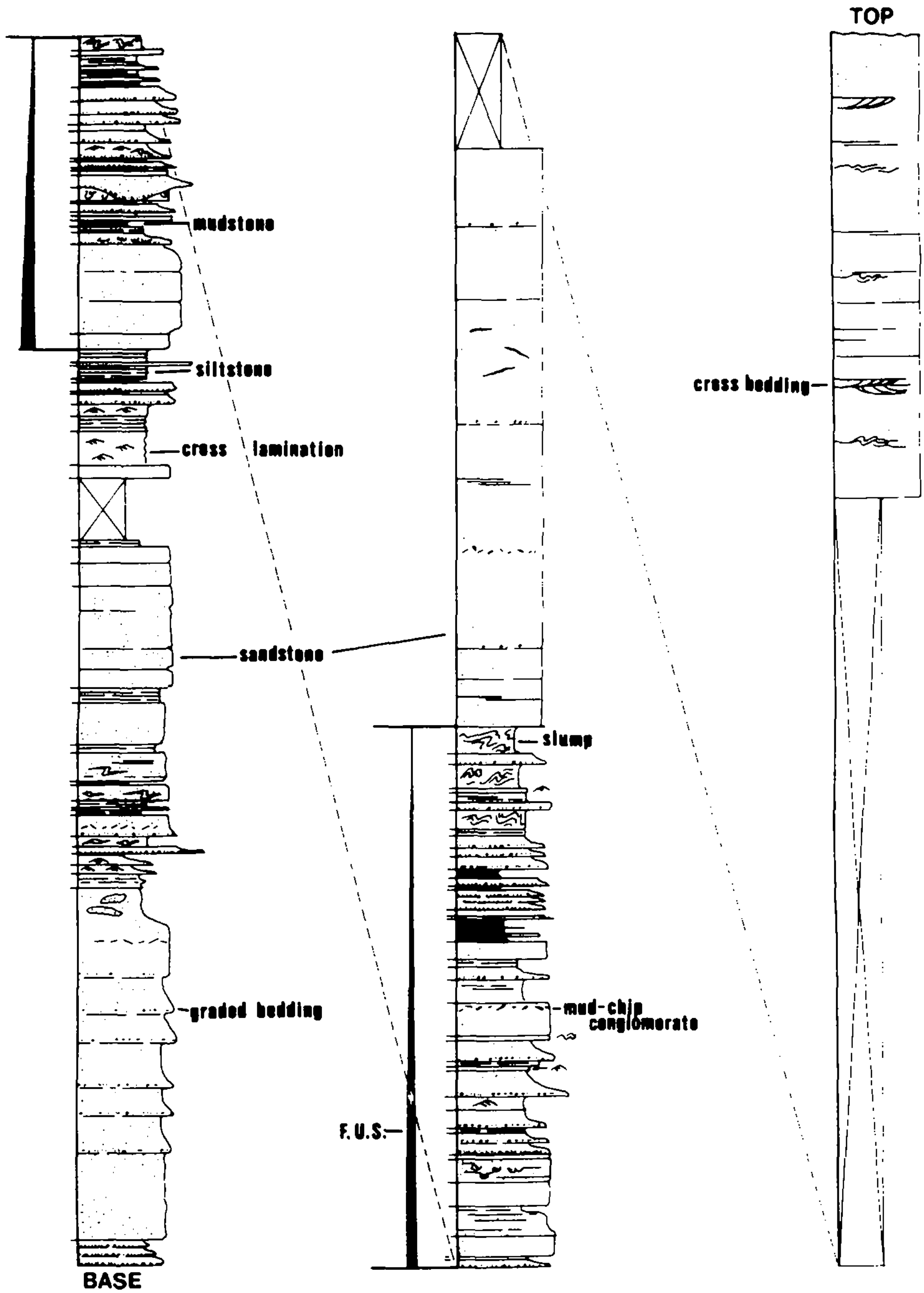


Fig. 12. Measured section of resedimented sandstones of Unit 3 at Deacon Lake near the Grenville Front. See Fig. 2 for location of Deacon Lake and Fig. 4 for the position of these rocks on a generalised stratigraphic section. Part of the section is interpreted as fining upward sequences (F.U.S.). Each column represents 27.5 m of section.

