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**SÉDIMENTOLOGY AND GEOCHEMISTRY OF THE FIRSTBROOK MEMBER OF THE
GOWGANDA FORMATION IN THE EASTERN COBALT BASIN, ONTARIO**

by

ROBERT H. RAINBIRD, BSc.

A thesis submitted to the Faculty of Graduate Studies Research
in partial fulfillment of the requirements for the degree of
Master of Science, Department of Geology

Carleton University

Ottawa, Ontario

December 20, 1985

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Sedimentology and Geochemistry of the

Firstbrook Member of the Gowganda Formation

in the Eastern Cobalt Basin, Ontario.

submitted by,

Robert H. Rainbird, B.Sc.,

in partial fulfilment of the requirements for

the degree of Master of Science.

.....
Chairman, Department of Geology

.....
Thesis Supervisor

Carleton University

January 15, 1986

ABSTRACT

The Gowganda Formation, within the northeastern part of the Cobalt Basin, includes the Coleman Member and the overlying Firstbrook Member. The Firstbrook Member differs from the Coleman Member in that its lithofacies display: 1) marked lateral continuity, 2) abundant diagenetic red coloration, 3) evidence of tidal deposition and 4) a complete lack of glaciogenic features. The Firstbrook Member is divided here into a lower mud-dominated facies, a middle silt-dominated facies, and an upper sand-dominated facies which are respectively equated with the prodelta, delta slope, and delta foreslope subenvironments of a prograding river-dominated delta. The delta was likely fed by a fluvial braidplain system, represented by the overlying Lorrain Formation, which produced a broad ramp-like depositional front at the basin margin. Uninterrupted delta progradation is suggested by a single coarsening-upward sequence up to 585m thick. Deposition within a marine (rather than lacustrine) basin is indicated by: 1) tidal bedding structures, 2) tidal paleocurrent patterns, 3) a nearly twofold increase in boron content compared to Coleman Member rocks, suggesting a transition from brackish to marine salinity after deglaciation, and 4) stratigraphic position between the glaciomarine Coleman Member and the fluvial Lorrain Formation. Red coloration in Firstbrook Member strata is due to diagenetic hematite and suggests the existence of free oxygen in the Earth's atmosphere at the time of sedimentation.

(approximately 2300-2200 Ma). Chemical weathering data from mudstones indicate an increase in chemical weathering of the source terrane for Firstbrook Member strata. This may reflect rapid climatic amelioration after deposition of the glaciogenic Coleman Member. Limited potential for redbed copper mineralization may exist where adjacent oxidized and reduced strata pinch out against Archean paleotopographic highs.

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1: INTRODUCTION

1-1 LOCATION

The study area, in the Timiskaming district of northern Ontario, is about 100km north of North Bay. It encompasses approximately 2000km², centred just west of the town of Cobalt on Highway 11 (Figure 1.1).

1-2 PURPOSE

The present study is part of a more extensive project designed to re-examine sedimentary strata of the Cobalt Group in light of recently published sedimentological models, to improve the data base for these strata on the basis of field mapping and to further assess the controls of mineralization. The study has confirmed that the Gowganda Formation is divisible within the study area into two distinct members with differing depositional histories. Previous authors have described the Gowganda Formation as being entirely glaciogenic; information presented in this thesis demonstrates that the upper part (Firstbrook Member) is not.

1-3 PREVIOUS WORK

The earliest recorded geological studies in this region are those of Logan and Murray (1863) and Barlow (1899). The first regional geological maps of the Timiskaming District were produced by Barlow and Young (1907) and Todd (1925; 1926). More comprehensive regional compilations by Ontario Department of Mines geologists include: NE Temagami District, (Simony, 1964); South Lorrain township, (McIlwaine, 1970); Maple Mountain Area, (Card et al., 1973); Henwood township, (Thomson, 1966) and Lorrain township, (Lovell and deGrijs, 1976). Many detailed maps and

reports of the Cobalt area were produced by Robert Thomson (1957; 1963a,b,c). Ontario Geological Survey studies of Cobalt Group sedimentary strata were initiated by Wood (1978, 1979, 1980) and continued by Legun (1981). Mapping of the Firstbrook Lake Area (Johns, 1985) and Lundy Townships (Owsiaki, 1985) has provided additional background data. The Timiskaming region was part of the study area for Lindsey's doctoral thesis on the Gowganda Formation (Lindsey, 1967) and for Hadley's doctoral study of the Lorrain Formation (Hadley, 1968). Thesis studies of the Cobalt area by Carleton University students include Master's studies by Kurt (1973), Kim (1980), Goodz (1985), Mustard (1985) as well as bachelor's studies by Rainbird (1980) and Scammell (1984), Dodd (1985), Gebert (1985), and McQueen (1985). Present studies of the Cobalt area in progress include those by B. Wilson and M. Smyk. A paleomagnetic study of hematite-rich strata from the Firstbrook Member was completed by Roy et al. (1975).

1-4 METHODS

The present study involved about 5 months of field work during the summers of 1983 and 1984. Regional mapping using Ontario Basic Mapping (OBM) 1:20,000 scale base maps was completed in the field and later generalized to 1:100,000 scale. All reasonably accessible roadside, lake and rivershore exposures were examined. Mapping was supplemented by detailed stratigraphic section measurements of cliff-side exposures and diamond drill cores. Section correlation, petrographic studies and geochemical analyses were completed in Ottawa.

GEOLOGIC SETTING

Early Proterozoic sedimentary rocks of the Cobalt Basin belong to the Huronian Supergroup, which forms a large part of the Southern Province of the Canadian Shield. These rocks unconformably overlie Archean volcanic and plutonic assemblages of the Superior Province. The Huronian Supergroup is subdivided into four groups; only the uppermost (Cobalt Group), is exposed in the study area (Figure 1.2). The Cobalt Group comprises, in ascending stratigraphic order: the Gowganda Formation, Lorrain Formation, Gordon Lake Formation and Bar River Formation. Of these only the Gowganda Formation and lower sections of the Lorrain Formation are present within the study area. Archean and Huronian rocks are commonly intruded by Nipissing diabase dikes and sills which have been dated by Rb-Sr methods at approximately 2150 Ma (Van Schmus, 1965; Fairbairn et al., 1969) and by U-Pb (zircon) at 2219 ± 4 Ma by Andrews et al. (in press). A minimum age for deposition of the entire Huronian Supergroup of 2300 Ma has been proposed by Frarey et al. (1982) using U-Pb zircons from the Creighton Granite. However, the precise timing of the Creighton intrusive event in relation to the depositional and tectonic history of the Huronian Supergroup is uncertain. A Rb-Sr date of about 2300 Ma was obtained by Fairbairn et al. (1969) for 10 samples of the Gowganda Formation. The Huronian Supergroup and the Gowganda Formation therefore were probably deposited sometime between 2400 Ma and 2150 Ma. Olivine diabase dikes of Keweenawan age (1200 Ma) are the youngest Precambrian rocks in the area. Dolostone, limestone

Figure 1.2 Generalized stratigraphic column of the Huronian Supergroup (after Young, 1973). Only the Cobalt Group is exposed within the study area.

and shale of Ordovician and Silurian age unconformably overlie Precambrian rocks in the northeastern part of the area. Quaternary sediments cover much of the bedrock.

The rocks have been subjected to structural disturbances at several stages in their geological history. The Archean rocks have been deformed into tight subvertical folds about southeast- to east-trending fold axes. The Proterozoic and Paleozoic rocks have been affected by less intense stresses and have, in general, gentle dips. Faults of at least two ages can be documented (Wood, 1979). These include the younger Laké Timiskaming-Bonnechere Graben system and small-scale northeast- and northwest- trending systems of middle Proterozoic age near Cobalt.

Huronian rocks of the eastern Cobalt Basin show evidence of weak metamorphism within the subgreenschist facies (Card, 1978a). Rare higher grade assemblages occur within the thermal contact aureole of Nipissing and Keweenaw diabase intrusions. At least two phases of regional metamorphism have been documented; one at about 2200 Ma and another at approximately 1850 to 1900 Ma (Card, 1978a) concurrent with the Penokean Orogeny.

II: REGIONAL STRATIGRAPHY AND TECTONIC SETTING OF THE GOWGANDA FORMATION

2-1 Regional Stratigraphy

The Gowganda Formation within the Cobalt Basin has been subdivided into the Coleman Member and the overlying Firstbrook Member (Figure 2.1). Coleman Member strata include both clast- and matrix-supported diamictite interbedded with laterally discontinuous units of sandstone and laminated mudstone. Most authors agree that the Coleman Member was deposited by glaciogenic processes, although both marine (Miall, 1983; Rosen, 1985; Mustard, 1985) and non-marine (Legun, 1981) settings have been proposed. The overlying Firstbrook Member is composed of laminated mudstone which grades upward into thinly bedded siltstone and then into fine grained arkose and finally into coarser sandstones of the overlying Lorrain Formation. The Firstbrook Member differs from the Coleman Member in that it shows no evidence of deposition by glaciogenic processes. The contact between the Coleman and Firstbrook Members is conformable; the nature of this contact will be discussed in the following chapter.

The possibility that these rocks are divisible into separate lithological units was first proposed by Todd (1925, 1926) during his mapping of the Matabitchuan and Anima Nipissing regions. On his maps Todd refers to the Coleman Member as conglomerate and to the Firstbrook Member as slate-like greywacke and quartzite. Both subdivisions were assigned by him to what was then called the "Lower Cobalt Series"; the Coleman and Firstbrook were given Formation status by Thomson (1956; 1963 a,b,c). However, this distinction has not gained acceptance in the literature owing to

Figure 2.1 Generalized stratigraphic column of the Gowganda Formation within the study area.

the lack of evidence for a twofold subdivision in other regions. Robertson et al. (1969) suggested that the name Gowganda Formation be retained for both sequences. Detailed and reconnaissance mapping have confirmed that subdivision is possible within the Cobalt Basin as far south as Rabbit Lake (15 km southeast of Temagami) and as far north as the town of Gowganda (50km. west of Henwood township).

In the southwestern part of the Huronian outcrop belt, a twofold subdivision of the Gowganda Formation was first described by Lindsey (1969). The upper unit, which Lindsey called the LaCloche Formation, comprises three coarsening-upward cycles containing lithologies similar to the Firstbrook Member. Field observations by the author as well as discussions with Dr. G.M. Young have confirmed these observations. This unit is presently under study by R. Junnila, University of Western Ontario.

Stratigraphy of the Gowganda Formation is less well understood in the central part (Region 2 of Young, 1981) of the Huronian outcrop belt. During reconnaissance examination of the ~~area northwest of Lake Wanapitei, Wood (1979) indicated that "a~~ simple two-fold subdivision of the formation was not apparent". Additional detailed work in this region would be required to confirm this. The possibility that upper Gowganda strata in this region have been removed by erosion should not be discounted.

Cobalt Group rocks have been correlated to the lower Libby Creek Group of southeastern Wyoming by Blackwelder (1926), Young (1970, 1973) and Karlestrom et al. (1983), to the Otish Group in north-central Quebec (Roscoe, 1973), and to the Sariolian and

Jatulian Groups of eastern Finland (R. Ojakangas, personal communication, 1985).

2-2 Tectonic Setting

The tectonic setting of the Huronian Supergroup remains uncertain (see summary in Young 1983, p. 16). A definitive interpretation has been hindered by Phanerozoic cover rocks to the south, and high grade metamorphic rocks of the Grenville Province to the east.

According to Sims et al. (1980), deposition of the Huronian Supergroup was a direct result of downfaulting along the Great Lakes Tectonic Zone (GLTZ). The zone is about 1200 km. long, extending eastward from Minnesota through central Ontario along the northern margin of the early Proterozoic Penokean fold belt (see Figure 2.2). The GLTZ is considered to coincide with the juncture of two different types of Archean crustal terrane: a greenstone-granite terrane to the northwest (approx. 2700 Ma) and an older (>3000 Ma) granite-gneiss terrane to the southeast (Morey and Sims, 1976; Sims et al., 1980). These authors suggested that deposition of the Huronian Supergroup was controlled by subsidence and related high-angle normal faults parallel to the GLTZ. The Murray Fault Zone (MFZ, Figure 4) is a prominent example. During the early stages of Huronian deposition, the MFZ was tectonically active, producing a system of southward-thickening clastic wedges (Sims et al. 1981; Zolnai et al., 1984). During the final stages of deposition, tectonism across this zone diminished, subsidence was distributed more evenly and Cobalt Group sediments were deposited across it without an abrupt.

Figure 2.2 Simplified tectonic map of the Great Lakes region.
Modified from Sims et al. (1981).

change in thickness. Card (1978b), suggested that the MFZ represents a sharp break between two contrasting tectonic domains: a mildly deformed and metamorphosed sequence to the north (Cobalt Basin) and a relatively strongly deformed and metamorphosed thicker succession in the south.

On the basis of his studies of the Gowganda Formation in the vicinity of Whitefish Falls, Young (1985) has suggested that the lower Huronian Supergroup was deposited during the rifting phase in the development of an early Proterozoic south-facing Atlantic-type margin. A significant period of regional (thermal) subsidence after the rifting phase is suggested by the widespread preservation of rocks of the upper Huronian Supergroup (Cobalt Group) and their unconformable relationship with older Huronian strata. The passive margin model is supported by the observation that the lower Huronian is a restricted, largely terrestrial succession, and that the upper Huronian represents deposition under more widespread marine conditions (Young, 1985).

According to this interpretation, the Gowganda Formation and ~~succeeding formations of the Cobalt Group were deposited as a~~ result of regional subsidence in a depressed zone (the Cobalt Basin) on the trailing margin of the craton. This interpretation is supported by the fact that the Gowganda Formation within the Cobalt Basin lies directly on Archean basement.

III: STRATIGRAPHY AND SEDIMENTOLOGY OF THE FIRSTBROOK MEMBER

3-1 Introduction

Firstbrook Member strata are divisible into three lithologically distinct and regionally mappable units. These units can be differentiated on the basis of grain size, bedding characteristics, colour, sedimentary structures, thickness variation and regional distribution. The units consist of, in ascending stratigraphic order: finely laminated siltstone and claystone (lower unit); parallel-laminated and lenticular-bedded siltstone (middle unit); and graded to parallel-stratified sandstone and wavy- to lenticular-bedded sandstone and siltstone (upper unit). Contacts between units are conformable and generally gradational at most localities. The entire sequence records a coarsening-upward trend.

3-2 Lower Unit - Finely-Laminated Mudstone

3-2a Lithologic Characteristics

An important attribute of the lower unit is its very fine grain size. The rock predominantly consists of alternating laminae of claystone and fine-grained siltstone (Plate 1a). The silt content tends to increase upward toward the contact with the middle unit. The base of the unit displays paper-thin parallel laminations; the lamination thickness increases upward in proportion to the increase in grain size. The contact with the overlying unit is marked by a distinct increase in lamination thickness. As well, the thickness of individual laminae is variable, whereas lower in the unit they are generally regular. Thin section examination (Plate 1b) reveals that many of the laminae are normally graded. On fresh surfaces the rock is

typically green to dark green-grey, although a notable exception is a distinctive and widely distributed black graphitic facies which occurs in parts of Firstbrook, Lundy and Henwood Townships (Figure A). Red coloration in outcrop was noted in variegated (alternating red and green) laminae at one locality on the Matabitchuan River in South Lorrain township (Figure A), as well as in lower unit strata from a deep drill hole in Henwood township (Eplett drill hole). Outcrop surfaces exhibit creamy grey-brown weathering, regardless of fresh surface coloration.

3-2b Sedimentary Structures

Parallel lamination is interrupted by tiny lenticular starved ripples, particularly in the upper part of the unit. These structures are 1-2 cm long, 3-4 mm high and display well-developed internal cross lamination. Symmetric forms are most prevalent, although asymmetric forms are more common near the top of the lower unit. The ripples are composed of coarse silt and fine-grained sand composed of quartz, chlorite and calcite. A single occurrence near the Mattawapika Dam (junction of Lady Evelyn River and Montreal River) contains recessive-weathering calcareous lenses within laminated siltstone and mudstone. This and a similar isolated example on Highway 558 are the only examples of macroscopic carbonate observed during this study.

Graded laminations, rarely visible in hand specimen, form alternating silt and clay couplets (rhythmites, Plate 1b). Petrographic examination reveals that grading occurs only in the silt layers, most of which are less than 1 mm thick. Graded laminations increase in frequency up section.

In an exposure along the Matabitchuan River (Plate 1c), basal layers of the lower unit drape over cobbles in a thin lag zone at the top of the Coleman Member. This draped zone is less than 0.5 m thick, and is overlain by normal parallel-laminated rhythmite. Syndepositional deformation features are generally absent from the lower unit, except in the Eplett drill hole where folded lamination and brecciation were noted.