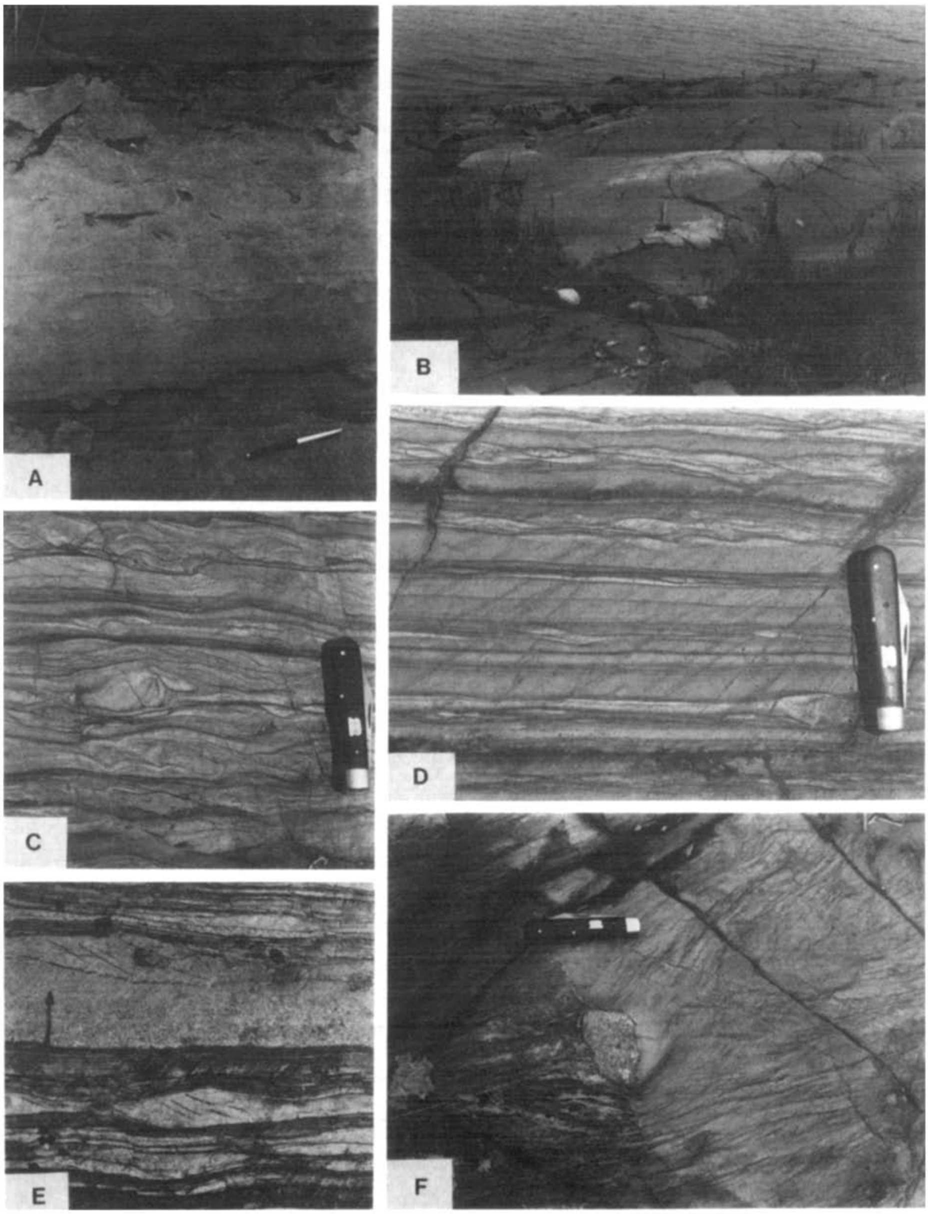


Fig. 13. (A) Rip-up clasts in a resedimented sandstone bed of Unit 3 at Deacon Lake (see Figs. 2, 4 and 12 for more information). Note flame structures in lower part of bed. Pen is 14 cm long. (B) Large (3 m across) granitic clast in the lower part of Unit 3 (upper diamictite complex) in the Bay of Islands. (C) Slumped wavy bedded and ripple cross laminated siltstones/mudstones in the central part of a westerly-thinning argillite unit in the upper diamictite complex (Unit 3) in the western part of Iroquois Bay (see also Figs. 2, 4 and 16). Knife is 10 cm long. (D) Parallel and wavy bedded mudstones in the upper

pebbly layers at the base, suggesting deposition in a proximal situation. There is considerable lateral variability. The topmost subdivision of Unit 3B in the Bay of Islands is sand-dominated. It is tentatively interpreted as grain flow deposits laid down in a channeled suprafan (Walker, 1975, 1978).

Palaeocurrents directions from small scale cross beds of Unit 3B in the Bay of Islands, at Iroquois Bay and at Deacon Lake near the Grenville front all have a strong easterly component (Fig. 6b) reflecting a palaeoslope towards the east. The lack of consistent facies changes in that direction suggests a broad source region such as the fault-bounded rim of the depositional basin. As was inferred for the basal diamictite complex, these largely resedimented rocks are considered to have been derived from glacially-transported debris shed from outlet glaciers which formed a marine ice shelf or glacier tongues with a grounding line close to the basin margin or continental shelf edge.

Unit 3C

As discussed above, Unit 3B shows lateral variability but the basal conglomerate is essentially through-going in the study area. Above Unit 3B and below the next extensive thick stratified diamictite there is a series of units that display interesting lateral variations. These are known only from the western part of the study area. Detailed mapping of the near-vertical beds (Figs 6a, b) shows that, in section, they comprise two wedge-shaped bodies nearly 100 m in maximum thickness. The units terminate against a fault in the west and pinch out in an eastward direction over a distance of a few kilometres. The stratigraphic succession in each of the bodies is similar, involving a lower diamictite followed by argillite, then a thick sandstone sequence.

The Eastern Wedge

The more easterly of the two wedges is bounded to the west by a NW-trending fault with apparent left-lateral movement of about 100 m (western part of Fig. 6b). A dyke of Nipissing diabase locally follows the fault trace, suggesting that the fault pre-dated the intrusion. On the east side of the fault some new stratigraphic units are introduced into the succession. The first of these, above sandstones of Unit 3B, is a diamictite with vague stratification

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part of the argillite unit in the upper diamictite complex (Unit 3), west side of Iroquois Bay (Figs. 2, 4 and 16). Note graded beds at the level of the knife which is 10 cm long. (E) Graded beds (arrow) and ripple cross laminations (enhanced by marker pen) in the upper part of the argillite unit in Unit 3 at the west end of Iroquois Bay. Photo represents about 20 cm of stratigraphic section. (F) Highly contorted and disrupted argillite beds of Unit 4 above the upper diamictite complex. These beds contain dropstones and are probably a distal equivalent of a thick diamictite unit at Three Narrows and Deacon Lakes (Figs. 2 and 4).

and broken and contorted beds of silty material in a finer grained muddy matrix. It contains many clasts up to 15 cm in diameter; one boulder with a diameter of 1.2 m was noted. This diamictite is 5 m thick near the fault but thins rapidly to the east and pinches out after about 500 m. It is overlain by a thin succession of sandstone and argillite containing some small granite clasts and abundant small angular clasts of argillite. This unit has a lateral extent of about 1.5 km and terminates in outcrops on the west side of Iroquois Bay. It is succeeded by about 20 m of silty and sandy argillite containing abundant mud chips. Sandstone lenses, 10—70 cm-thick, are scattered throughout this unit but are especially common near the top. Towards the east mud chips are less abundant. The top unit has a lateral extent of about 1 km.

Interpretation of the Eastern Wedge

Because these stratigraphic units are recognised only on one side of a fault their development may be related to penecontemporaneous movements of the fault. The easterly-thinning wedge-like shape of the units suggests derivation from a fault scarp and sedimentation in an apparently eastward direction. The fault was probably a normal down-to-basin fault downthrown to the east (Fig. 14).

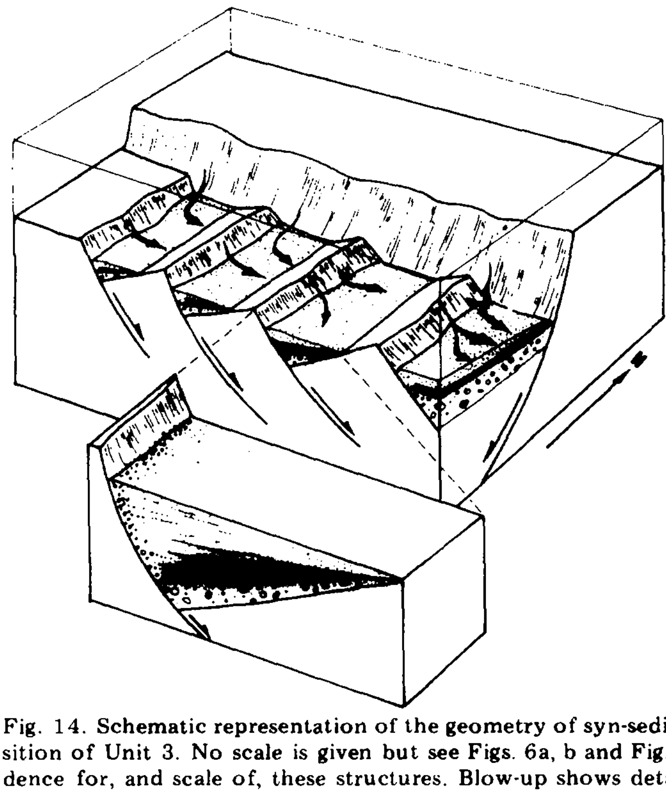

Fig. 14. Schematic representation of the geometry of syn-sedimentary faults during deposition of Unit 3. No scale is given but see Figs. 6a, b and Fig. 11 for depiction of the evidence for, and scale of, these structures. Blow-up shows details of the stratigraphic succession in one of the wedge structures.

The origin of the diamictite at the base of the sedimentary wedge is problematic for there is no obvious source of such coarse grained material in the immediately underlying beds. It might possibly represent locally preserved deposits of a glacial advance preceding that which deposited the widespread diamictites at the top of Unit 3C. The succeeding mud-chip-bearing argillite and sandstone units are interpreted as the coarsening-upward deposits of a prograding submarine fan complex shed from the fault scarp. The abundant mud chips indicate reworking and resedimentation of earlier deposited muds. The eastern limit of these mudstones and sandstones is probably an approximate depositional limit of the submarine fans.

The Western Wedge

A succession similar to that described above is present at about the same stratigraphic level in the Bay of Islands. This westerly wedge has a lateral extent of at least 9 km. On the eastern shore of the Bay of Islands (Fig. 10, col. 6, Fig. 11) the succession above resedimented conglomerates and sandstones of Unit 3B begins with about 11 m of "diamictite" containing some silty and sandy beds and lenses. This is overlain by up to 5 m of silty argillite with slumped bedding and flame structures. There are scattered granitic clasts up to 15 cm in diameter in the argillite. The upper surface of the argillite is undulose and irregular with large lenticular sandstone bodies depressing it into a series of open "synclines" and sharp "anticlines". Some of the sandstones have erosive contacts with the argillite and are probably channel fillings. The bases of some sandstone bodies are graded pebble and cobble orthoconglomerates. These grade up into massive-to-laminated medium-to-coarse sandstones, some of which are ripple cross laminated. A few scattered granules and pebbles of plutonic rocks are present in the sandstones.