3-2c Petrography

Thin sections reveal that about 80% of the rock is composed of very fine-grained silt- and clay-size ($10-7\phi$) particles of magnesium-rich chlorite and muscovite. The bases of graded laminae are composed of silt-size ($6-4\phi$) quartz and albite grains embedded in finer grained chlorite and muscovite. Starved ripples are composed of silt to fine-grained sand-sized ($6-3.25\phi$) particles of quartz and albite with intergranular calcite and chlorite cement. In one sample, fine silt-sized granular aggregates of sphene are evenly distributed throughout the rock and compose about 5% of its volume. Sphene is a common accessory mineral in most of the Precambrian rocks in the study area and has been described by several authors including Rainbird (1980) and Scammell (1984). Textures and distribution indicate that the sphene was developed during metamorphic overprinting.

Lamination thickness ranges from 0.3 to 2.5 mm and averages about 1 mm. In four samples studied in detail, approximately 25 per cent of the laminae display faint to well-developed normal grading (Plate 1b); the remainder consist of non-graded laminae of clay and fine silt.

3-2d Thickness and Regional Distribution

Lower unit rocks are best exposed in the central region of the Cobalt Basin, particularly along the Lady Evelyn River (between Lady Evelyn Lake and the Montreal River) and eastward along Highway 558, as well as along concession roads in the southeastern corner of Henwood township (see Figure A). In this region the Firstbrook Member and in particular the lower unit attains its greatest thickness. The greatest known thickness of Firstbrook strata is 535 metres (Eplett drill hole, Figure 3.1). Of this, about two-thirds (365 metres) belongs to the lower unit.

In contrast, the lower unit is relatively thin and therefore less well exposed at the basin margin. One of the best exposures of the lower unit at the basin margin is along the Matabitchuan River where there is almost continuous outcrop in cliffs of Firstbrook Member strata. At the South Lorrain section it is about 15m thick, representing less than 20% of the complete Firstbrook Member (Figure 3.2). The lower unit represents a similar proportion of the exposed Highway Junction section (Figure 3.3), where it is about 20 metres thick. In the section at Ragged Chutes (Figure 3.4), the lower and middle units are absent. The regional correlation (Figure 3.5) illustrates rapid thinning of the entire Firstbrook Member, including the lower unit, toward the basin margins. Thomson (1957) first recognized a distinct thinning of Cobalt Group rocks and an absence of Gowganda strata toward the east. In an outcrop on Baie Joanne on the eastern shore of Lake Timiskaming, Lorrain Formation arkose lies unconformably on Coleman Member orthoconglomerate (Plate 1d).

Figure 3.1

Figure 3.1. Eplett drill hole stratigraphic section. Section measurement was from drill logs of core stored at the Kirkland Lake drill core library. See Figure 3.5 or Figure A (measured section A) for location.

SCHEMATIC SECTION: EPLETT DRILLHOLE, HENWOOD TOWNSHIP, ONTARIO

Figure 3.2

Figure 3.2. South Lorrain Township stratigraphic section. Measured along an outcrop on the west side of the Matabitchuan River between the Matabitchuan dam and the Montreal River. See Figure 3.5 or Figure A (measured section E) for location.

GOWGANDA FORMATION: SOUTH LORRAIN TOWNSHIP SECTION

Figure 3.3

Figure 3.3. Highway-Junction stratigraphic section. Measured at outcrops on the east side of Highway 11, 0.5 km south of the Highway 558 intersection. See Figure 3.5 or Figure A (measured section B) for location.

The diagram illustrates a geological column with two main members: the Firstbrook Member and the Coleman Member. The vertical axis represents height in meters, ranging from 0 to 140. The horizontal axis is divided into three units: Lower Unit, Middle Unit, and Upper Unit.

Firstbrook Member (Top): This member spans from approximately 75 meters to 140 meters. It includes the following units and features:

- Thickly Laminated Siltstone / Sandstone:** Located at the top of the Firstbrook Member, around 135-140 meters.
- Laminated Siltstone:** Located below the thickly laminated siltstone/sandstone, around 125-135 meters.
- Graded Sandstone:** Located below the laminated siltstone, around 115-125 meters.
- Thinny-Laminated Mudstone:** Located below the graded sandstone, around 105-115 meters.
- Massive Sandstone:** Located below the thinny-laminated mudstone, around 95-105 meters.
- Lenticular Beddings:** Located at the base of the Firstbrook Member, around 75-95 meters.

Coleman Member (Bottom): This member spans from 0 to 75 meters. It includes the following units and features:

- Wavy Bedding:** Located at the top of the Coleman Member, around 65-75 meters.
- Load Structures / Scour Marks:** Located below the wavy bedding, around 55-65 meters.
- Upper Diamictite:** Located at the base of the Coleman Member, around 0-55 meters.

A dashed line indicates a correlation between the Coleman Member and the Firstbrook Member, showing a transition from the Upper Diamictite to the Lenticular Beddings.

Figure 3.4

Figure 3.4. Ragged Chutes stratigraphic section. Measured at an outcrop on the Ragged Chutes Road, 1km south of the Ragged Chutes compressed air plant on the Montreal River. See Figure 3.5 or Figure A (measured section D) for location.

GOWGANDA FORMATION: MONTREAL RIVER-RAGGED CHUTES SECTION

Figure 3.5

Figure 3.5. Regional Stratigraphic Correlation. Note the rapid thinning of lower unit strata between the Eplett and Highway Junction sections as well as the thinning trend toward the southeast. Note also the proximity of the individual sections to Archean inliers and compare with unit thicknesses.

No Firstbrook Member strata were observed or have been reported east of Lake Timiskaming.

3-2e Relationship to the Underlying Coleman Member

The Coleman Member-Firstbrook Member contact is everywhere conformable, but varies in abruptness relative to its position within the basin. Near the central or thicker parts of the basin, the contact is gradational from laminated diamictite to thinly laminated mudstone containing dropstones (Plate 1e) upward into thinly laminated mudstone of the Firstbrook Member which contains no dropstones. This relationship is best illustrated in the Eplett drill hole section (Figure 3.1). The contact was placed at 1260 metres, where the uppermost dropstone was observed. Field examples of this gradational contact are best exposed along the southern arm of Anima Nipissing Lake near the mouth of Dart's Bay, and on northern Lake Temagami on Beaver and Deer Islands. Toward the edge of the basin, the contact appears to be non-gradational. Several examples of the contact along the Matabitchuan River show it to be extremely sharp. An excellent exposure below the dam on the Matabitchuan River displays laminated mudstone of the lower unit draped directly over a 1- to 2-metre thick rounded gravel and cobble orthoconglomerate of the Coleman Member (Plate 1c). The orthoconglomerate overlies a thick clast-poor diamictite and is continuous for several kilometres southward along the Matabitchuan River. The unexposed contact near Highway Junction is assumed to be either sharp or abruptly gradational on the basis of a stratigraphic separation of less than 5 metres between outcrops above and below the contact (see Figure 3.3).

3-3 Middle Unit - Parallel-laminated and Lenticular-bedded Siltstone

3-3a Lithologic Characteristics

The lower contact of the middle unit was chosen at a point where silt content exceeds mud content. This upward transition, exposed in the South Lorrain section (Figure 3.2), takes place within an interval of less than one metre. In more central parts of the basin, the contact is gradational over several metres.

The middle unit is characterized by medium- to thick-laminated siltstone and mudstone with minor fine-grained sand, interbeds which increase in abundance up section (Plate 2a). Sand also forms starved, lenticular ripples (Plate 2b) and thick graded-arkose beds (Plate 2c). Grain size generally increases upward.

Bedding typically consists of parallel to slightly wavy, thick interlaminae of siltstone and mudstone. The bed thickness increases upward as does grain size. Lenticular bedding and ripple lamination are common in the upper part of the unit, but generally are rare in the lower part. The graded-arkose beds occur locally throughout the unit and range in thickness from several centimetres to two metres.

A characteristic feature of the middle unit is its pronounced red coloration in many areas. Fresh surface exposures commonly display variegated or intercalated red and green lamina. Red coloration is typical of the clay-rich layers, whereas drab coloration (green) is characteristic of the siltstone layers and fine-grained sandstone lenses (Plate 2d). Rare reversals of this relationship also occur. The most striking example of

variegation occurs within sections containing graded arkose beds where red sand beds grade upward into drab mudstone laminae (Plate 2e and 2f). A similar relationship is seen in Plate 2g, where drab mudstone rip ups are incorporated in pink arkose. Regional variations in coloration are apparent. For example, middle unit rocks from outcrops along Highway 11 south of Highway 558 show ubiquitous red coloration, whereas in the region south of Diamond Lake (Figure A), the Firstbrook Member is completely drab. Red colour is absent within the contact aureoles of diabase dikes and sills.

3-3b Sedimentary Structures

Ripple cross lamination in starved ripples is common in the upper part of the middle unit. Sand lenses range from 2 to 5 cm long and from 0.5 to 1.5 cm high. On bedding, lenticular bedding is expressed as both sinuous and straight-crested ripple forms (Plate 3a). Wavelengths range from 5 to 10 cm.

Normally graded lamination and bedding occur throughout the unit, and are locally accentuated by variegation, because the colour difference is a function of grain size.

The graded arkose bedsets mentioned previously are laterally continuous for at least 100 metres, and generally are tabular, with little lateral thickness variation. Typical examples (Plate 2e) display a thick well-developed graded basal component capped by a relatively thin parallel laminated division, and finally an upper unit of massive mudstone. Mudstone rip-ups occur near the tops of some graded units (Plate 2g). Cross stratified interlayers were noted in several graded arkose bedsets from the middle part of the Highway Junction section (Plate 3b). Flute

scours, flame structures and load structures (Plates 3c to 3f) are commonly preserved at the bases of these units. Dewatering features resembling dish structures and water escape tubes also have been noted within the lower graded subunit of these bedsets (Plate 3g and 3h) and are described in detail by (Dodd 1985). A notable feature of these beds is that the lower graded portion is mineralogically and texturally similar to lower Lorrain Formation arkoses. Sandy graded arkose bedsets have been observed at several localities along Highway 1, and along the Montreal River 1 km east of Latchford, but are best exposed at the Highway Junction outcrops.

Soft-sediment folding is preserved throughout the Firstbrook Member, but is most abundant in middle unit strata, particularly in association with graded arkose bedsets. Both coherent (simple) and noncoherent (chaotic) forms were noted, but are randomly distributed (Plate 4a and 4b). Rare soft-sediment faulting was also noted, and at one locality on Highway 11 (1 km south of the Highway Junction section), a soft-sediment fold is developed on the hanging wall side of a slightly concave-upward fault.

Another soft-sediment deformation structure observed in middle unit strata are "homogenized" beds, consisting of massive to faintly stratified silt and mud enclosing thin lenticular and folded wisps of clay-rich material. Homogenized beds are similar to soft-sediment folded beds in that they are concordant with undisturbed overlying and underlying strata and occur in close association with graded arkose beds at the Highway Junction

outcrops. The overall geometry of these soft-sediment deformation layers could not be properly assessed because of limited lateral exposures.

Sedimentary breccias, widely distributed in the Firstbrook Member, consist of broken, angular, and rotated fragments of laminated siltstone and mudstone. Breccia zones in some instances are concordant with bedding, whereas in other instances they are distinctly cross cutting. Clasts in both breccia types display evidence of plastic deformation.

Concordant breccia zones were noted in several island outcrops in the southern part of Lady Evelyn Lake, and have been described from various localities on Lake Temagami by Simony (1964) and Card et al. (1973). Discordant or cross cutting breccias were noted at several outcrops on the east side of Highway 11, 1 km south of Latchford, and also have been described at localities in Barr and Firstbrook townships by Johns (1985).

A very thick (up to 10 m) arkose bedset described in detail by Dodd (1985), occurs near the top of the Highway Junction section (Plate 4c). This unit comprises several discrete layers including massive sand, crossbedded sand, and sand containing plastically deformed laminated siltstone rip-ups (Plate 4d). Bounding strata have been extensively disturbed, especially above the unit, where numerous injection features are apparent (Plate 4e).

3-3c Petrography

Middle unit strata, mineralogically similar to the lower unit, are composed essentially of muscovite, chlorite, quartz and hematite with accessory albite, calcite, sphene and opaques (probably ilmenite and magnetite). Typical specimens consist of coarse silt to fine sand (5-3 ϕ), drab laminae with intervening very fine to medium silt (8-5 ϕ) and red mudstone laminae. The coarse laminae are composed on average of about 40% quartz, 35% chlorite, 10% muscovite, 5% albite, 5-10% hematite, opaques and sphene. They have sharp lower contacts and typically grade upward into a fine lamination. Some contacts are convoluted and display small flame and load structures (Figure 4f). Other coarse-grained non-graded beds and thick laminae show fine inclined laminations.

The thin laminae contain less quartz (10%) and more muscovite (50%), chlorite (15%) and accessories (about 10%). Red coloration is imparted by abundant hematite (about 15%).

3-3d Thickness and Regional Distribution

Middle unit rocks occur throughout the study region, but are best exposed at outcrops along Highway 11 between Rib Lake and the Highway 558 junction (Figure A). Regional thickness variations are less pronounced than in lower unit sections.

Drill hole data show that the middle unit thickness ranges from approximately 200 metres (Eisen Lake DDH 81-3) in northern Coleman Township up to more than 300 metres (Dotsee Mine DDH-M1) in western Bucke Township (Agnico-Eagle Mines, B. Thorniley, personal communication, 1984). The regional correlation (Figure 3.5) illustrates that the middle unit is thickest in this region

and thins both basinward and toward the basin edge. In the Eplett drill hole (Henwood township), it is only about 150 metres thick. In comparison to the lower unit, the middle unit shows an opposite trend in thickness between the Dotsee and Eplett sections.

3-4 Upper Unit - Wavy- and Parallel Stratified Sandstone and Siltstone

3-4a Lithologic Characteristics

The middle unit-upper unit boundary is defined as the level at which sand content exceeds silt content. It is less abrupt than the lower unit-middle unit contact, and is gradational over several to several tens of metres.

The upper Firstbrook Member is composed of fine-grained arkose with interbedded medium-grained arkose, siltstone and minor mudstone. As with underlying units, the upper unit shows an overall coarsening upward trend. In the Eplett drill hole and South Lady Evelyn stratigraphic sections (Figure 3.1 and 3.6), this trend is seen to comprise at least two coarsening upward cycles. The upward increase in sand content is reflected in a transition from predominant lenticular bedding to predominant wavy bedding as well as an increase in overall bed thickness.

Thin to medium beds of graded and massive to parallel-stratified fine-grained sand occur between lenticular and wavy-bedded sections (Plate 4g) and also show an up-section increase in abundance and bed thickness.

Both variegated and non-variegated lithologies occur within the upper unit. Variegated beds and red coloration appear to be most abundant in the lower part where the mud content is highest.

Figure 3.6

Figure 3.6. South Lady Evelyn Lake stratigraphic section. Measured at the narrows between Mady Evelyn Lake and Diamond Lake. See Figure 3.5 or Figure A (measured section F) for location.

GOWGANDA FORMATION - LORRAIN FORMATION TRANSITION SOUTH LADY EVELYN LAKE SECTION

Drab and reverse variegated beds (pink sand with green mud) predominate in the upper sections. The reverse variegated lithologies show no regional stratigraphic pattern of distribution.

3-4b Sedimentary Structures

Wavy bedding, similar to that described by Reineck and Singh (1980), is the most abundant sedimentary structure in the upper unit. Most examples consist of 2 to 3 cm thick ripple cross-laminated sand beds separated by thin (< 1 cm) laminated mud interlayers that tend to be thickest in the ripple troughs (Plate 4h) and thinner on their crests. Lenticular bedding is as abundant as in the middle unit, but starved ripples are generally larger and coarser-grained. Rare flaser bedding occurs in association with wavy bedded strata.

Wavy and lenticular bedding are associated with a variety of ripple bedforms. In vertical section, ripple forms display both symmetric and asymmetric profiles and pronounced inclined cross laminations (Plate 4h). Bedding exposures of ripple crests indicate that for the most part they are straight to slightly sinuous crested. Some straight-crested forms bifurcate. Asymmetric ripples are rare, although linguoid crests were observed at 3 localities within the upper unit. Rib and furrow structures are present at several localities along Highway 11, south of the Highway Junction (Plate 5a).

A unique example of herringbone crossbedding was observed in a large angular block of upper Firstbrook Member strata in a gravel pit on the west side of Highway 11, approximately 3 km south of the Highway 558 intersection. The adjacent face of the

block displays well-developed interference ripples (Plate 5b) associated with wavy and lenticular bedded fine-grained arkose and siltstone.