In some exposures the sandstones have the form of "pods" or "pillows" (Fig. 10) a few metres to tens of metres long. The pods are separated and surrounded by thinner (a few tens of centimetres) units of dark grey argillaceous material. These sandstones commonly have large scale load structures and there are injections of mudstone into the sandstones. About 16 m of this material is succeeded by a sequence of lenticular pebble and cobble conglomerate showing inverse-to-normal grading. These conglomerates pass up into massive coarse sandstones with poorly defined contorted laminations.

To the west, in the Bay of Islands (Fig. 11), the same stratigraphic units are much thicker (compare columns 6 and 4 of Fig. 11). The glaciomarinite that forms the base of Unit 3C at the east end of the Bay of Islands (Fig. 11, col. 6) is much thicker and comprises laminated and faintly bedded silty and finer grained mudstones with scattered clasts. Convolute bedding is common. In some areas the basal and upper parts are more massive and diamictite-like. This unit is overlain by a thick succession of massive, laminated and locally cross laminated sandstones like those at the east end of the Bay of Islands.

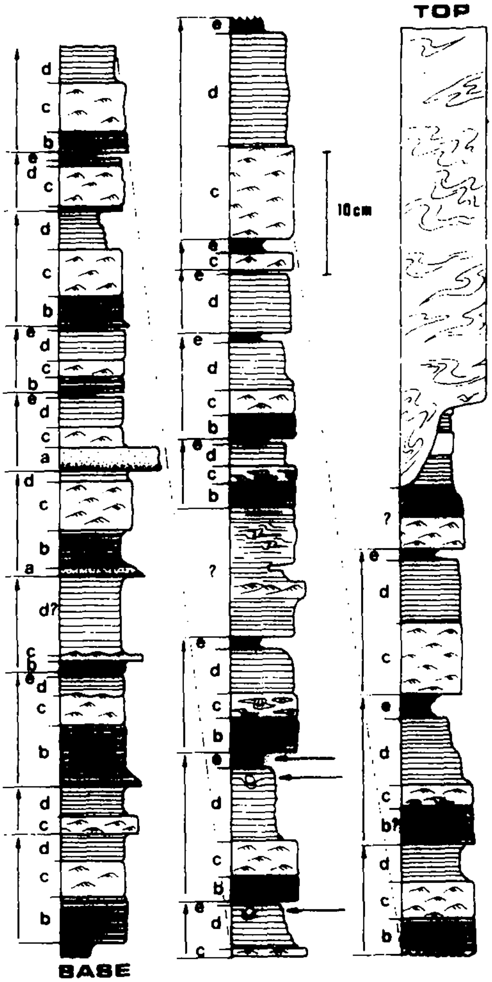

Fig. 15. Detailed section to illustrate part of the turbidite succesion in Unit 3 in the Bay of Islands. These beds are also illustrated in Figs. 7E, F and in Fig. 11 (horizontal stripes). See text for discussion.

The various units involved in the western wedge are up to 100 m thick in the west and pinch out in an eastward direction over a strike length of about 9 km. The basal diamictite is the least extensive of the three units; the argillite is the most extensive.

In the western part of the Bay of Islands these units are underlain by another coarsening upward succession. It comprises a basal 6—10 cm-thick argillite which passes gradationally upward into rhythmically bedded sandstones and argillites. This is terminated in some areas by a thin (1.5 m) silty argillite, followed by a thick succession of massive-to-thick bedded fine-to-medium grained white, grey and pink arkosic sandstones with subordinate thinner beds of poorly exposed silty argillite. The sandstones have few sedimentary structures. In one section (column 2, Fig. 11) part of the succession is repeated by faulting.

The rhythmically bedded unit is illustrated in Fig. 7E. A small measured section is shown in Fig. 15. It consists of fine sandstones, siltstones and mudstones. Common sedimentary structures include laminations, graded beds, ripple cross laminations (Fig. 7F), load casts and slumped beds. In the middle part of the measured section several small (few cm diameter) granitic clasts were noted. At the top of the detailed section (Fig. 15) a 60 cm-thick bed with an erosive base is highly contorted.

Interpretation of the Western Wedge

The western wedge is thicker and more complex than that on the east side of Highway 6. It involves two coarsening upward sequences from argillite to sandstone. The basal argillite grades up into coarser grained rocks interpreted as more proximal facies of a submarine fan complex. The middle portion of the lower coarsening upward sequence is a series of turbidites. Rare graded beds represent the "A" division of the Bouma sequence. Most beds begin with the "B" portion, suggesting deposition in a rather distal setting. The dominance of fine sandy material and the presence of slumped beds suggests an intermediate position in the outer fan environment. Scattered granitic clasts, particularly those in the "E" portion of the turbidite sequences (Fig. 15), indicate the presence of floating ice. Repetition of parts of this succession in the western Bay of Islands area (Fig. 11) may be due to contemporaneous down-to-basin faulting.

The overlying beds also comprise a coarsening upward sequence. In Section 6 (Fig. 11) a basal diamictite is shown whereas in other sections to the west, the second coarsening upward sequence (diagonal hatching) begins with a unit called an argillite. This differentiation is somewhat arbitrary for in some places in the western Bay of Islands the argillite contains many clasts, particularly near its base and top. This unit was probably formed by rain out and reworking of ice-transported debris, but the upward transition from dominantly argillaceous material to sandy deposits suggests progradation of a submarine fan complex. These units extend farther east than the deposits of the underlying coarsening up sequence.