Longitudinal scour structures are well preserved in bedding-surface exposures of upper unit rocks. The most abundant type is a sinuous longitudinal scour structure which resembles the flute rill marks described by Reineck and Singh (1980, p. 75), or the longitudinal meandering grooves of Allen (1969). The structure consists of regularly spaced anastomosing (sinuous) furrows (Plate 5c). Furrow spacing varies from 5 to 10 mm, with a relief of a few millimeters. Large longitudinal scours resembling small gutter casts were seen in strata just below the transition zone into the Lorrain Formation (Plate 5d).

Penecontemporaneous deformation features including ball-and-pillow structures, convolute lamination, soft-sediment folds, load casts and flame structures have all been recognized in upper unit rocks. Of these, ball-and-pillow structures are the most widespread, and are best developed in outcrops along the southern shore of Lady Evelyn Lake (Dane Township). They occur as isolated ellipsoidal sand bodies (0.1 up to 2 m across) set in a matrix of slightly finer-grained sand or silt (Plate 5e). Ball-and-pillow structures occur in thick (up to 10 metre) zones within the transition zone between the upper unit and overlying Lorrain Formation arkose (see Figure 3.6). Ball-and-pillow structures also occur on a microscopic scale, at the base of thin graded sand beds. Related structures such as load-casted ripples, similar to those described by Reineck and Singh (1980,

p.87), have been recognized throughout the middle and upper unit rocks (Plate 5f). Other loading features include load casts (Plate 5g), which are preserved on the undersides of both graded and non-graded arkose beds. Flame structures are also developed at macroscopic and microscopic scales. Flame structures consist of curved and pointed tongues of mud which pierce upward (between loaded lobes) into overlying sand layers. In some instances, the flame structures show a preferred inclination toward the south (see Plate 3d).

Convolute lamination and soft-sediment folding are similar to that described for middle unit strata. Load casts, flame structures and convolute lamination are associated with thinner (<1 metre thick) sand beds which are distributed throughout the unit. Slump structures are more typical of the lower part of the upper unit.

Mud-chip breccia layers are a common component of fine to medium-grained arkose beds from the upper unit-Lorrain Formation transition zone (Plate 5h) and are especially common in strata from the the Eplett drill hole. These zones comprise angular, plastically deformed fragments (up to 10 cm long) set in a matrix of drab-coloured sand.

Mudcracks and syneresis cracks were not recognized during mapping of the study area. However, they have been described by Lindsey (1967), who noted "very small (about 2 mm wide and 0.5 mm deep) shrinkage features resembling mudcracks" in redbeds at the top of the Firstbrook Member. Mudcracks have also been reported by Johnston (1954, p.1054) from an area in South Lorrain township, near the Grenville Front. However, the stratigraphic

position of this occurrence could not be interpreted from his description.

3-4c Petrography

Thin section analysis of 10 samples from the upper unit show that the fine-grained interbeds consist mainly of silt-size (7-5 ϕ) chlorite (40%), muscovite (30%), hematite, magnetite and sphene (10%) surrounding angular grains of quartz (15%) and feldspar (5%). The hematite content ranges from <10% in red layers to <3% in drab layers. The coarse-grained interbeds are composed of a condensed framework of fine-grained sand (2 ϕ) in a micaceous cement and pseudomatrix. The framework is composed of angular to subrounded grains of quartz (40-50%), K-feldspar and albite (10-15%) and 5% heavy minerals (magnetite, sphene, hematite and zircon). The feldspar grains, especially albite, have been variably sericitized. These grains are cemented by approximately equal amounts of fine-grained chlorite and muscovite. Some of the matrix may actually represent rock fragments that have been squeezed between more competent grains of quartz and feldspar to form pseudomatrix. In red specimens, the mica appears to have been partially replaced by fine-grained hematite. In at least two specimens, blotchy patches of calcite have replaced up to 20% of the section (Plate 6a).

Samples of the lower Lorrain Formation sandstones consist of subangular to subrounded medium-grained arkose and subarkose (Plate 6b).

Most grains exhibit curved to slightly seriate line contacts. The framework mineralogy consists of quartz (25-65%),

K-feldspar (15-35%), plagioclase (albite; 10-20%), rock fragments (5-10%) and heavy minerals, including zircon, tourmaline, magnetite and sphene (<5%). The cement comprises sericite, chlorite and minor amounts of silica and carbonate. As in the underlying unit, hematite in the red arkose is present as interstitial cement, as a fine dusting on original grain boundaries which have been overgrown by syntaxial silica and as a replacement of detrital Fe-Mg silicates (Plates 6c to 6e).

3-4d Thickness and Regional Distribution

The upper Firstbrook Member is best preserved around the periphery of the study area. This is due to its relatively higher stratigraphic position, combined with the fact that it has been eroded from much of the central region. For example, only upper Firstbrook strata are preserved in the Ragged Chutes section. (Figure 3.4). As pointed out in section 3-2d, there is a rapid eastward thinning of the lower and middle units (toward the basin margin). The regional correlation (Figure 3.5) indicates that upper unit thickness variation is less pronounced than in the lower units, although there is, as expected, a moderate thinning trend toward the basin edge. The upper unit rocks generally have a thickness less than 100 metres, except in the Eplett drill hole, where the upper unit is about 140 metres thick. The best outcrops of upper unit rocks occur on lakeshores on the eastern side of Lady Evelyn Lake, Fischer's Rock, (north of Hillview, in Hudson Township), near Maidens Lake in South Lorrain Township and of the Ragged Chutes Section on the Montreal River.

3-4e Relationship to the Overlying Lorrain Formation

A 3- to 10-metre-thick gradational and conformable coarsening-upward contact occurs between the Firstbrook Member and the overlying Lorrain Formation. Exceptions to this are noted in the South Lady Evelyn Lake section (Figure 3.6) and in the Eplett drill hole section (Figure 3.1), where the upward transition is marked by at least two coarsening-upward cycles. As with the lower units, an increase in bed thickness is associated with the grain size increase. Soft-sediment deformation structures such as described in the preceding section are abundant in the transition zone. The contact is marked by the disappearance of wavy bedding and silt and mud interbeds and in some areas by a change from red to drab-coloration. The lower Lorrain Formation is characterized by parallel and crossbedded medium-grained arkose (Plate 7a) and the colours of these strata are drab (grey and green), except in a few outcrops in the northern parts of the study area, where the strata are generally red. Crossbedding is predominantly trough-type, but planar crossbedding also occurs (Plate 7b).

IV: PALEOENVIRONMENTAL INTERPRETATION OF THE FIRSTBROOK MEMBER

4-1 Previous Interpretations:

Since Coleman's (1907) pioneering study, the Gowganda Formation has been recognized and accepted as a classic example of paleoglacial deposition. Until recently, however, nearly all studies of this formation have focused on the lower, diamictite-rich Coleman Member.

Laminated mudstones and siltstones which compose the Firstbrook Member of the Gowganda Formation were interpreted by Thomson (1966, p.15) and by Card et al. (1973) as proglacial varves. Lindsey (1967) disagreed with this interpretation because the individual laminae do not exhibit convincing varve characteristics. Lindsey also maintained that the Firstbrook Member is not a glaciolacustrine deposit owing to its vast lateral extent and great thickness (particularly in Henwood Township). In contrast, inferred proglacial rhythmite units in the Coleman Member are thin, lenticular and discontinuous (Mustard, 1985). In his study of the Gowganda-Miller Lake area, McIlwaine (1978, p.27-28) concluded that the Firstbrook Member could be either lacustrine or glaciolacustrine. In a more recent study, Johns (1985) avoided making a marine or lacustrine distinction, concluding only that the fine-grained sediments were deposited during a cold climatic regime, with the introduction of coarser grained sediments as warming ensued. Lindsey (1967;1971) and Young (1973) interpreted the upper Gowganda Formation near Whitefish Falls to be a prograding marine delta which was transitional to braided fluvial arkose of the Lorrain Formation.

Most authors are in agreement that, in the southern part of the Huronian outcrop belt, the sediments of the Gowganda Formation were deposited in a marine basin. On the basis of facies analysis of laminated mudstone, Lindsey (1967) suggested that the region northeast of Diamond Lake (essentially the Cobalt area) represents an area of non-marine deposition. Card et al. (1973) and Wood (1978), concurred with this interpretation. Recent work by Miall (1983), Legun (1984), Rosen (1985) and Mustard (1985) has indicated that the Coleman Member of the Gowganda Formation in the northern part of the Huronian outcrop belt may also be marine.

4-2 Depositional Model

A prograding river-dominated delta model is proposed herein for deposition of the Firstbrook Member. The model (Figure 4.1) comprises prodelta, delta slope and delta foreslope subenvironments which are respectively equated with the lower, middle and upper units of the Firstbrook Member. The delta braid plain subenvironment is represented by lower Lorrain Formation strata. This association forms a relatively large-scale coarsening-upward package which records passage from the mud-rich prodelta facies upward into the generally sandstone-dominated delta-plain facies. The coarsening-upward sequence results from progradation of the delta front.

Figure 4.1 Proposed depositional model for the Firstbrook Member. The lower, middle, and upper units of the Firstbrook Member are respectively equated with the prodelta, delta slope, and delta foreslope subenvironments of a prograding, river-dominated delta. The lower Lorrain Formation represents the delta braidplain subenvironment. This coarsening-upward sequence overlies glacial sediments of the Coleman Member.

4-2a Prodelta Facies (lower unit)

Lithologic features such as fine grain size, thin lamination, lateral continuity and the lack of erosional structures all suggest deposition within a low energy, relatively deep water setting. In combination with lateral and vertical facies associations, these characteristics point to a prodelta as opposed to an open marine shelf environment. Clay-rich paper-thin laminations suggest suspension deposition in quiet water, with slight grain size variations being the result of minor fluctuations in sediment supply or influx energy. Lamination may also be due to short-term fluctuations within more sustained current deposition (Collinson and Thomson, 1982, p. 56). Thin graded silty mudstone intercalations are inferred to be the product of weak low-density, low-velocity turbidity currents flowing close to the bed; the clay-rich upper parts of each graded lamination are inferred to represent the background suspension-load sedimentation. Microscopic load structures at the base of some graded units are suggestive of gravitational instability resulting from rapid deposition. The turbidity current interpretation is reinforced by evidence for large-scale sediment gravity flows in the more proximal facies.

Although both traction load and suspension load processes probably were operative, the former likely became more important as the delta prograded basinward. This is indicated by an upsection increase in the frequency of graded lamination. Graded mudstone laminae are more common in lower unit strata near the basin margin (e.g. South Lorrain township), where more proximal

conditions are inferred.

Small-scale symmetrical starved ripples, intercalated within thinly laminated lower unit mudstones, may be attributed to the oscillatory motion of waves (cf. Reineck and Singh, 1980, p.32). Oscillation ripples have been described in prodelta muds from the Mississippi River delta by Coleman and Gagliano (1965). Some starved ripples, however, may have been formed by deep water ocean or tidal currents. Larger asymmetric forms are more common toward the contact with the middle unit, where winnowing of the substratum by river and tidal currents in shallower water, provides the more likely ripple-forming mechanism (cf. Reineck and Singh, 1980).

Slumped lamination and sedimentary breccia observed in lower unit strata of the Eplett drill core probably formed by slow gravity-induced sliding on the lower part of the delta slope. These structures are most abundant within the main delta slope environment and are discussed in detail in the following section, although the lack of well-exposed lower unit sections might also explain their apparent paucity in the prodelta environment.

4-2b Delta Slope Facies (Middle Unit)

The relatively abrupt contact between the lower and middle units is interpreted as the record of a change from prodelta to delta slope sedimentation (see Figure 4.1). The delta slope, representing the seaward sloping margin of the prograding delta sequence, is characterized by sediments that are significantly

coarser grained than the prodelta sediments. These sediments coarsen and become increasingly well sorted up section.

The lower part of the middle unit is characterized by beds of parallel-laminated mudstone and siltstone that probably represent deposition of the background, suspended load. Graded siltstone laminations likely are the lateral and proximal equivalents of thinner graded laminae in the lower unit, and represent deposition by traction load. Upwards in the sequence, graded laminations become thicker and more abundant, as is typical of river-dominated deltas (Elliot, 1976; 1978), suggesting an increasing influence of flood-generated sediment incursions from the distributary mouth.

Ripple cross laminations and lenticular bedding are common within strata of the middle unit, and also increase in size and abundance upsection. This evidence of sediment agitation probably reflects an increasingly lower wave base in the succession (Elliot, 1978; Siedlecka and Edwards, 1980). The maximum fair weather wave base according to Walker (1985) is approximately 15 metres, although storm waves can move bottom sediments down to depths of 200 metres (Komar, 1972). Studies of similar strata types from the Mississippi River delta slope environment indicate deposition at water depths of between 5 and 75 metres (Coleman, 1980). Opposed asymmetry and cross lamination in starved ripples in suprajacent beds of the upper part of the middle unit suggests that at least some ripple forms were produced by tide-generated ebb and flood currents.

The locally developed thick graded arkose bedsets that display lateral continuity, Bouma divisions (Bouma, 1962), sole marks and other bedding irregularities are interpreted as turbidity current deposits (a variety of sediment gravity flow,

Figure 4.1). The thick basal sand components of these units most closely resemble the S_3 subunit of Lowe's (1982) high density sandy turbidite (Figure 4.2). Stacked S_3 units are common (Figure 3.3; compare with Figure 4.2b) and may represent deposition by a surging flow (Lowe 1982). Overlying T_{b-e} divisions, where present, form the residual and lower density stage of deposition. The absence of traction carpet layers (units S_1 and S_2) reflects the negligible dispersive pressures which are developed in such fine-grained deposits (Lowe, 1982).

Firstbrook Member sandy turbidites display remarkable similarity to the delta-fed proximal submarine ramp facies of Heller and Dickinson (1985), particularly in that individual sand bodies are rarely channeled and exhibit lateral continuity with minimal thickness variation. Heller and Dickinson maintain that this is evidence for the development of an aggrading ramp-like deposit in front of the advancing delta rather than a broad fan formed by point source input from a master slope, channel or canyon. Firstbrook Member sandy turbidites are similar in scale to proximal submarine ramp turbidites, and contain similar sedimentary structures, including groove casts, flute casts and flame structures.

Deposition of sandy turbidites is a function of slope instability caused by rapid accumulation of sediment and subsequent oversteepening on the upper delta foreslope (see Figure 4.1). Coleman et al. (1983) noted that rapid sedimentation rates can lead to the development of elevated pore pressures, thereby reducing sediment shear strength, allowing

Figure 4.2 (A) Ideal sequence of divisions deposited by a single high-density turbidity current declining through discrete gravelly and sandy sedimentation waves. Because of downslope separation of gravel and sand depositional stages, complete high density sedimentation units such as this are rarely formed.

(B) Complex sedimentation unit deposited by surging sandy high-density turbidity current. Compare with Figure 3.3.

redrawn from Lowe (1982)

gravity-induced sliding on relatively low-angle slopes.

Analogous deposits from the Mississippi and other modern deltas require slopes of less than one degree (Coleman and Prior, 1980).

Apart from oversteepening due to rapid sedimentation, additional triggering mechanisms may be required to induce slope failure (Lindsay et al., 1984). Mechanisms that have been proposed include:

(1) Diapirism. A feedback mechanism caused by loading of the underlying prodelta sediments in which mud protrusions are forced upwards, causing rapid oversteepening of delta foreslope sediments (Coleman et al., 1974). However, large-scale mud diapirs have not been noted within Firstbrook Member strata;

(2) Storm Waves. According to Coleman and Prior (1980), Woodrow and Isley (1983), Lindsay et al. (1984) and Walker (1985), storm waves produce submarine landslides as a result of stress generated from wave-sea-floor interaction, and by a combination of cyclic loading and heightened pore fluid pressures;

(3) Water-level Fluctuations. Studies of glaciolacustrine deltas by Shaw (1977) and Gilbert (1975) indicate that slope failure can occur in response to increased seepage generated by lowered lake levels. In a marine setting, tidal fluctuations could produce the same effect;

(4) Shock-induced Failure. Earth tremors emanating from nearby faults could provide enough shock to produce failure (see

Seilacher, 1984).

The latter mechanism has been invoked to explain the deformation of the thick arkose bedset exposed at the Highway Junction outcrop (Figure 3.3, Plate 4c). The bedset was initially studied by Kurt (1973), who suggested that the entire unit is a clastic sill intruded in response to a shock event, possibly an earthquake. A more detailed study by Dodd (1985) has led to reinterpretation of this unit as a sequence of stacked sediment gravity flows which were subsequently deformed by shock-induced liquefaction.

Sandy turbidites have been described from the delta slope facies of numerous ancient deltaic examples including the Bideford Group in North Devon, England (de Raaf *et al.*, 1965) and the Catskill clastic wedge (Woodrow and Isley, 1983).

Related to the sandy turbidites in the Firstbrook Member are coherent and non-coherent soft-sediment folds and homogenized beds, all of which probably represent gravity induced sliding down the delta slope. Coherent slumps therefore, indicate short distance transport, perhaps on relatively low-angle slope segments. This is in contrast to homogenized beds, in which most of the original layering has been destroyed, suggesting more extreme sliding on steeper slope segments. In instances where the substrate was more cohesive, slope failure resulted in brecciation. The breccia zones are inferred to be syn-sedimentary on the basis of plastic deformation displayed by most of the component clasts, and by the truncation of some zones by undisturbed overlying strata.

Concordant breccia zones and slumped beds are analogous in

some respects to the deltaic mudflow deposits described by Coleman et al. (1983). (See Figure 4.1).

Simony (1964) and Card et al. (1973) attributed the origin of brecciation in the upper Gowganda stata to soft-sediment slumping as opposed to tectonic brecciation. The occurrence of these zones in mudstone and interbedded mudstone/siltstone (but not in sandstone and conglomerate beds) is cited by Simony (1964) as evidence for a contemporaneous origin.

McIlwaine (1978), who noted discordant breccias in Firstbrook Member rocks northeast of the study area, attributed their formation to brecciation associated with slumping and faulting along active fault scarps. The occurrences reported by Johns (1985), are related to faults and occur in an arcuate pattern which is concave toward the southeast (this approximates the predominant southward paleotransport direction inferred from other data). This observation, in combination with a proposed synsedimentary origin for the breccias, suggests the development of arcuate growth faults on the delta foreslope. Arcuate rotational slumps related to contemporaneous growth faults commonly develop as a result of slope instability due to progradation of river-dominated deltas (Coleman and Prior, 1980; Coleman et al., 1983). Most are generally active along the peripheral margin of the delta front.

The fault described in section 3-3b is considered to be contemporaneous, as evidenced by its close association with a coherent slump fold and by the undisturbed nature of overlying strata. Its concave upward geometry resembles that of the growth

faults described by Coleman et al. (1983). Mud flow deposits are commonly associated with growth faulting, particularly on the downthrown side of the the fault system (Coleman and Prior, 1980).

4-2c Delta Foreslope Facies (upper unit)

Fine-grained sandstone and interbedded siltstone and mudstone of the upper Firstbrook Member are inferred to represent deposition within a delta foreslope subenvironment. The gradational contact with the middle unit probably reflects the poorly defined lateral transition from delta slope to delta foreslope.

The association of interbedded mud, silt and sand characterized by wavy, parallel and lenticular bedding is a product of alternation of bedload and suspension deposition; similar to the tidal bedding described by Reineck and Wunderlich (1968), Reineck (1972), Klein (1977) and Reineck and Singh (1980). The type of bedding preserved is somewhat dependent on the texture of the sediment. Where mud is dominant, lenses of sand or coarse silt, produced by ripples migrating across muddy substrate, are preserved. Many starved ripples show opposing senses of transport, providing support for the postulation of tidal influence. Higher in the section, where the content of sand increases, the dominant structure is wavy bedding consisting of rippled sand layers alternating with draped mud. Flaser bedding is similar to wavy bedding except that mud is preserved only as concave-upward lenses in ripple troughs, reflecting reduction in supply of mud. According to Reineck and Singh

(1980), preservation of these bedforms requires alternating conditions of current and/or wave action (deposition of sand) and slack water conditions (deposition of mud). In bedding-parallel exposures of wavy and lenticular bedding, ripples are primarily straight-crested, suggesting that they were formed by waves. Rare sinuous-crested and linguoid examples are most likely current-generated. Reineck and Singh (1980, p.118) stated that the ripple bedding of flaser and lenticular bedding is commonly current-generated, but that wave action can be a locally important mechanism.

The isolated example of herringbone crossbedding and interference ripples is considered significant because its association with flaser, wavy and lenticular bedding lends further support to the postulation of tidal influence (cf. Eriksson, 1977; Vos, 1977).

Most parallel lamination or "horizontal parallel stratification" in sandstones is the product of unidirectional upper flow regime conditions (cf. Picard and High, 1973), and can occur in a variety of settings including braided fluvial (McKee et al. 1967; Smith, 1971) and intertidal (Reineck and Singh, 1980) environments. The occurrence of parallel stratified sandstone with interbedded wavy- and lenticular-bedded sandstone and siltstone suggests deposition by periodic river flood incursions and subsequent reworking by tidal currents and waves.

Longitudinal scour structures such as flute-rill marks (Reineck and Singh, 1980, p.75) and gutter casts are unique to upper unit strata, and are interpreted as the product of river-

borne flood currents and/or ebb tide currents in shallow water, subtidal areas on the delta foreslope. Both types of structure form due to the action of small-scale current vortices close to the bed surface where the spiral vortices have axes parallel to the current (Collinson and Thompson, 1982; Allen, 1984).

Gutter casts are described by Allen (1984) as being diagnostic of tidal current flow in either intertidal or subtidal settings down to water depths of several tens of metres. The gutter casts are larger than the flute-rill marks, indicating higher energy and possibly shallower water conditions, although the Firstbrook example (Plate 5d) is relatively small in comparison to published examples (e.g. Collinson and Thompson, 1982, p.41), suggesting relatively weak tidal currents.

Features such as those interpreted herein as flute-rill marks were originally described by Dzulynski and Walton (1965) as rill marks; however, they should not be confused with true intertidal rill marks, which generally are dendritic rather than anastomosing (cf. Reineck and Singh, 1980). Allen (1969) produced similar structures experimentally, naming them "longitudinal meandering grooves". Allen (1984) emphasized, however, that these structures are rare in the rock record and are an indication of the path and turbulent nature of currents, but are not otherwise environmentally diagnostic.

Soft-sediment deformation structures occur throughout the upper unit, but are concentrated within the transition zone beneath the overlying Lorrain Formation. In the model (Figure 4.1), this zone corresponds to the delta braidplain (topset) - delta slope (foreset) break; a region where an abrupt change in

flow regime should result in rapid deposition of river-borne sediment. These structures are inferred to be related to rapid deposition of thick dense sand layers on top of less dense, muddy, water-saturated sediment. Reviews of such structures (Dzulynski and Walton, 1965; Reineck and Singh, 1980; Collinson and Thomson, 1982; Allen, 1984; and many others) have suggested that rapid loading can result in an immediate increase in hydrostatic pressures due to a change in packing of the underlying sediment. As a result, water is squeezed from the sediments, promoting liquefaction and subsequent deformation. Potter and Pettijohn (1963) and Allen (1984) have pointed out that liquefaction and formation of ball-and-pillow structures can be catalyzed by seismic shock.

The type of structure formed is dependent on the horizontal mobility of the system as well as the difference in kinematic viscosity between the two layers (Reineck and Singh, 1980). Most of the structures described, including ball-and-pillow structures, convolute lamination and load casts can be categorized as deformation structures related to "gravitationally unstable vertical profiles of bulk density" (category 1 of Allen's 1984 classification of soft-sediment structures, Appendix 1).

Where the horizontal mobility of the system is greater, such as on the delta slope, different structures such as soft-sediment folds and inclined flame structures are formed by gravity-induced sliding and slumping on the delta slope. This is a probable explanation for the occurrence of these structures lower in the

upper unit as well as within the middle unit. These slide- and slump-related structures can be categorized as deformation structures related to a "downslope component of body force" (category 3 of Allen's 1984, classification of soft-sediment structures, Appendix 1).

Mud-chip breccia zones within the Firstbrook Member-Lorrain Formation transition zone are interpreted as evidence of subaerial exposure on the delta top. Mudclasts were probably incorporated and deformed by sand-laden river flood incursions which overrode previously exposed cohesive and possibly cracked muddy surfaces. The limited occurrence of mud chip breccia and mud cracks below the transition zone suggests that the Firstbrook Member was primarily deposited below sea level.

Sedimentary structures and limited paleocurrent data from upper Firstbrook Member strata suggest that deposition on the upper delta foreslope was controlled by a complex interaction of river-, tide- and wave-generated currents. Fluvial processes were responsible for initial deposition, although in most areas, wave and tidal processes reworked the sediment. The tide and wave currents were probably weak, as suggested by the overall textural and mineralogical immaturity and by the lack of tidal channels, beach deposits and offshore bars.

Upper unit strata coarsen upward into trough-crossbedded arkose of the Lorrain Formation, interpreted as delta braidplain (delta topset) deposits. In the South Lady Evelyn and Eplett drill hole sections (Figures 3.6 and 3.1), this coarsening-upward trend is seen to comprise at least two small-scale coarsening-upward cycles. In river-dominated deltas, such sequences

represent repeated progradational cycles separated by thin, fine-grained delta abandonment facies (Elliot, 1976; 1978). The fine-grained zone within upper unit strata of the Eplett drill hole (620-625 metres), may represent abandonment. This zone, similar to typical middle unit lithologies, displays sedimentary structures such as lenticular bedding and ripple cross lamination, suggesting some reworking by waves and possibly tidal currents after a prograding delta lobe had shifted.

Multiple cycles are unusual in the Firstbrook Member; one continuous coarsening-upward sequence is more characteristic (e.g. South Lorrain Township section, Figure 3.2). This suggests that fluvial input did not occur from one point source, as is the case for the Mississippi River and most other modern river deltas. Instead, a broad fluvial braidplain is envisaged in which upper delta foreslope sands formed a long continuous prograding front or ramp. The model (Figure 4.1) most closely resembles that of a lobate delta where numerous distributary channels with closely spaced river-mouth bars produced a sheetlike distribution of sand (cf. Elliot, 1976). Elongate or birdfoot deltas (e.g. Mississippi Delta) have fewer distributaries, and sand bodies are confined to "bar fingers" which have limited lateral distribution and are separated by broad wedges of interdistributary bay silts and muds (cf. Coleman and Gagliano, 1965).

4-2d Delta Braidplain Facies (lower Lorrain Formation)

The transition zone (described above) between the Firstbrook Member and the overlying Lorrain Formation represents a transition from delta slope to a delta braidplain setting. Some previous workers (Hadley, 1968; Young, 1973) invoked a shallow marine origin for the lower Lorrain Formation; however, their interpretations were based upon strata which in this study are classified as strata of the upper Firstbrook Member.

The lower Lorrain Formation was not studied in detail, but features such as a unidirectional paleocurrent pattern (Figure 4.4) indicating strong southward transport and a relative paucity of siltstone and mudstone (vertical accretion deposits) suggest deposition in a braided fluvial setting. Hadley (1968) compared lower-middle Lorrain Formation rocks from the Cobalt area to the coarse clastic phase of a coarsening-upward regressive marine or delta fringe sequence. On the basis of similar evidence, Young (1973) invoked a braided fluvial origin.

In the model favoured in this study, sediment input is envisioned as coming from a broad braidplain rather than from a point source at the mouth of a meandering river. Meandering systems would be more likely to develop in post-Ordovician settings in response to the advent of landplants which allowed stabilization of the substrate (Schumm, 1977). During Precambrian and early Paleozoic time, a severe microclimatic environment characterized by extreme and rapid temperature changes combined with a lack of effective vegetation cover would produce conditions similar to those observed in modern arid

environments (Schumm, 1977). Constant uplift due to glacial rebound in the source region may have maintained a steeper depositional slope which would also favour braided stream development. Braided streams therefore, would be likely to develop at the time of deposition of the Huronian Supergroup.

4-3 Modern and Ancient Analogues

Wright (1978) noted that individual delta systems display unique attributes which set them apart from others, and that most generalizations do not adequately convey the realities of an individual system. A comparison of 34 modern river systems by Wright et al. (1978) does, however, indicate that in terms of particular sets of morphologic features and environmental variables, deltas tend to cluster together in individual groups. Coleman and Wright (1975) further subdivided these groups into six general types based on their gross geometry.

None of the six classes uniquely describes the morphological features of the delta model proposed in section 4-2. Many features, particularly those described for the prodelta and delta slope subfacies, closely resemble the attributes of the type 1 delta of Coleman and Wright (1975). Type 1 is characteristic of a deltaic environment having low wave energy, low tide range, flat offshore slope, low littoral drift and high fine-grained suspended-sediment load. Examples of this type include the Mississippi, Parana, Dneiper and Orinoco deltas (Coleman, 1980). Progradation of a type 1 delta will result in the development of highly elongate and isolated distributary mouth bar sands oriented at a high angle to the coastline. This differs greatly

from the proposed model (Figure 4.1) in which the distributary mouth bar (upper delta foreslope) sands show high lateral continuity and an overall sheet-like geometry; a pattern more characteristic of the type 5 delta. Type 5 geometry, however, is a function of persistent high wave energy acting over relatively steep offshore slopes. Textures and sedimentary structures in the Firstbrook Member do not offer evidence for strong reworking by waves (development of beaches, barriers and spits), and a shallow offshore slope is more likely in river-dominated deltas.

Clearly, no modern analogue aptly defines all major sedimentological aspects of the Firstbrook Member. One explanation for this is that large deltas formed by braided streams or braidplains generally are uncommon at present, except in extremely arid regions. In these areas the runoff rates and sediment yield are high and erratic, and the lack of vegetation prevents stabilization of sedimentary deposits and stream channels. Coleman (1980) pointed out that these circumstances will produce a river which tends to change its course frequently and migrate rapidly. This type of channel migration produces a braided pattern which results in a sheet-like distribution of sand as opposed to the elongate shoestring sand bodies typical of meandering channel configurations.

Documented analogues from the rock record, particularly from the Precambrian, are rare. River-dominated delta sequences have been described by de Raaf *et al.* (1965) and by Elliot (1976) from the Carboniferous of north Devon, England. These studies describe the cyclic occurrence of coarsening upward sequences containing basal mudstones, delta front siltstones and

turbidites and overlying fluvial sandstones. Elliot (1976) has stressed criteria for the recognition of delta type in ancient successions, and has distinguished between lobate and elongate (birdfoot) river-dominated deltas. Woodrow and Isley (1983) described a threefold facies subdivision similar to that proposed for the Firstbrook Member to interpret the Devonian Catskill clastic wedge of New York and Pennsylvania.

Descriptions of tidally influenced ancient delta sequences are rare. One such example, from the Devonian-Carboniferous Tindouf Basin in southern Morocco (Vos, 1977) records regressive and transgressive episodes due to separate phases of constructive and destructive delta building. Tidal facies were most strongly developed during the transgressive (destructive) phase when a less actively depositing fluvial system enabled marine processes to rework the margin of the delta plain. Eriksson (1977) has described a tidally influenced delta from the Archean Moodies Group of South Africa. Tidal currents are the dominant formative agent in this example, as evidenced by the development of tidal channels and sand shoals; features which are not evident in Firstbrook Member strata. Tidalites from the Proterozoic Animikie Basin of Wisconsin and Michigan (Ojakangas, 1983), although not directly associated with a deltaic environment, are similar to the Firstbrook Member delta foreslope facies.

The most applicable ancient analogue to the Firstbrook Member is the upper Proterozoic Basnaering Formation: a fluviodeltaic complex in northeast Finnmark in northern Norway. Regional and detailed sedimentological investigations of this

unit (Siedlecka and Edwards, 1980; Pickering, 1982) have outlined prodelta (lower Naeringselva Member), delta slope to delta front (upper Naeringselva Member) and delta plain (Segladden Member) subenvironments. The sequence displays a coarsening-upward trend interpreted as progradational and river dominated, with minor wave and tidal current influence in the Naeringselva Member. Slope instability processes are indicated by slump structures and low density turbidity current deposits. A lobate delta was proposed (Siedlecka and Edwards, 1980), based on the probable sheet-like distribution of sand on the delta plain, and by evidence for reworking by marine processes around the delta margin.

A lithologic correlation between Cobalt Group strata and the lower Libby Creek Group of southeastern Wyoming was first proposed by Blackwelder (1926) and later reinforced by Young (1970, 1973) and by Karlstrom et al. (1983). Young (1973, Figure 6) has suggested that the Headquarters Formation and Heart Formation are correlative with the lower and upper members of the Gowganda Formation. More recent sedimentological studies by Lanthier (1979) and Karlstrom et al. (1983) indicate a two-fold subdivision (glacial/marine deltaic) of the Headquarters Formation, similar to that proposed for the Gowganda Formation in this study. The overlying Heart Formation, interpreted by Karlstrom et al. (1983) as delta front, is likened to the upper unit of the Firstbrook Member. The thick (>1700 metres) Medicine Peak Quartzite displays lithological characteristics similar to the Lorrain Formation.