Like the deposits of the eastern wedge, these rocks may have been shed from contemporaneous fault scarps. Water cover in the Bay of Islands precludes identification of a specific fault but the regional map of Card (1978) shows a large northwest-trending fault just to the west of Ireson Island. Paleocurrent directions from ripple cross laminations in the turbidite and eastward thinning of stratigraphic units suggest easterly transport.

Unit 3D

In the western part of the study area in the Bay of Islands the upper diamictite is > 200 m thick (Fig. 4). To the east it is between 60 and 100 m in thickness. The basal contact is irregular but sharp. In some areas irregular-shaped masses of the underlying sandstone are incorporated in the diamictite. The diamictite is typically vaguely stratified. West of Highway 6, Unit 3 is composed almost entirely of diamictite with some silty lenses and beds and slumped pods of siltstone and laminated argillite. In the Bay of Islands a granite clast 3 m across (Fig. 13B) was noted near the base. It also includes laminated argillites with dropstones and there are lenticular beds of granule and pebble orthoconglomerate with normal and inverse-to-normal grading. About 10 km to the east, near Highway 6, Unit 3 is only about 30 m thick and contains abundant contorted and slumped argillite, siltstone and sandstone layers and lenses.

Farther east the diamictite includes an eastward-thickening argillite up to 50 m thick. Diamictites above and below the argillite include massive and stratified facies. In some places the upper part of the diamictite can be subdivided into stratified and more massive facies.

Interpretation of Unit 3D

These diamictites are interpreted as glacial marine deposits probably formed by rain out from floating ice. Massive facies represent periods of rapid deposition and/or weak bottom currents. More stratified parts with interbedded graded conglomerates, sandstones, siltstones and mudstones are, at least in part, resedimented. Some cross laminated siltstones were probably deposited by traction current during periods of decreased rain out of glacial debris.

Unit 3D:Argillite

The argillite unit appears just east of Highway 6 and thickens eastward to more than 50 m on the west side of Iroquois Bay (Fig. 11). Just east of the highway the argillite comprises a coarsening upward sequence of massive argillite, laminated argillite with clasts and argillite with siltstone lenses and fine sandstone beds up to 5 cm thick. It passes gradationally into sandstone/diamictite of the overlying diamictite complex.

A well exposed section in the western part of Iroquois Bay is illustrated in Fig. 16. The section begins with vaguely stratified silty argillite and passes up into highly slumped laminated silty argillite. About 4 m above the base a unit with convolute bedding includes lonestones. These beds pass upward into thin bedded siltstones and mudstones which are in turn succeeded by wavy and lenticular bedded ripple cross laminated siltstones with finer grained mudstone interbeds. This silty facies is in abrupt contact with a fine grained pervasively slumped argillite unit which passes in turn into a thin (3—4 m) wavy bedded unit of ripple cross laminated siltstone and fine mudstone (Fig. 13C). This is followed by a thick (26 m) coarsening upward unit of parallel bedded siltstone and argillite (Fig. 13D). This unit contains some graded silty mudstone beds up to 25 cm thick. The top 9 m of the argillite is pervasively slumped siltstones with minor finer grained material. Above a sharp contact there are silty diamictites, sandstones etc. of the upper part of the diamictite complex.

Interpretation of Unit 3D: Argillite

At the measured section in Iroquois Bay this unit forms two coarsening upward sequences. An unstable depositional slope is suggested by the pre-

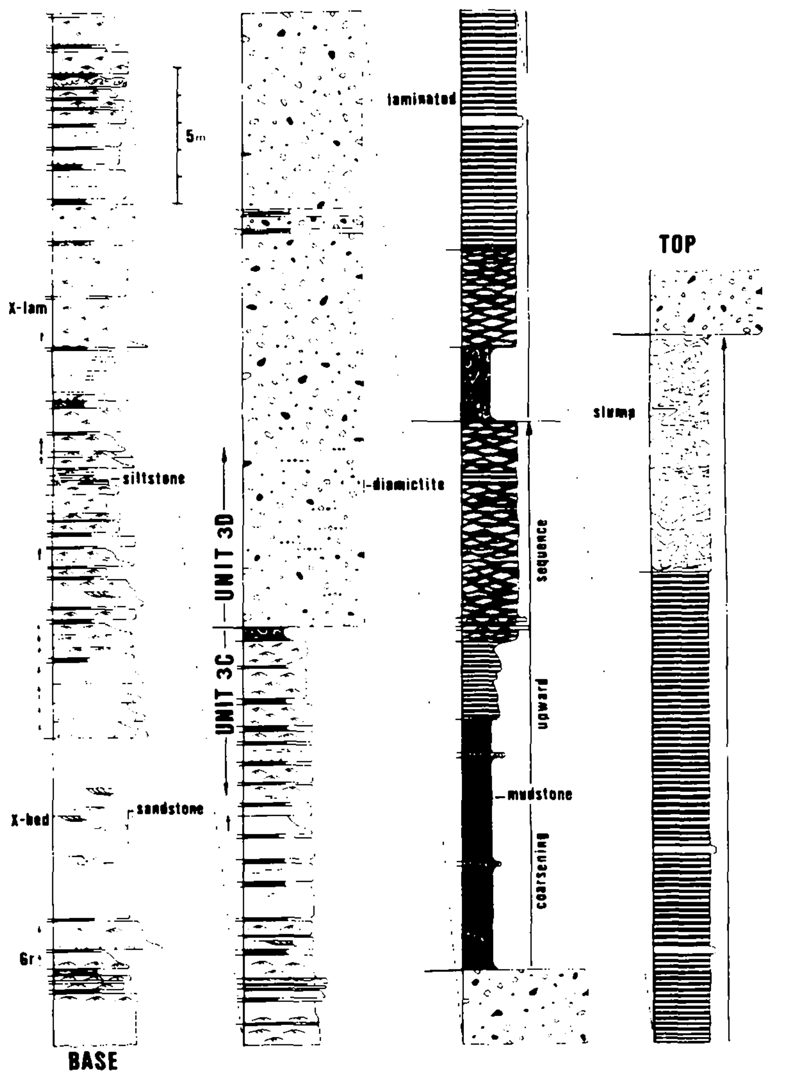

Fig. 16. Measured section of part of Unit 3 at the west end of ıroquois Bay. Unit 3C is a series of sandy turbidites. Unit 3D is mostly diamictite but in this area (see Fig. 2 for location of Iroquois Bay and Fig. 4 for regional stratigraphic context) it also includes a stiltstone/mudstone unit.

sence of contorted and slumped beds and graded layers formed by homogenization of the enclosing laminated materials during downslope movements. Palaeocurrents from small scale cross beds in silty units of the argillite at Iroquois Bay (Fig. 13E) indicate transport to the ENE. The virtual absence of dropstones in the argillite is puzzling in view of its association with diamictites of presumed glacial origin. The argillite could have been deposited under conditions of near-complete withdrawal of glacial ice when the grounding line lay far to the north and the basin was starved of coarse debris. Alternatively, if glacial ice were still present in the vicinity it may have been a frozen-base ice sheet ending as a tidewater front. Such an ice sheet would have produced very little coarse sediment (Powell, 1984). Another possibility is that sea ice temporarily prevented the movement of debris-rich icebergs. The coarsening upward nature of the sequences within the argillite unit suggests a progradational regime, possibly a series of deltas. This interpretation is also favoured by the evidence of slope instability in some parts of the argillite.

UNIT 4: THE LOWER COARSENING UPWARD SEQUENCE

This study is concerned mainly with the diamictite-bearing portion of the Gowganda Formation which has generally been considered to terminate at the top of the Upper Diamictite Complex, Unit 3. In the course of field work, however, and partly as a result of geochemical investigations to be reported elsewhere, it became apparent that there is additional evidence of glaciation higher in the succession.

The upper part of the Gowganda Formation in the Whitefish Falls area is made up of a series of large scale coarsening upward sequences that were interpreted by Lindsey (1969) as deltaic cycles. The basal part of each cycle is fine grained, finely laminated argillite which has a sharp contact with underlying beds. The lowest argillite unit is pervasively slumped and is typically disrupted and fragmented (Fig. 13F). Isolated clasts of granite and other basement rock types are present in laminated siltstones about 50 m above the base of the argillite. In upward succession the argillite becomes coarser and less slumped. The upper limit for mapping purposes was taken at the first occurrence of lenticular sandstones. In the eastern part of the study area, near the Grenville front, a thick (200 m) diamictite is developed in the lower argillite (Fig. 4). The diamictite thins to the west. On the east shore of Helen Lake it is succeeded by an argillite unit containing a thin diamictite immediately below lenticular sandstones like those noted to the west. Thus the thick diamictite is locally developed in the coarsening upward argillite at the base of Unit 4. The upper thin diamictite appears to be more widespread.

Interpretation of Unit 4: The lower coarsening upward sequence

After Lindsey (1969), the coarsening upward argillite—siltstone—sandstone sequence is interpreted as the product of a prograding delta. Scattered clasts in the lower part suggest the presence of floating ice. Widespread slumping in the lower part of the succession probably reflects contemporaneous tectonic activity. Ice rafted clasts which are widespread at about 50 m above the base of the argillite may be a distal expression of the glacial event indicated by a thick diamictite in the eastern part of the study area. These relationships suggest easterly derivation of the ice.

A thin diamictite is also present near the top of the argillite. The coarsening upward succession of the argillite is probably due to progradation of a deltaic complex during the waning phase of the Gowganda glaciation. The succeeding coarsening upward sequences are also considered to be deltaic but contain no field evidence of glaciation.

SUMMARY OF DEPOSITIONAL HISTORY

A dramatic change in depositional environment occurs at the Serpent–Gowganda boundary (Fig. 17). The Serpent Formation formed in fluvial, eolian and possibly shallow marine conditions. These essentially subaerial environments indicate a basin-full condition even in the southern areas studied for this report. Palaeocurrents from the Serpent Formation indicate