4-4 Paleogeography

4-4a Thickness Variations

The thickness of the Firstbrook Member varies markedly within the Cobalt basin (see Regional Correlation, Figure 3.5). It attains a maximum thickness of 535 metres (Eplett drill hole) but may be even thicker southwestward (toward the inferred depocenter of the Cobalt Basin). The Firstbrook Member thins southeastward, towards the Ragged Chutes section where it is only 40 metres thick. Farther to the east, arkose of the lower Lorrain Formation lies directly on Coleman Member diamictite (see Regional Compilation Figure A and Plate 1d).

Lower unit sections exhibit the most pronounced stratigraphic thickness variations, and thus provide an indication of basin paleotopography before deposition of the Firstbrook Member. The thickest accumulations, which occur in the central and northern parts of the study area, are inferred to represent the deepest parts of the basin where marine shelf and prodelta environments prevailed.

Thinning of the lower unit toward the east and southeast is controlled by the influence of Archean basement topographic highs. Local basin topography has been described in Barr and Firstbrook townships by Johns (1985), and in Lundy township by Owsicki (1985). The abrupt change in lower unit thickness between the Eplett drill hole and Highway Junction sections (Figure 3.5), may be related to an Archean topographic high (described by Owsicki, 1985) which transects the south-eastern part of Lundy Township.

Basin topography may have been enhanced by south-dipping

normal faults developed during the initial rifting phase of basin development (see section 2-2); however, no faults of this type have been documented. The existence of a fault on the northern margin of the Cobalt Basin was suggested by D. Long (1984, personal communication) as a possible explanation for the great thickness of the Firstbrook Member in Henwood township.

The nature of the contact between the lower unit and the underlying Coleman Member provides some clues as to former basin configuration. A gradational contact occurs where the lower unit is thickest (eg. Eplett drill hole), representing deeper parts of the basin away from the main locus of sedimentation. In contrast, sharp contacts are associated with relatively thin lower unit sections near the edge of the basin (eg. South Lorrain township). Abrupt contacts also reflect relative proximity to source areas adjacent to the basin margin. The thin cobble orthoconglomerate exposed at the sharp contact along the Matabitchuan River (Plate 1c) probably represents a lag deposit formed in relatively shallow water.

Thickness variations in the overlying middle and upper units are less pronounced than in the lower unit. Infilling of the basin through deposition of lower unit sediments presumably "smoothed out" the effects of Archean topographic relief. Both units, however, display lateral pinch-out toward the edge of the basin. The greater marginal distribution of each succeeding unit is inferred to reflect shallowing ~~and~~ delta progradation infilled the basin.

4-4b Paleocurrents and Provenance

Paleocurrent data were obtained from ripple cross laminations in the middle and upper units of the Firstbrook Member, and from trough and rare planar crossbeds in the overlying Lorrain Formation. Data collected from 16 widely scattered localities (6 Firstbrook and 10 Lorrain) indicate an average transport direction toward the south. Data sets comprising less than 5 readings were not plotted on rose diagrams but do agree with the overall observed trend.

Ripple cross laminations from the middle unit display predominantly southward transport; although a strong northward component also is apparent (Figure 4.3). Paleocurrent reversals of suprajacent ripple forms were noted in a few outcrops where cross laminations could be viewed in three dimensions; apparent reversals commonly can be seen in two-dimensional vertical sections (Plate 8). The bimodal-bipolar pattern which emerges may be associated with tide-generated currents which are directed onshore and offshore during flood and ebb (cf. Pettijohn, 1975). A general southward asymmetry (average, 3:1) is attributed to the dominance of ebb currents aided by river current outflow.

Data from the upper unit display a slightly more scattered to bimodal-oblique distribution (Figure 4.3). In this shallow-water environment, the effects of wave-generated currents and possibly longshore currents would have been more pronounced. Superimposed on tidal and river currents, a complex paleotransport pattern could be expected. Additional measurements of the upper unit bedforms would be required to

Figure 4.3 Paleocurrent distribution diagram for the upper and middle units of the Firstbrook Member based on measurements of ripple crosslamination. Measurements are grouped into 30 degree classes. The rose diagram in the top right corner summarizes the entire data set. The stippled area represents the approximate distribution of the Firstbrook Member.

substantiate this.

Crossbed rose diagrams for the lower Lorrain Formation indicate a unimodal distribution with dominant transport toward the south and southeast (Figure 4.4), in agreement with the patterns established by Hadley (1968, p.170). The generally low variance within the individual data sets imply relatively low sinuosity (cf. Pettijohn, 1975), which would be expected in a delta braidplain environment. A strong easterly trend, apparent in the region south of Cobalt, is interpreted to represent a deflection of paleocurrents around an Archean basement promontory to the south (see Figure A). A north-directed paleocurrent pattern observed at one locality from northern Lake Temagami, also may be the result of local basement topographic control.

Rare paleoslope indicators such as current scours and inclined flame structures are in accordance with the above observations. Measurement of slump fold axes in the vicinity of the Highway Junction locality (Dodd, 1985, Figure 4.5) indicate a generally random pattern of orientation (within the bedding plane) and therefore are an unreliable paleoslope indicator. A possible explanation is that, during slumping, friction at the margin of the slump may have caused it to rotate out of strike alignment (cf. Miall, 1984, p.257; Alvarez et al. 1985).

Paleocurrent data indicate that the source area for Firstbrook Member sediments was north of the basin. The predominantly granite-gneiss composition of this region is reflected in the arkosic composition of Firstbrook Member and lower Lorrain Formation sandstone. Clasts in diamictite of the underlying Coleman Member are predominantly of granitoid

Figure 4.4 Paleocurrent distribution diagram for the lower Lorrain Formation based on measurements of crossbedding. Measurements are grouped into 30 degree classes. The rose diagram in the top right corner summarizes the entire data set. The stippled area represents the approximate distribution of the Lorrain Formation.

Figure 4.5 Stereogram of slump fold axes from middle unit outcrops in the Highway Junction area (redrawn from Dodd, 1985). A generally random pattern (within the bedding plane) is indicated.

composition (Rainbird, 1980), although concentrations of felsic and intermediate volcanic rocks, chert, and clastic sedimentary rocks occur locally (P. Mustard, personal communication, 1984). Lindsey (1967) and Hadley (1968) also concluded that both the Gowganda and Lorrain Formations were derived from a northern plutonic terrane and that pre-existing Huronian rocks did not contribute to the Gowganda Formation. However, geochemical study of mudstones (McLennan, 1977) suggests that the source terranes for most Huronian rocks generally was more mafic than that suggested by petrographic studies of the coarse-grained units. (see Section 5-3).

4-5 Origin and Significance of Redbeds

Redbeds are best developed within the middle and upper units of the Firstbrook Member, and generally are variegated. In the middle unit, red coloration is typically confined to the fine-grained laminae which enclose thin green sandy lenses and lamination (Plate 2d). An exception to this trend is observed where the section is dominated by sandy turbidite beds; these usually are red and are bounded by drab or normally variegated siltstone/mudstone laminites (Plate 2c and 2e). Red coloration is confined primarily to sand-rich layers in the upper unit strata and to mud-rich layers in the middle unit, although exceptions to this have been noted. Where variegation occurs, red coloration generally is best developed in the texturally dominant lithology.

Red coloration in the Firstbrook Member is attributed to the presence of diagenetic pigmentary hematite. Hematite in

mica-rich layers occurs mainly as very fine, evenly distributed grains. In this case, hematite likely formed during diagenesis by compaction-related dehydration (or ageing, Van Houten, 1968; Berner, 1969) of amorphous iron hydroxide or goethite (Langmuir, 1971) under oxidizing conditions. According to this hypothesis, yellow-brown hydrates are derived from the source area by weathering and erosion and are transported as thin grain coatings on clay minerals.

Hematite also occurs as a replacement of detrital iron-magnesium silicates (chlorite, biotite, pyroxene and hornblende) in both fine and coarse grained layers (Plate 6e). Similarly, hematite locally pseudomorphs blocky euhedral grains which are assumed to be opaque oxides (possibly magnetite or ilmenite). These occur mainly in the coarser grained layers as part of thin heavy mineral bands.

Alteration of detrital iron-magnesium silicates and oxides to hematite was likely catalyzed by percolation of iron-bearing groundwaters through permeable layers. Under high Eh and low pH conditions (i.e. within the stability field of hematite), ferric iron from detrital grains is exchanged for ferrous iron in solution to form metastable iron oxyhydroxides which eventually age to form hematite. A local source for ferrous iron may be through intrastratal dissolution of iron-bearing framework grains (Walker, 1967; 1976). Evidence for this process is not overwhelming, although partially dissolved grains were observed in several thin sections along with authigenic micaceous cement (Plate 6f), representing reprecipitated alumina, silica, and alkalis (Walker, 1978).

Hematite in red sandy layers occupies several textural sites, including fine-grained envelopes surrounding framework grains (Plate 6d), granular aggregates in interstitial areas (Plate 6c) as well as replacements of iron-bearing silicates and oxides. In several samples of lower Lorrain Formation arkose, enveloped grains are overgrown by authigenic quartz (Plate 6d), suggesting early diagenetic pigmentation.

The association of coarse red layers with drab fine layers is unusual: variegated redbeds typically display drab coarse layers and red fine layers (eg. Aspler and Donaldson, 1985). A similar relationship has been described for marine redbeds by Lajoie and Chagnon (1973) and by Ziegler and McKerrow (1975), who suggested that the coarse layers represent redbeds reworked or resedimented from adjacent paralic environments. The proposed turbidite origin for most middle and upper Firstbrook Member red arkose beds would make this hypothesis feasible, but several lines of evidence do not support this. Abraded hematite rims, suggestive of early diagenetic reddening and subsequent transport, were not observed. Instead, hematite occurs as interstitial aggregates and disappears at grain contacts (Plate 6c) and therefore probably developed in situ. Secondly, except for a few scattered occurrences northwest of the study area, red strata are rare in the lower Lorrain Formation, a likely source for resedimented material.

A diagenetic model involving in situ reddening by iron-bearing oxidizing groundwater is favoured to explain variegation in this instance. The drab laminae could not redden because they

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were less permeable to groundwater migration. Further supportive evidence includes the presence of mud rip-ups in sandy turbidites which are either completely red or at least display a thin red envelope with a drab core. Similarly, drab mud layers show thin red mantles at their bounding surfaces with sandy layers, indicating that groundwater did at least partially penetrate the less permeable material.

Within thin coarse-grained laminae and particularly in sandy starved ripples, detrital iron oxides and clay cement have been replaced by chlorite (Plate 6g). Brown micas (possibly biotite) within the chlorite altered zones may have replaced hematite, suggesting alteration under late-stage reducing conditions. An identical relationship has been observed in reduction spots from red Lorrain Formation arkose (Plate 6h).

Chlorite alteration, a characteristic of Huronian rocks from the study area, is a consequence of regional and local contact metamorphism. The strongest alteration occurs within contact aureoles adjacent to Nipissing Diabase intrusions (Rainbird, 1980). Chlorite is preferentially developed in sandy layers which presumably were permeable to metasomatic fluids emanating from the diabase. A reducing environment is indicated by the paucity of red coloration within the metamorphic aureole.

As mentioned previously, the intensity of red coloration varies regionally (laterally) as well as stratigraphically. Wood (1980), suggested that the appearance of red coloration in the Gowganda Formation occurs at a lower stratigraphic level in northern areas than in the southern part of the Cobalt Basin, and thus may represent a time line indicating that Firstbrook strata

in the northern parts of the basin are younger than similar strata to the south. However, field observations for the present study indicate that red coloration does occur in lower parts of the Gowganda section in the southern part of basin. Red coloration is well developed in Coleman Member sandstone at the Montreal River dam in South Lorrain township and in several roadside outcrops on Highway 11 north of Temagami. Wood's (1980) suggestion that Gowganda Formation rocks in the north are younger than those in the south is therefore difficult to reconcile with these observations, particularly if the delta which deposited the Firstbrook Member, as paleocurrent data suggest, prograded from north to south. The fact that redbeds are absent south of Lake Temagami (Wood, 1979) is more likely a result of post diagenetic reduction associated with a higher degree of regional metamorphism in this region (Card, 1978a). Regional variations in coloration intensity could also be a function of localization of oxygenated groundwater.

Stratigraphic colour variations are in part due to Eh-pH changes with water depth. Early diagenetic reddening is possible in the shallow marine environment where wind-driven mixing can cause aeration (Yeo, 1984). The adjacent terrestrial environment and its atmosphere is assumed to be oxidizing, as indicated by the development of primary redbeds in the overlying Lorrain Formation. Although normal marine waters are oxygenated, the pore solutions are not, due to organic degradation which produces reducing conditions (Turner, 1979). During the early Proterozoic, organics would not be deposited in shallow-water

(higher energy) environments suggesting that oxidizing conditions in pore fluids are quite possible. Shallow water strata (upper and middle units) may also have reddened from oxidizing pore fluids which originated above sea level.

Strata of the lower unit are mostly drab owing to the low Eh conditions which prevailed in the inferred deeper water environment. Some lower unit beds, particularly the black laminated mudstone, contain appreciable amounts of organic carbon, also suggesting anoxic conditions. Finely laminated red mudstone occurs at the gradational contact between the Firstbrook and Coleman Members in the Eplet drill hole, and in similar rocks in Aston township (near the northern tip of Lake Temagami). Yeo (1984) has suggested that deep-water redbeds may be related to the development of dense oxygenated brines produced through the formation of sea ice in frigid regions. Also, cold, dense oxygenated water from melting glaciers could have been transported into deeper water environments as underflows. These situations seem possible considering that the Firstbrook Member prodelta mudstones directly overlie Coleman Member glaciogenic deposits. Red mudstone also occurs in modern deep-water oligotrophic environments, where organic matter generally is absent (Franke and Paul, 1980).

The significance of red coloration in the Gowganda Formation was first emphasized by Roscoe (1968; 1973) who suggested that the presence of redbeds above otherwise comparable, drab-coloured lower Huronian strata (containing pyrite and detrital uraninite) signalled the beginning of a build-up of free oxygen within the Earth's atmosphere. The concept of the "oxygenation" (Roscoe,

1973) was first proposed by Cloud (1968; 1972) who also suggested that approximately 2000 Ma ago, the production of oceanic oxygen by marine photosynthesis exceeded its consumption by dissolved ferrous iron (formation of Archean banded iron formation), such that oxygen began to escape to the atmosphere. Evidence for this changeover is manifest in the appearance of the first terrestrial redbeds and the concomitant disappearance of siliceous banded iron formation. Sulphur isotope variations in the Huronian Supergroup (Hattori et al., 1983) are in accord with an increase in atmospheric oxygen at approximately 2200 Ma and are consistent with the appearance of redbeds in the Cobalt Group.

Several workers have contended, however, that atmospheric photodissociation rather than photosynthesis was the primary contributor of free oxygen to earlier Precambrian environments (Brinkman, 1969; Towe, 1978). Dimroth and Kimberly (1976) and Clemmy and Badham (1982) maintained that an early oxygenated atmosphere existed throughout Archean time, and that many of the features advanced to support an anoxic model can be explained by diagenetic alteration.

A review of the literature suggests that the build-up of free oxygen was not an instantaneous development, and that periods of relative oxygenation gradually began to punctuate the reducing conditions which prevailed in both terrestrial and marine environments. With time, the appearance of regionally extensive rather than locally oxidized deposits of iron and sulphur (redbeds and evaporites) signalled "the beginning of the end of the general Precambrian reducing hydrosphere" (Towe, 1978;

V: GEOCHEMISTRY

5-1 Introduction

As pointed out in the preceding section, the transition between the Gowganda Formation and the overlying Lorrain Formation may be significant from the standpoint of an evolving Precambrian atmosphere. Although it may be fortuitous, several previous studies of Cobalt Group rocks suggest a rapid climatic amelioration, from the frigid conditions implied by lower Gowganda Formation deposition, to a humid and possibly subtropical regime during deposition of the Lorrain Formation (Chandler et al. 1969; Young, 1973 and Nesbitt and Young, 1982). If this interpretation is correct, geochemical evidence should be manifest within upper Gowganda (Firstbrook Member) rocks which mark the transition between these two contrasting climatic regimes.

A total of sixty-three samples were prepared and analyzed at the University of Ottawa and at X-RAL Labs, Don Mills, Ontario. All elements were determined by XRF, with the exception of boron which was analyzed by DCP; and L.O.I. (analyzed gravimetrically). The analytical techniques and precision are discussed in Appendix 2; all analytical results have been tabulated in Tables 5.1 and 5.2 (Appendix 2). Samples selected for analysis were primarily mudstones from the Coleman and Firstbrook Members, but also included were several samples from the overlying Lorrain and Gordon Lake Formations, as well as one sample of diamictite matrix from the Coleman Member. Sample locations are shown in Figure 5.9 (Appendix 2).