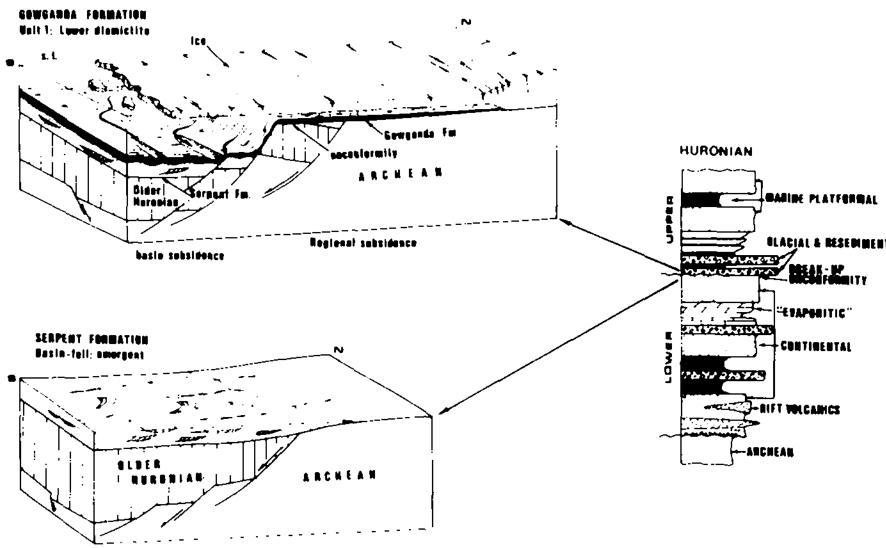

Fig. 17. Interpretation of the Huronian succession (stratigraphic column represents a maximum thickness of about 12 km) in terms of a continental separation. The lower Huronian (below the Gowganda Formation) is considered to have formed in response to contemporaneous rift faulting. Carbonates of the Espanola Formation may represent a restricted "evaporitic" phase prior to separation. Stratigraphic relationships beneath the Gowganda Formation are comparable to those at the "breakup" unconformity in other successions ascribed to continental separation. Sketches on the left contrast basin-full condition at deposition of the Serpent Formation with deeper water conditions inferred for the Gowganda Formation. Both local, fault-related subsidence, and regional subsidence, accompanied deposition of the Gowganda Formation.

a local palaeoslope to the southwest prior to deposition of the Gowganda Formation in contrast to easterly palaeocurrents obtained from small scale cross beds in the Gowganda Formation.

The basal unit of the Gowganda Formation was largely the result of resedimentation of glacially transported debris. The most likely glacial regime (Powell, 1984) is where outlet glaciers with melting/freezing bases entered the sea as an ice shelf or floating glacier tongue. If the grounding line were near the fault-bounded basin margin, large volumes of debris would have been resedimented into deeper environments (Powell, 1984). The formation boundary is commonly erosional with resedimented coarse ortho-conglomerates filling channels in the upper Serpent Formation. Turbidite beds near the base of the Gowganda Formation were commonly disrupted by early slump movements. Thus the base of the Gowganda Formation marks a significant and probably rapid deepening of the basin (Figs. 17, 18). This was probably due to tectonic subsidence. Such tectonic readjustment is also in keeping with observed unconformable relationships beneath the Gow-

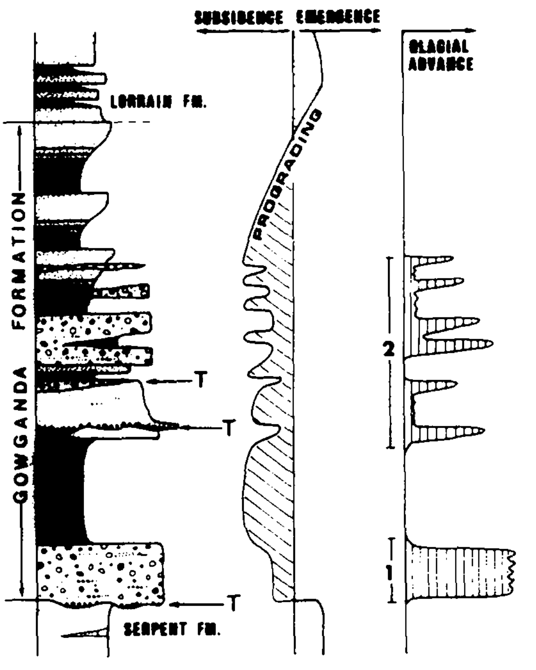

Fig. 18. Schematic representation of the stratigraphy of the Gowganda Formation in the southern part of the Huronian outcrop belt. Ornaments are as in Fig. 4. The diagram also includes an interpretation of subsidence—emergence and glacial advance—retreat. There were two major glacial advances, the younger one being more complex. The basin was also tectonically active. Major periods of tectonic subsidence are indicated by the letter "T". Note that the inferred subsidence at the base of the Gowganda Formation was accompanied by a major glacial advance and was therefore probably largely of tectonic origin. Glaciation would normally be expected to result in a eustatic sea level drop.

ganda Formation in more northerly parts of the Huronian outcrop belt. Recently Miall (1983) suggested a glacial marine origin for the Gowganda Formation in the Cobalt region. This interpretation lends support to the idea of regional subsidence during Gowganda deposition. The phase in the tectonic evolution of the Huronian depositional basin was ascribed by Young (1982) to a period of post-rifting regional subsidence that characterizes many orogenic belts (Hoffman et al., 1974).

After deposition of the lower diamictite complex, which is considered to be mainly resedimented glaciogenic debris, argillites of Unit 2 were deposited in deep water during a glacial recession. Northward retreat of the ice grounding line during this phase may have excluded coarse debris from more distal parts of the basin. A second glacial advance (Fig. 18) was responsible for deposition of Unit 3, the upper diamictite complex. At the base of Unit 3 a discontinuous glaciomarinite is followed by a regionally extensive resedimented boulder conglomerates with erosive basal contacts. The conglomerate is succeeded by finer grained resedimented rocks including turbidites. Widespread development of these conglomerates and associated rocks is thought to be related both to advance of the ice grounding line and tectonic subsidence. No palaeocurrent indicators were found in the basal coarse deposits but their wide distribution suggests derivation from a broad source area in the vicinity of the tectonically active basin margin to the north. Palaeocurrent data from the finer grained upper portions show a consistent eastward transport related to the palaeoslope of the axial part of the basin.