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5-2 Chemical Weathering of Cobalt Group Mudstones

The elemental variations between stratigraphic units can best explained in terms of chemical weathering of Cobalt Group source rocks. Pettijohn (1975, pp. 492-493), pointed out that the degree of chemical weathering of a rock is a direct function of the climatic regime which prevails at the time of weathering (assuming constant topographic relief). More specifically, chemical weathering and the nature of the residual products are primarily related to hydrolysis and the degree of leaching to which a parent rock has been subjected (Loughnan, 1969 pp. 51-52). For instance, chemical alteration is at a maximum in warm humid regions where high rainfall is responsible for deep, well-developed weathering profiles. In contrast, profiles in arid region soils are thin and composed of only slightly altered parent rock. Temperature variations also are important because they influence the rate of water-rock interaction (see Nesbitt and Young, 1984). According to "van't Hoff's rule", a chemical reaction increases by a factor of from 2 to 3 for each 10 degrees C rise in temperature. It thus should be possible to monitor any rapid change in climate by noting stratigraphic variations in the chemical mobility of the major element oxides.

Nesbitt and Young (1982) have applied this principle in their analysis of Huronian mudstones. Assuming that the dominant process operative during chemical weathering of the Earth's crust is the breakdown of feldspars to form clay minerals, a chemical weathering index (chemical index of alteration, or CIA, Nesbitt and Young, 1982; 1984) can be calculated on the basis of molar

proportions:

$$CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100,$$

where CaO^* is the amount of CaO in the silicate fraction of the rock. The index is derived on the assumption that during chemical weathering, the proportion of alumina to labile oxides increases. Lime (CaO^*) and soda (Na_2O) are most readily lost under leaching conditions. Potash (K_2O) is also leached, but at a much slower rate.

The classic studies of modern weathering profiles by Goldich (1938) and Reiche (1950) have indicated that the low mobility of K relative to Na is due to the greater resistance to decomposition of potash feldspars relative to plagioclase. The rate of K removal may be retarded by its "fixation" within the structure of illite (and possibly chlorite) during weathering reactions (Loughnan, 1969). McLennan (1977) attributed this to generally higher pH (7-8) in surficial waters, although Loughnan (1969) claimed that the unique size of the potassium ion is responsible for its preferential fixation in layered lattice silicates. Alumina (Al_2O_3) is totally immobile under a normal pH range of 4.5 to 9.5 (Loughnan, 1969; Pettijohn, 1975). Table 5.3 summarizes the mobilities of the common cations under normal weathering conditions.

1. Calculation of CaO^* does not take into account CaO as carbonate (CO_2). Unpublished data from the Ontario Geological Survey of Gowganda Formation mudstones from the study area indicate average CO_2 values less than 0.05 percent, an amount which would not affect calculation of the CIA.

TABLE 5.3

Mobilities of the Common Cations

>increasing rate of loss from the environment>

1. Ca^{2+} , Mg^{2+} , Na^{+} - readily lost under leaching conditions.
2. K^{+} - readily lost under leaching conditions but rate may be retarded through fixation in the illite structure.
3. Fe^{2+} - rate of loss dependent on the redox potential and degree of leaching.
4. Si^{4+} - slowly lost under leaching conditions.
5. Ti^{4+} - may show limited mobility if released from the parent material as $\text{Ti}(\text{OH})_4$; if in the TiO_2 form, immobile.
6. Fe^{3+} - immobile under oxidizing conditions.
7. Al^{3+} - immobile in the pH range 4.5-9.5.

from Loughnan (1969, p.52)

Similar chemical weathering characteristics have been observed in Archean (Shau and Henderson, 1983) and in lower Proterozoic paleosol profiles (Fryer, 1977; Button, 1979; Gay and Grandstaff, 1980), suggesting that conditions which prevailed during weathering of Gowganda Formation source rocks were not significantly different from the present day.

According to Nesbitt and Young (1982), Pleistocene clays yield CIA values in the 60-65 range, whereas average shales plot between 70-75. Extensively weathered residual clays generally show values greater than 85.

Of the samples analyzed in the present study, thirty-one are Gowganda and lower Lorrain Formation mudstones from the Eplett drill hole in Henwood township (Appendix 2). Samples of similar grain size were selected, because of mineralogical differentiation related to size sorting (Pettijohn, 1975), which may modify the CIA (Nesbitt and Young, 1982). The CIA data, presented stratigraphically in Figure 5.1, indicate an overall increase in chemical weathering up section.

Coleman Member mudstones plot just below the values for Pleistocene clays. Young and Nesbitt (1982) have suggested that low CIA values in Gowganda mudstones reflect incorporation of unweathered material such as glacial flour, supporting a glacial origin for this unit. In contrast, Firstbrook Member mudstones plot closer to the values for average shale, suggesting the incorporation of more weathered material. An abrupt increase in the CIA index across the Coleman Member-Firstbrook Member boundary is interpreted to be a function of increased weathering associated with a rapid amelioration of the climate. The

Figure 5.1

Figure 5.1 Chemical index of alteration (CIA) versus depth plot for Gowganda and lower Lorrain Formation mudstones from the Eplett drill hole (see Figure 3.1). The arrowed line (a moving average curve through the data points) indicates an overall upsection increase in chemical weathering. Note that Nipissing diabase sills are not included in the depth axis measurement, to give a more realistic indication of relative sample spacing.

decreasing trend in CIA values for the upper Firstbrook Member is more difficult to interpret, but likely is due to mineralogical differentiation associated with a possible up-section increase in sample grain size. Because of the difficulty in selecting only mud-sized material, some samples from the upper part of the drill hole may be slightly coarser grained, particularly those from the Lorrain Formation. Coarse-grained samples are likely to contain abundant feldspar, which should yield lower CIA values than finer-grained clay-mineral-rich material. According to Nesbitt and Young (1982), fresh feldspar has a CIA value of 50.

The ratio of $\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{SiO}_2) \times 100$ displays an almost identical trend to CIA values for the Eplett drill hole samples (see Figure 5.2) and is therefore useful, in this instance, as an abbreviated index of weathering. The up-section increase in the ratio indicates removal of silica, suggesting that a more humid climate prevailed during weathering of the source material for Firstbrook Member strata. Caution should be exercised when using this ratio, because silica values may vary markedly with any grain size variation or minor diagenetic alteration (G.M. Young, personal communication, 1985).

A significant increase in the weathering index between 1100 metres and 1300 metres in both the CIA-vs-depth plot (Figure 5.1) and the $\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{SiO}_2)$ -vs-depth plot (Figure 5.2) may have resulted from increased weathering during a period of interglacial warming. A similar interpretation was confirmed by

Figure 5.2

Figure 5.2 $\text{Al}_2\text{O}_3/(\text{Al}_2\text{O}_3+\text{SiO}_2) \times 100$ versus depth plot for Gowganda and lower Lorrain Formation mudstones from the Eplett drill hole (see Figure 3.1). The arrowed line (a moving average curve through the data points) indicates an overall upsection increase in removal of silica, perhaps related to an increasingly humid climate during weathering. Note that Nipissing diabase sills are not included in the depth axis measurement, to give a more realistic indication of relative sample spacing.

Young (1985), with the recognition of an interglacial unit from lower Gowganda Formation strata near Whitefish Falls, Ontario.

Other plots, which include the entire data set (Appendix 2), also support the hypothesis of increased chemical weathering after deposition of the Coleman Member. A distinct bimodal pattern is evident in data plotted on the $Al_2O_3-(CaO^*+Na_2O)-K_2O$ diagram (Figure 5.3). Coleman Member samples are relatively enriched in CaO^*+Na_2O , reflecting their unweathered character (low CIA values). Samples from the Firstbrook Member, Lorrain Formation and Gordon Lake Formation are notably depleted in CaO^*+Na_2O , reflecting stronger chemical weathering (higher CIA values). The samples with higher CIA values are also enriched in K_2O . A negative correlation between Na and K is indicated in Figure 5.4. Potassium enrichment in this case may be due (as mentioned above) to its fixation into layered lattice silicates during weathering. An alternative explanation is that potassium was added preferentially to the more weathered Firstbrook Member rocks during diagenesis. Diagenetic potassium enrichment has been noted by Button (1979) and by Gay and Grandstaff (1980) in the strongly weathered horizons of several lower Proterozoic paleosols.

Major element data are predictably reflected in certain trace element trends. A strong positive correlation exists between K and Rb (Figure 5.5) owing to their similar ionic and atomic properties. Billings (1978) suggested that the K/Rb ratio decreases during weathering. The K/Rb ratios for the Coleman Member and Firstbrook Member mudstones are 239 and 195 respectively, supporting this proposal. Likewise, because Sr is

Figure 5.3 Al_2O_3 -($\text{CaO}^* + \text{Na}_2\text{O}$)- K_2O diagram for Cobalt Group mudstones from the study area. Note relative K_2O and Al_2O_3 enrichment and $\text{CaO}^* + \text{Na}_2\text{O}$ depletion in Firstbrook Member samples relative to the Coleman Member.

Figure 5.4 Potassium versus sodium plot for Cobalt Group mudstones from the study area. The data points indicate a negative correlation coefficient of 0.8.

Figure 5.5 Rubidium versus potassium plot for Cobalt Group mudstones from the study area. The data points indicate a positive correlation coefficient of 0.9.

closely associated with Ca, the Sr content can be expected to decrease with increasing plagioclase decomposition as Ca is removed. The Rb/Sr ratio illustrates the dramatic change in chemical weathering trends between the Coleman Member (avg. = 0.38) and the Firstbrook Member (avg. = 2.53).

5-3 Boron: A Possible Paleosalinity Indicator

Boron analysis was applied as a possible paleosalinity indicator; boron is enriched in saline waters and therefore should also be enriched in argillaceous sediments deposited in marine as opposed to fresh water environments (Harder 1970; 1978). It was originally proposed that an increase in basin salinity brought on by the reduction of fresh glacial meltwater influx following Coleman Member deposition combined with a possible marine transgression, which initiated deposition of the Firstbrook Member, could be monitored by comparing the boron values of similar rocks from the Coleman and Firstbrook Members.

However, Shaw and Bugry (1966) and Harder (1970; 1978) caution that water salinity alone does not account for the observed boron content of argillaceous sediments, and that a number of other factors should be considered:

(a) Grain Size. Landergren (1958, cited in Shaw and Bugry, 1966), Shimp et al. (1969) and Dewis et al. (1972) demonstrated that B content increases with decreasing grain size (except where detrital tourmaline in the coarse fraction reverses this relationship). This increment represents preferential adsorption by clay minerals which are enriched in the finer fraction.

(b) Mineralogy. Harder (1978) maintained that phyllosilicates contain more boron than the other silicates. It is enriched in dioctahedral micas, especially muscovite and illite (Harder 1978), where it replaces aluminium or silicon in the tetrahedral positions. Although some workers have separated these minerals for boron analysis, Shaw and Bugry (1966) and Shimp et. al. (1969), have concluded that the whole rock method of analysis (used in this study) is valid.

(c) Rate of Sedimentation. Presumably the uptake of boron by sediments is related to the duration of their exposure to marine waters. Harder (1970) indicated that deep marine clays contain relatively more boron than shallow marine clays which are buried more rapidly by nearshore processes.

(d) Water Temperature. Cody (1971) and Harder (1970) cited temperature as being one of several factors which control the adsorption of trace elements, such as boron, to clays.

(e) Diagenesis and Metamorphism. Review of the literature indicates the boron content of argillaceous sediments is not significantly affected by diagenetic processes, but that the boron content of sedimentary rocks is reduced by metamorphism. Shaw and Bugry (1966) cited the common occurrence of tourmaline-bearing veins in schists in support of this.

(f) Source Area. It seems likely that sediments derived from source regions containing boron-rich lithologies will have higher boron values than those derived from source areas which contain little boron.

A comparison between mudstones of the Firstbrook and Coleman

Member is considered feasible in that most of the above factors are relatively constant for the samples analyzed, and therefore can be eliminated. Water temperature, which probably was lower during deposition of the Coleman Member, and a slight grain size increase toward the top of the Firstbrook Member, may have affected the observed trend. X-ray data (Section 5-5) suggest a greater relative abundance of muscovite in Firstbrook mudstones.

Data from this study (Appendix 2) indicate a higher boron content for Firstbrook Member mudstones, suggesting an increase in basin salinity after deposition of the Coleman Member. The average boron content for 22 Coleman Member mudstones is 32 ppm, and for 34 Firstbrook Member mudstones is 54 ppm (lower unit, 53 ppm; middle unit, 51 ppm; upper unit, 58 ppm).

Data from the Eplett drill hole samples provide a suitable stratigraphic framework to observe changes in boron content over time. The data (Figure 5.6) indicate relatively constant values for Coleman Member samples followed by a rapid increase across the Coleman-Firstbrook contact.

The boron trend is similar to the chemical weathering trends observed in Figures 5.2 and 5.3, and thus may be a function of K enrichment associated with increased chemical weathering. Approximately 100 m. above the contact zone, the boron curve exhibits a departure from the weathering trend, displaying a rapid decrease over the next 300 metres. Samples from this zone also contain relatively high K values, suggesting that there is no simple relationship between K and B.

Alternatively, the rapid increase across the contact could be attributed to increased basin salinity brought on by the

Figure 5.6

Figure 5.6 Boron versus depth plot for Gowganda and Lorrain Formation mudstones from the Eplett drill hole (Figure 3.1). The arrowed line (a moving average curve through the data points) indicates an overall upsection increase, suggesting higher basin salinities during deposition of the Firstbrook Member. Note that Nipissing diabase sills are not included in the depth-axis measurement, to give a more realistic indication of relative sample spacing.

reduction of glacial meltwater influx combined with a possible marine transgression. The boron decrease above the contact zone could then be explained in terms of sedimentation rates. The deeper marine prodelta muds should contain relatively more boron than the delta slope muds which are buried rapidly by nearshore processes. This interpretation should be viewed with caution, however, because a slight upsection decrease in clay content could reduce the boron value (c.f. Dewis et. al. 1972). An increase at the top of the section could be due to detrital tourmaline incorporated in these coarser-grained samples. Rare detrital tourmaline was noted during petrographic study of the lower Lorrain Formation.

5-4 Provenance

Petrographic data and previous studies (Lindsey, 1967; Hadley, 1968) support derivation of the Gowganda and Lorrain Formations from a mainly granitic terrane with some component of mafic and felsic volcanic material (see section 4-4b). Paleocurrent data support a mixed "greenstone"-granitoid source region to the north. These conclusions are supported by the mudstone geochemistry of this study. The TiO_2 vs Al_2O_3 plot provides an approximate measure of the relative concentrations of the residual products of the breakdown of basaltic (titania) versus granitic (alumina) material. This ratio is generally higher in more mafic rocks, and because both oxides are stable under most weathering conditions, should approximate the provenance of the sedimentary rocks (G.M. Young pers. comm. 1985). The data (Figure 5.7) indicate that the Coleman Member,

Firstbrook Member and lower Lorrain Formation all were derived from a similar source region which had a composition of between 2 and 3 parts granite to 1 part basalt. Limited data (3 analyses) suggest a granitic source for Gordon Lake and Bar River Formation mudstones. A comparable pattern was established in a more exhaustive geochemical study by McLennan (1977), who maintained that the source terrane for Huronian rocks was generally more mafic than suggested by petrographic studies of the coarse-grained units.

5-5 Mineralogy: X-ray Diffraction Analysis

Mudstone mineralogy was determined by X-ray diffraction analysis of air-dried smear mounts of crushed whole rock samples. Eleven samples from the Eplett drill hole (930 to 1455 metres) were examined to seek a mineralogical explanation for the rapid geochemical variations which occur across the Coleman Member-Firstbrook Member transition. The X-ray diffractograms confirm the presence of minerals identified by petrographic examination (i.e. an assemblage of quartz, albite, chlorite and muscovite). The assemblage for both the Coleman and Firstbrook Members is essentially the same; but different relative abundances are suggested by varying intensities of individual diffraction peaks (Figure 5.8). The peak intensity for quartz (3.34Å, 4.26Å, 2.46Å, 1.82Å) is relatively constant for all samples; however, the albite peaks (3.20Å, 4.04Å, 6.4Å) are stronger in the Coleman Member samples. Those for muscovite (10.2Å, 3.36Å, 4.49Å) and chlorite (chlinochlore, 7.1Å, 14.5Å, 3.55Å) are more pronounced.

Figure 5.7 Alumina versus titania plot for Cobalt Group mudstones from the study area. The data suggest that the Firstbrook and Coleman Members were derived from a similar source region which had a composition of between two and three parts granite to one part basalt. Average basalt values are from the Abitibi greenstone belt (Goodwin 1977). Average granite values are from the Superior Province of northwestern Ontario (Smith and Williams 1981). These granites are assumed to have a similar chemical composition to those from the Superior Province of northeastern Ontario-western Quebec.

Figure 5.8

Figure 5.8 X-ray diffractograms for Cowganda Formation mudstones from the Eplett drill hole (Figure 3.1) show stronger chlorite and muscovite peaks for Firstbrook Member samples and stronger albite peaks for Coleman Member samples, suggesting greater chemical weathering of source areas for Firstbrook Member strata. Diagrams were drawn by averaging the peak intensities for 7 Firstbrook Member samples and 4 Coleman Member samples. The original diffractograms and sample numbers are shown in Appendix 3. Samples were prepared as air-dried smear mounts of whole rock powders, and were scanned using Cu-K-alpha radiation.

FIRSTBROOK MBR. (average)

COLEMAN MBR. (average)

in the Firstbrook Member samples.

These observations are in general agreement with the observed geochemical trends and therefore support the suggestion that the sodium abundance is mainly a function of albite preservation in Coleman Member samples. The Firstbrook Member samples contain less albite and a relatively greater proportion of potassium-rich micas, suggesting a greater degree of chemical weathering in the source area.

VI: ECONOMIC GEOLOGY

6-1 Economic Considerations

The Cobalt-Gowganda area has been an active silver producing region since the turn of the century, although production dropped significantly after the Second World War. A continued emphasis on silver exploration may have masked the exploration possibilities for Archean and Huronian sediment-hosted stratiform base and precious metal deposits. Initial investigations of sulphide mineralization potential in the Cobalt area (eg. Patterson, 1979) are presently being supplemented by more detailed examinations (e.g. Wilson, in progress; and Smýk, in progress).

Recent studies by Colvill (1983), Mossman and Harron (1984) and Long (1984) have also outlined gold enrichment in Lorrain Formation quartz pebble conglomerates from the Cobalt Basin; preliminary studies outlined by Donaldson *et al.* (1985) and Mustard (1985) indicate potential for paleoplacer gold concentrations in Coleman Member proglacial fan complexes.

Stratiform base metal mineralization in Coleman Member laminites was investigated by Kim (1979) and can be seen in several outcrops and mine workings in and around the Cobalt townsite. To date no significant concentrations have been located within Firstbrook Member strata. A small Cu showing on Highway 11 south of Latchford (Plate 9a) was noted by Wood (1979). This showing consists of finely disseminated bornite within grey laminated siltstone of the middle unit. Copper concentrations from slabbed specimens were visually estimated at less than 1 percent. Similar concentrations of disseminated chalcopyrite were noted in middle unit siltstones at one locality.

on the Matabitchuan River in South Lorrain Township. Malachite-stained chalcocite(?) was observed in deformed sandstone beds of upper unit strata on an island in northern Lady Evelyn Lake (Plate 9b). These showings are shown on the regional compilation (Figure A).

Although these occurrences are volumetrically insignificant, they likely represent the oldest known occurrence of redbed copper mineralization in North America.

6-2 Copper Mineralization in the Firstbrook Member

Firstbrook Member strata exhibit many characteristics which are considered favourable for sediment-hosted stratiform copper mineralization. These include:

1. Redbeds. The presence of redbeds within the middle and upper units of the Firstbrook Member suggest that oxidizing conditions prevailed during deposition and diagenesis (see Section 4-5). This is in accordance with previous observations that relatively high Eh and low pH conditions are required for the uptake and transport of metals (Rose, 1976).
2. Aquifers. Thick, laterally continuous and permeable turbidite beds in the middle unit could have acted as aquifers for the transport of mineralizing fluids.
3. Source Rocks. Gustavson and Williams (1981) have noted that volcanic detritus, particularly that derived from tholeiitic basalts, provides an important source for copper. Paleocurrent data suggest that a significant source area for Firstbrook Member sediments may have been the Abitibi greenstone belt, which contains abundant mineralized tholeiites. Archean interflow

sediments from the Cobalt area are also known to contain anomalous concentrations of copper (Patterson, 1979).

4. Host Beds. Drab-coloured (anoxic) lower unit strata (perhaps containing some organic carbon) could have acted as reductants to high-Eh fluids containing dissolved metals. Owsilacki (1985) has indicated that black lower unit mudstones from Lundy Township are significantly enriched in Zn, Ni, Cu, As, and Co.

5. Traps. A common feature of sediment-hosted stratiform copper deposits is the association of ore with a pinch out or pinch down of host or footwall beds at paleotopographic highs (Gustavson and Williams 1981). A regional correlation of stratigraphic sections from the eastern part of the study area shows that a rapid thinning or pinch out toward the margins of the basin is controlled by underlying Archean basement topography.

On the basis of these observations, the most favourable Firstbrook strata for mineralization are the lower unit mudstones which are interbedded with red sandy turbidite horizons. Specific target areas could be selected where these strata pinch out against Archean paleotopographic highs.

VII: SUMMARY AND CONCLUSIONS

1. The Gowganda Formation, within the study area, is divisible into two distinct units: the Coleman Member and the overlying Firstbrook Member. Firstbrook Member laminite units are distinguished from similar Coleman Member rocks on the basis of: (a) a greater lateral continuity and thickness; (b) the presence of lenticular bedding; (c) abundant red strata and; (d) the lack of features such as dropstones and sediment pellets which are suggestive of deposition in a frigid climatic regime. Diamictite, a significant component of the Coleman Member, is conspicuously absent from the Firstbrook Member. The contact between the two members is sharp at the basin margins, but generally is gradual over several to several tens of metres elsewhere.

2/ The Firstbrook Member was deposited in a river-dominated delta that was slightly modified by waves and tidal currents. The depositional model comprises prodelta, delta slope, delta foreslope and delta braidplain subenvironments which are respectively equated with the lower unit, middle unit and upper unit of the Firstbrook Member, and the lower unit of the Lorrain Formation. The generally coarsening upward sequence resulted from delta progradation and lateral migration of the subenvironments.

(a) Thinly laminated mudstone of the prodelta subenvironment formed by deep-water suspension deposition in combination with traction deposition from low density turbidity currents originating on the delta foreslope.

(b) Thickly laminated mudstone and graded siltstone of the delta slope facies are the proximal equivalents of the prodelta

facies. Ripple cross lamination and lenticular bedding are evidence of reworking of delta slope sediments by wave- and possibly river-generated currents; the increase in abundance upsection probably reflects increasingly shallower water. Local opposed asymmetry of cross lamination suggests local tidal current activity. The thick locally developed graded arkose bedsets are interpreted as turbidity current deposits which may have originated due to failure of oversteepened delta foreslope sediments triggered by shocks related to seismic or storm events. Soft sediment breccia zones, folded beds and homogenized beds are likened to mudflow deposits described from the Mississippi River delta.

(c) The delta foreslope environment is characterized by wavy, flaser and lenticular bedding interbedded with normally graded and parallel stratified sandstone. This association, in combination with bimodal to polymodal paleocurrent patterns, suggests a complex interaction of river-, tide- and wave-generated depositional processes. River currents are considered responsible for initial deposition, with wave and tidal processes having reworked the sediment. However, the wave and tidal currents were relatively weak, as evidenced by the overall textural and mineralogical immaturity and by the lack of tidal channels, beach deposits, and offshore bars. The Firstbrook Member section typically forms one continuous coarsening upward cycle. This suggests that fluvial input did not occur from one point source for which minor coarsening upward cycles, representing successive overlapping of delta lobes, would be expected. Instead, a broad

fluvial braidplain is envisaged in which upper delta foreslope sands formed a long continuous prograding front or ramp.

(d) The delta braidplain subenvironment is characterized by trough and minor planar cross-bedded arkose, parallel stratified arkose and minor mudstone and siltstone intercalations. This association, in combination with a unimodal paleocurrent pattern, suggests deposition in a fluvial braidplain setting. A braided stream pattern would be more likely to develop in the Precambrian because of the absence of an effective vegetation cover which would allow stabilization of the substrate.

3. The Firstbrook Member was likely deposited at the edge of a marine basin for the following reasons:

(a) Bedding features suggest that tidal currents played a significant part in remolding the delta front sediments. The most convincing evidence for this is the association of wavy, flaser and lenticular bedding with bimodal-bipolar paleocurrent patterns. Comparisons with modern and other ancient examples indicate that these features can only develop in marine settings where tidal currents were operative.

(b) The Firstbrook Member conformably overlies the Coleman Member, which has been interpreted as being marine within the Cobalt Basin by Miall (1983), Rosen (1985), and transitional to marine by Mustard (1985). After deposition of the Coleman Member, ice retreat would have allowed establishment of normal marine conditions (and therefore normal marine salinities and circulation patterns). Boron, a probable paleosalinity indicator, is enriched in Firstbrook Member mudstones relative to Coleman

Member mudstones, lending support to this hypothesis.

Other evidence consistent with the marine hypothesis is:

(d) The fact that finely laminated Firstbrook Member mudstone sharply overlies reworked Coleman Member diamictite at the basin margin suggests that glacial retreat may have been followed by rapid basin deepening as a consequence of marine transgression.

(e) The Firstbrook Member bears similarity to ancient marine fluviodeltaic sequences (cf. Elliot, 1976; Vos, 1977; Siedlecka and Edwards, 1980), as well as to some modern counterparts (cf. Coleman and Gagliano, 1965).

(f) The passive margin model of Young (1983) implies that the Gowganda Formation was probably deposited within a marine basin which was open to the south.

(g) The occurrence of rare herringbone crosslamination; a feature considered diagnostic of tidal current deposition.

4. The most applicable analogue to the Firstbrook Member is the Upper Proterozoic Bånaering Formation: a fluviodeltaic complex from northeast Finnmark in northern Norway (cf. Siedlecka and Edwards, 1980). A possible correlative is the Headquarters Formation (lower Libby Creek Group) of southeastern Wyoming (cf. Karlstrom et al., 1983).

5(a) Red coloration in the Firstbrook Member is attributed to the presence of diagenetic pigmentary hematite. Reddening of clay-rich strata likely occurred by compaction-related dehydration of amorphous iron hydroxide under oxidizing

conditions. Reddening of sand-rich strata, particularly red sandy turbidites, is attributed to diagenetic alteration by oxidizing groundwaters which percolated through the more permeable (sand-rich) layers.

(b) The presence of diagenetic pigmentary hematite in the Firstbrook Member indicates the existence of free oxygen in the Earth's atmosphere at the time of sedimentation (approximately 2300-2200 Ma).

6. Paleocurrent, petrographic and geochemical data suggest that the source area for the Firstbrook Member was the mixed "greenstone"-granitoid terrane located to the north of the study area.

7. Geochemical weathering indices from mudstones indicate a pronounced increase in weathering of source terranes across the Coleman Member-Firstbrook Member contact. This change is attributed to a rapid climatic amelioration from the frigid conditions implied by Coleman Member deposition to a humid (possibly subtropical) regime which prevailed during deposition of the Lorrain Formation.

8. No economically significant concentrations of primary sediment-hosted base or precious metals were discovered during mapping of the study area. Small showings of finely disseminated chalcopyrite, bornite, and chalcocite(?) do, however, indicate a potential for sediment-hosted stratiform (redbed) copper accumulations. The most favourable strata for future exploration are mudstones of the lower unit (reducing environment) in areas

where they are interbedded with red sandy turbidite horizons (oxidizing environment). Target areas exist where these strata pinch out against Archean paleotopographic highs.

Plate 1

Plate 1 Lower Unit

- A. Finely laminated lower unit mudstone. Photo, looking west, of an outcrop on the Matabitchuan River, 10km. south of the Montreal River junction. Upper scale in centimetres.
- B. Graded laminae in mudstone of the lower unit. Note the loaded starved ripple at the top of the photo. Field of view is 5.2mm wide.
- C. Basal layers of the lower unit draped over cobble lag and matrix-supported diamictite of the Coleman Member. Photo looking west; outcrop below the Matabitchuan Dam, 3km. south of the Montreal River Junction.
- D. Contact between Coleman Member clast-supported conglomerate and Lorrain Formation trough crossbedded arkose. Photo, looking southeast, of an outcrop on Baie Joanne on the eastern shore of Lake Timiskaming.
- E. Dropstone in thinly-laminated mudstone from the gradational contact zone between the Coleman and Firstbrook Members. Lowering of laminae on left side of clast is attributed to soft-sediment deformation. Photo, looking west, of an outcrop on the west shore of Beaver Island, north end of Lake Temagami.

Plate 2

- A. Moderate to thickly interlaminated red siltstone and mudstone of the middle unit. Photo, looking east, of an outcrop on Highway 11 about 3km. north of the Highway 11B turnoff.
- B. Lenticular bedding laminated siltstone of the middle unit. Sandy lenses appear black due to abundant intergranular chlorite. Outcrop on a small island outcrop near the northern tip of Lake Temagami; photo looking north.
- C. Graded red arkose beds within normally variegated middle unit laminated siltstone and mudstone. Photo looking west; Highway Junction stratigraphic section (Figure 3-1, approx. 92m.) Length of rod is 1.5m.
- D. Colour variegation in middle unit strata. Dark green (chloritic) sand lenses within laminated couplets of graded siltstone (light green) and mudstone (red). Slab from a bed at top of outcrop shown in Plate 2c.
- E. Detail of graded arkose bed from Highway Junction stratigraphic section. Note that colour change accentuates grading in the lower bed. Note also the parallel stratified upper portion of the bed which is overlain by a thin mud-rich top.
- F. Drill core from upper portion of the middle unit (Eplett drill hole) showing graded laminae of fine sandstone (red) and siltstone (light green). Note that the variegation is opposite to that seen in the graded siltstone-mudstone laminae.
- G. Drab, angular mud rip-ups in pink arkose. Slab is from the upper portion of a 1.5m. thick graded arkose bed in the Highway Junction stratigraphic section.

Plate 3

Plate 3

Middle Unit Sedimentary Structures

- A. Bedding exposure of straight-crested and bifurcating ripples from an outcrop of middle unit siltstone on the east side of Highway 11, east of Rib Lake. Hammer is 50cm. long.
- B. Cross stratified interlayer in a graded arkose bed from the Highway Junction stratigraphic section. Photo looking west.
- C. Flute scours on the underside of a graded arkose bed from the Highway Junction stratigraphic section. Inferred transport direction is from left to right.
- D. Flame structures between middle unit laminated siltstone and graded arkose. Note that the flames are inclined toward the south, suggesting post-depositional sliding on a paleoslope. The photograph looks west at an outcrop on Highway 11, 3km. south of the Highway 558 junction.
- E. Loaded arkose bed has deformed middle unit laminated siltstone. Where loading of this type occurs, arkose beds exhibit pronounced local-scale lateral thickness variations (eg. doubling of thickness over 2-3 metres). Photo, looking west, of an outcrop on Highway 11, approx. 3km south of the Highway 558 junction.
- F. Loaded contact between two graded arkose beds within a stacked sequence from the Highway Junction stratigraphic section. Such structures suggest rapid deposition on a soft water-saturated substrate.
- G. Dewatering structures interpreted as deformed lamination or dish structures (cf. Lowe and LePiccolo, 1974) in a graded arkose bed from the Highway Junction area.
- H. Dewatering structures interpreted as water escape tubes in a graded arkose bed from the Highway Junction area. Both dish structures and water escape tubes suggest post depositional, compaction induced, water escape within unconsolidated or quick beds of sand.

Plate 4

Plate 4 Middle and Upper Unit Sedimentary Structures

- A. Coherent fold in middle unit laminated siltstone. The undeformed nature of the bounding strata suggests penecontemporaneous deformation. Photo looking east of outcrop on Highway 11 at Highway Junction.
- B. Chaotic folds within a deformed zone overlying a thick (up to 10m) sandstone bedset (Plate 4c) from the Highway Junction stratigraphic section (Figure 3.3).
- C. Sandstone bedset on east side of Highway 11, 0.5km south of the Highway 558 junction. This unit occurs at the top of the Highway Junction stratigraphic section (Figure 3.3). Cliff face is about 3m high in centre of photo.
- D. Plastically deformed laminated siltstone rip-up clasts within the upper part of the sandstone bedset illustrated in Plate 4c.
- E. Sand infilling en echelon tension gashes in middle unit laminated siltstone in a zone directly overlying the sandstone bedset illustrated in Plate 4c. Key near top is 5cm. long.
- F. Microscopic load and flame structures along the base of a sandstone layer within laminated siltstone of the middle unit. Field of view is 5.2mm. wide.
- G. Typical upper unit lithology consisting of graded and parallel-laminated fine sandstone interbedded with wavy and flaser bedded siltstone and mudstone. View, looking south, of an outcrop on the southeast shore of Anima Nipissing Lake.
- H. Wavy bedded fine sandstone of the upper unit. Arrows indicate thinning of mudstone lamination on ripple crests and thickening in ripple troughs. Ripple cross lamination indicates apparent transport from right to left. View, looking west, of a small island outcrop near the northern tip of Lake Temagami.