After deposition of a third thin glaciomarinite there was a third period of tectonic instability. This resulted in development of contemporaneous fault scarps that shed sediment to the east. The discontinuous units produced during this phase have been problematic in earlier attempts to understand the stratigraphy of the Gowganda Formation in this area (Lindsey, 1969; Young, 1981). Because the resedimented units become thinner to the east, and palaeocurrents in associated rocks indicate easterly transport, the faults are interpreted as north-trending step faults, downthrown towards the east.

Stratified diamictites overlie the fault-controlled resedimented beds. Towards the east the diamictites include an argillite unit interpreted as part of a deltaic complex. Above the diamictites a pervasively slumped argillite represents another period of tectonic instability. The argillite is part of a coarsening upward sequence of probable deltaic origin. A thick diamictite is present in this argillite in areas close to the Grenville front but it thins to the west where it is represented only by scattered dropstones in the middle portion of the argillite. The diamictite may have been derived from the northeast whereas palaeocurrent data and thickness variations in the underlying units suggest transport to the east, down the axis of the depositional basin. An extensive but thin diamictite layer near the top of the argillite reflects a final phase of glaciation.

THE HURONIAN AS A PASSIVE MARGIN SUCCESSION

Recent studies of passive continental margins particularly in the peri-Atlantic area (Grow, 1981) have led to development of a generalised tectono-stratigraphic model which includes the following elements:

(1) a fault-related, spatially-restricted, largely terrestrial succession with associated volcanic rocks;

(2) a marine facies that formed in tectonically restricted basins. In appropriate latitudes this succession includes evaporites (Burke, 1975); and

(3) a widespread open marine assemblage that commonly begins with resedimented rocks and displays evidence of upward shallowing. These are the deposits of the wedge, slope and continental rise. They are commonly separated from the underlying sedimentary rocks by the "breakup" unconformity which is attributed to regional subsidence after thinning of the crust and removal of the newly formed continental margin from the heat source that produced the initial rifting.

The Atlantic borderlands provide the "type area" for the classical stratigraphic assemblage produced at a passive continental margin (Evans, 1978; Ojeda, 1982). An ancient example was described by Hoffman et al. (1974) from the early Proterozoic of the northwestern part of the Canadian Shield. Other types of stratigraphic succession are, however, known from passive continental margins. For example the succession on the north side of the Bay of Biscay (Graciansky et al., 1979) and portions of the ancient continental margin of the Tethyan ocean (Bernoulli, 1981) lack the early rift-related and restricted facies of (1) and (2) above. Instead they consist of shallow marine deposits that were faulted and unconformably overlain by a deeper marine assemblage.

The Huronian succession has many of the attributes of the classical Atlantic margins. The lower Huronian with its rift-type volcanic rocks (Sawiuk, 1977) and fault-related, largely continental succession would correspond to Phase 1 above. The lower Huronian does not include any classical evaporites such as bedded sulphate deposits but calcareous and dolomitic rocks of the Espanola Formation may have formed as chemical precipitates in a restricted evaporitic setting (Fig. 17). The wide distribution and resedimented nature of the Gowganda Formation invite comparison with Phase 3 and suggest deposition during a period of regional subsidence. The unconformity beneath the Gowganda Formation (Zone 2, Fig. 1) is comparable to the breakup unconformity of many continental margin assemblages. One significant difference is the glaciogenic nature of the Gowganda Formation; such rocks are not preserved in the sedimentary assemblage that records continental fragmentation around the Atlantic Ocean. Such an association is, however, common in late Proterozoic successions in many parts of the world (Schermerhorn, 1974). The basal deposits of the late Proterozoic Windermere Supergroup along the length of the Canadian Cordillera are glaciogenic (Aalto, 1971; Young, 1976, 1982; Eisbacher, 1978; Yeo, 1981). Yeo (1983) proposed a causative relationship between continental rifting and glaciation. He suggested that uplift associated with continental rifting may have initiated glaciation which was then propagated by the opening up of new seaways into the continental seaway to provide the necessary moisture. In southeastern Australia Preiss (1983) interpreted the middle—late Proterozoic succession in the Adelaide Geosyncline as the product of evolution of a continental margin. The breakup unconformity was placed at the base of the widespread Sturtian tillite. Thus in many, but not all, Proterozoic examples of continental rupture, the breakup unconformity appears to be overlain by glaciogenic deposits. The absence of such rocks from the "type area" of the Atlantic margin may be related to the relatively warm global climatic conditions that prevailed at the time of initiation of the Atlantic Ocean (Dorf, 1969; Crowell and Frakes, 1970; Williams, 1972).

During early Proterozoic time continental fragmentation in what is now the Great Lakes region, and possibly also in southeastern Wyoming (Karlstrom et al., 1983) appears to have been contemporaneous with a major glacial epoch. The association between glaciation and continental breakup is also common in late Proterozoic successions throughout the world. This association suggests, but does not prove, a causative relationship (Yeo, 1983, 1984) between continental fragmentation and some glacial deposits.

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