Plate 5

Plate 5

Upper Unit

- A. Bedding surface view of wavy bedded sandstone showing rib and furrow structure (the horizontal expression of trough cross-lamination. Note that the laminae are concave downcurrent (toward top of photo). Photo of an island outcrop near the northern tip of Lake Temagami.
- B. Bedding surface view of a sandstone bed showing interference ripples, as seen in a block of upper unit sandstone exposed in a gravel pit on the west side of Highway 11, 3km south of the Highway 558 intersection.
- C. Flute rill marks (Reineck and Singh, 1980 p.75) or longitudinal meandering grooves (Allen, 1969) developed on the base of a sandstone bed which has scoured into a weakly cohesive muddy substrate. Transport direction is indicated by the arrow.
- D. Sandstone-filled gutter casts produced by fluid scour of a weakly cohesive muddy substrate.
- E. Ball-and-pillow structure formed by liquefaction of a sand bed into a less dense (finer-grained) substrate. Example shown exhibits partial detachment. View looking southwest of an island outcrop near the northwestern end of Anima Nipissing Lake.
- F. Load casted ripples formed by liquidized failure of sandy ripple crests into underlying siltstone beds. View looking west, of an outcrop on the side of Roosevelt Lake Road, 7km. southwest of Latchford.
- G. Load casts on the underside of a sand bed.
- H. Mud chip breccia in medium-grained arkose at the Firstbrook Member-Lorrain Formation transition. View looking northwest of an outcrop on the south shore of northeastern Lady Evelyn Lake.

A

B

C

D

Plate 6

- A. Calcite cement has partially replaced quartz grains in lower Lorrain Formation arkose. Field of view is 1.3mm wide (polarized light).
- B. Typical Lorrain Formation arkose. Field of view is 5mm wide (polarized light).
- C. Interstitial cement composed primarily of fine-grained granular hematite which has replaced micaceous cement. Section is from the lower part of the red graded arkose bed shown in Plate 2e. Field of view is 2.6mm wide (plane polarized light).
- D. Syntaxial quartz overgrowth on grain outlined by very fine granular hematite, demonstrating an early origin for red colour. Lower Lorrain Formation from the Eplett drill hole. Field of view is 0.65mm wide (polarized light).
- E. Hematite has replaced ferromagnesian mineral grains in upper Firstbrook Member arkose. Dark blade-like grain in center of photograph probably was originally biotite. Field of view is 1.3mm wide (plane polarized light).
- F. Altered feldspar grains with authigenic micaceous cement in sample of upper Firstbrook Member arkose. Walker (1978) suggested that clay cements are formed through the breakdown of feldspars during the latter stages of intrastratal alteration; a common reddening process in which iron-bearing framework grains are dissolved, releasing iron to form hematite. Field of view is 1.3mm wide (polarized light).
- G. Close-up of sand lens in middle unit siltstone, showing chlorite alteration of clay cement and detrital iron oxides. Brown haloes around some iron oxide grains may be biotite: compare with Plate 6h. Field of view is 2.6mm wide (plane polarized light).
- H. Alteration of hematite grains (originally biotite?) to biotite at the margin of a reduction spot in red Lorrain Formation arkose. Note that biotite prevails in the reduced zone (lower part of photo) and hematite in the red, oxidized zone. Field of view is 1.3mm wide (plane polarized light).

Plate 7

Lorrain Formation

- A. Trough crossbedded arkose of the lower Lorrain Formation. View, looking south, of an outcrop at the extreme southern tip of Lady Evelyn Lake. (top of South Lady Evelyn Lake stratigraphic section, Figure 3.6).

- B. Planar crossbedding in arkose of the lower Lorrain Formation. View, looking southeast, of an outcrop on the south shore of Lady Evelyn Lake, central narrows region.

Plate 8

Apparent paleocurrent reversals as indicated by ripple crosslamination and ripple asymmetry in lenticular bedded siltstone of the middle unit. View, looking west, of an outcrop on Highway 11 about 1km south of the Highway 558 intersection. Traced from photograph.

Plate 9

Copper Mineralization

- A. Iron oxide staining of disseminated bornite in siltstone of the middle unit. View, looking south, of an outcrop on Highway 11, near Rib Lake (also shown on regional compilation, Figure A).

- B. Malachite alteration of chalcocite(?) at a deformed contact between two red arkose beds of the upper unit. View, looking west, of an island outcrop on northern Lady Evelyn Lake (also shown on the regional compilation, Figure A).

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APPENDIX 1**Classification of Soft-sediment Structures**

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APPENDIX 1

Classification of Soft-sediment Structures

I. Gravitationally unstable profiles of bulk density

1. Continuous profiles (single sedimentation units) (convolute lamination)
2. Discontinuous profiles
 - (a) single sedimentation units (dish and pillar structures)
 - (b) paired sedimentation units, upper layer not pierced (load casts)
 - (c) paired sedimentation units, upper layer pierced (ball-and-pillow structures)
 - (d) multilayer complexes of sedimentation units, with more dense layers pierced (sand balls)

II. Non-uniform confining loads

1. Single sedimentation units (complexly deformed cross-stratification)
2. Paired sedimentation units (folding and faulting due to laterally spreading sand bodies)

III. Downslope component of body force

1. Slides (internal stratification substantially disturbed)
2. Slumps (considerable disturbance of internal stratification, usually much overfolding and internal thrusting)

IV. Fluid flow (usually sediment-bearing)

1. Shear stress essentially horizontal (simple deformed cross-stratification)
2. Shear stress steeply inclined to general bedding (eroded and/or bent up laminae)

from Allen (1984, p.II-348)

APPENDIX 2

Chemical composition of mudstones from the Cobalt Basin

General notes and symbols

1. Map unit symbols:

2 = Coleman Member mudstone.

2dm = Coleman Member diamictite matrix

3a = Firstbrook Member, upper unit mudstone

3b = Firstbrook Member, middle unit mudstone

3c = Firstbrook Member, lower unit mudstone

4 = Lorrain Formation

5 = Gordon Lake Formation

6 = Bar River Formation

2. $\text{Fe}_2\text{O}_3(\text{T})$ = total iron as Fe_2O_3 .

3. Blank space = no analysis for this element.

4. Sample numbers from Table 5.1 (following page) refer to actual footages from the Eplett drill hole. (i.e. E3709 is 3709 feet below surface).

5. Sample locations for all geochemical analyses are shown in Figure 5.9.

Discussion

1) Analyses in Table 5.1 and Table 5.2 were performed using a fused pellet X-ray fluorescence technique (XRF) by Ron Hartree at the University of Ottawa. Samples were analyzed for 11 major and 10 trace elements. Samples E4511, E4771, E5015, E5256, E5485, E5776, and E6007 were analyzed by XRF at X-ray Assay Laboratories Ltd., Don Mills, Ontario. Samples were analyzed for 11 major elements, 7 trace elements and volatiles (LOI). Sample E3223

from Thomson (1966), was analyzed by Laboratory Branch, Ontario Department of Mines. Results of the internal standards, control standards and duplicates were not included. All were within the boundaries of error indicated by the laboratories concerned.

2. Boron analyses were performed by John Loop, University of Ottawa using samples prepared by $\text{NaCO}_3\text{-NaNO}_3$ fusion, followed by H_2O leach at the laboratories of the Geological Survey of Canada. Analysis was by Direct Current Argon Plasma (DCP) Atomic Emission Spectrometer (detection limit 2ppm) at the University of Ottawa. Precision and accuracy of the results were determined to be within the limits of experimental error.

3. Loss on Ignition (LOI) was determined by a gravimetric technique at the University of Ottawa.

Table 5.1: Mudstone Geochemistry - Eplett Drill Hole, Herwood Township, Ontario.

Sample No.	E751	E881	E1009	E1102	E1222	E1500	E1617	E2516	E2707	E3047	E3223	E3320	E3457	E3597	E3622	E3672
Map Unit	4	4	3a	3a'	3a	3b	3c	3c	3c	3c	3c	3c	3c	3c	3c	3c
Weight %																
SiO ₂	59.62	59.70	61.62	59.02	57.13	57.39	56.36	54.10	54.20	54.20	52.77	53.62	56.71	57.32	58.28	59.02
TiO ₂	0.79	0.76	0.65	0.70	0.79	0.75	0.75	0.79	0.73	0.78	0.84	0.76	0.68	0.75	0.75	0.74
Al ₂ O ₃	19.16	19.14	18.44	19.56	20.65	19.22	19.95	20.50	20.55	20.50	21.70	20.47	18.76	18.91	18.84	18.36
Fe ₂ O ₃ (T)	5.87	7.43	6.96	6.44	7.57	10.68	9.48	11.10	10.07	11.00	11.69	11.23	11.33	10.12	9.71	10.22
FeO											9.14					
MnO	0.02	0.03	0.04	0.04	0.04	0.04	0.07	0.26	0.05	0.26	0.28	0.94	0.56	0.16	0.15	0.13
MgO	3.41	3.13	2.95	2.85	2.90	2.88	3.02	3.20	3.33	3.21	3.28	3.29	3.23	3.02	2.90	2.59
CaO	0.70	0.55	0.65	0.70	0.56	0.77	0.40	0.45	0.51	0.45	1.30	0.67	0.94	0.82	0.65	0.81
Na ₂ O	1.31	2.10	3.05	3.06	2.60	2.08	1.87	1.73	2.16	1.78	1.41	1.40	1.78	1.82	1.88	1.71
K ₂ O	5.84	4.59	3.55	3.96	4.50	3.47	4.06	3.27	3.38	3.27	2.63	3.45	2.85	3.46	3.46	3.90
P ₂ O ₅	0.27	0.25	0.25	0.22	0.25	0.25	0.28	0.21	0.24	0.21	0.29	0.24	0.28	0.29	0.28	0.26
S	0.01	0.01	0.01	0	0	0	0		0		0.15	0.01	0.01	0	0	0
L.O.I.	3.98	3.48	3.12	3.27	3.52	3.50	4.17	3.93	3.87	4.08	5.33	4.34	4.15	4.00	3.75	3.48
PPM																
Ba	701	610	558	744	696	484	519	660	529	650	587	587	417	823	880	840
Cr	186	172				203		210		210				210	204	136
Zr	238	188	172	141	153	150	131	110	115	110	117	117	112	119	107	54
Sr	60	97	124	125	86	104	40	40	43	40	28	28	44	81	74	175
Rb	207	172	137	147	167	176	189	180	135	170	155	155	129	170	169	23
Y	27	22	17	18	14	30	19	40	20	40	21	21	20	20	20	10
Nb	11	10	10	13	10	7	12	30	15	20	12	12	8	7	9	11
Zn	20	29	54	48	53	73	46		75		286	286	147	95	96	61
Ni	41	40	50	56	64	50	72		72		85	85	73	55	46	112
V	137	121	95	51	117	134	124		140		138	138	126	146	154	72
B	65	72	51	43	76	58	49	29	46	59	54	54	75	65	88	52
Total	100.1	101.2	101.3	99.8	100.5	101.0	100.4	99.7	99.1	99.9	100.8	100.4	101.3	100.7	100.7	101.2
C.I.A.	67.8	68.5	64.2	66.0	68.3	70.7	72.6	73.9	73.1	73.6	74.2	75.4	72.7	71.5	71.9	70.0
K/Rb	234	222	214	224	223	164	178		208		185	185	183	170	170	185
Rb/Sr	3.5	1.8	1.1	1.2	1.9	1.7	4.8		3.2		5.5	5.5	2.9	2.1	2.3	2.2

Table 5.1: (cont.)

Sample no.	E3709	E3842	E3948	E4511	E4771	E5015	E5069	E5256	E5485	E5776	E6007	E6162	E7001	E7468	E7648
Map Unit	3c	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Height	58.84	61.25	60.63	59.9	59.9	60.4	59.43	59.90	62.1	64.8	59.2	59.30	64.62	59.49	62.45
SiO ₂	0.77	0.63	0.54	0.69	0.68	0.75	0.78	0.77	0.66	0.55	0.72	0.72	0.58	0.56	0.57
TiO ₂	18.72	16.70	15.29	17.2	17.3	17.2	18.19	17.60	16.20	14.90	17.10	17.78	15.28	17.21	16.23
Al ₂ O ₃	9.19	6.86	6.14	7.43	7.41	8.26	9.32	8.65	6.38	6.23	7.85	9.19	5.93	7.61	6.35
Fe ₂ O ₃ (T)															
FeO	0.11	0.12	0.08	0.08	0.08	0.16	0.18	0.15	0.05	0.04	0.08	0.10	0.08	0.11	0.11
MnO	2.47	3.80	2.97	3.43	3.42	3.07	3.22	2.84	4.06	3.63	3.57	3.71	2.78	3.84	3.33
MgO	0.73	1.72	1.72	1.01	1.00	0.80	0.91	0.91	1.67	0.95	2.25	2.28	2.87	1.87	2.15
CaO	1.59	4.93	4.30	3.47	3.52	3.02	3.00	2.75	3.93	4.25	4.77	3.38	4.77	4.00	4.70
Na ₂ O	4.03	1.15	2.15	2.89	2.88	2.54	2.74	2.81	1.74	1.32	1.83	2.33	1.50	1.87	2.51
K ₂ O	0.25	0.20	0.16	0.17	0.17	0.17	0.23	0.17	0.16	0.13	0.24	0.19	0.12	0.26	0.13
P ₂ O ₅	0	0.05	0.06				0					0.01	0.03	0.02	0.02
L.O.I.	3.57	3.19	2.61	3.39	3.16	3.32	3.39	3.23	2.93	2.70	2.54	1.35	1.60	2.63	2.17
PPM															
Ba	1234	486	504	610	650	600	539	670	380	240	730	431	642	713	669
Cr	209				190	200	197	210	200	300	170	202	208	48	113
Zr	139	129	129	110	120	150	155	160	240	130	120	122	130	91	110
Sr	62	163	231	100	110	60	80	80	80	160	280	307	356	270	356
Rb	195	51	72	140	130	140	120	140	80	50	80	94	42	112	77
Y	21	20	20	10	30	20	31	20	30	10	10	24	23	20	20
Nb	8	10	9	10	30	20	9	20	10	30	20	8	4	4	6
Zn	78	116	86				91					63	80	81	63
Ni	40	57	47				44					46	34	49	41
V	163	96	101				142					143	105	114	108
B	66	25	15	31	38	31	33		18	22	17	17	13	18	16
Total	100.3	100.6	98.7	99.8	99.7	99.7	99.9	99.9	100.0	99.6	100.3	100.4	100.2	100.5	100.4
C.I.A.	70.8	58.2	55.7	61.7	61.8	65.2	66.9	65.8	58.7	59.3	55.2	60.2	51.5	58.0	54.2
K/Rb	173	187	248				191					206	296	213	292
Rb/Sr	3.1	0.3	0.3				1.50					0.3	0.1	0.4	0.2

Table 5.2

Mudstone Geochemistry - Cobalt Basin, Ontario.

Sample No.	RC 1	RC 2	RC 3	RC 5	RC 8	RC 13	RC 14	RC 15	RC 22	RC 23	RC 25	RC 26	RC 32	MB 1	MB 2	MB 3	MB 4
Map Unit	2dm	3b	3b	3a	3b	3a	3b	3c	3b	3b	3b	3b	3c	3a	3a	3b	3b
Weight %																	
SiO ₂	74.81	59.02	58.67	58.47	58.07	54.02	60.08	60.82	58.66	54.64	58.69	59.24	53.49	61.21	57.86	56.87	54.11
TiO ₂	0.36	0.70	0.73	0.76	0.74	0.75	0.72	0.61	0.76	0.75	0.76	0.70	0.83	0.68	0.75	0.74	0.73
Al ₂ O ₃	12.71	18.79	19.22	19.71	19.60	20.36	18.26	16.99	20.02	20.55	19.82	18.76	19.66	18.11	19.58	20.13	19.94
Fe ₂ O ₃ (T)	2.92	8.21	9.05	7.84	9.65	11.48	8.27	8.48	8.82	11.73	8.47	8.79	12.31	7.27	8.92	9.18	8.99
FeO																	
MnO	0.05	0.07	0.07	0.05	0.08	0.13	0.12	0.09	0.06	0.13	0.04	0.05	0.95	0.06	0.06	0.06	0.08
MgO	1.22	2.68	2.55	2.94	2.48	2.78	2.53	2.29	2.87	2.82	3.39	2.92	3.36	3.31	3.24	2.97	3.23
CaO	0.63	0.88	0.62	0.75	0.40	0.58	0.74	1.47	0.44	0.72	0.52	0.43	1.18	0.07	0.43	0.42	1.30
Na ₂ O	5.64	2.49	2.20	2.37	2.10	2.02	1.86	2.38	2.37	2.01	2.23	3.16	0.89	2.56	2.42	1.88	1.79
K ₂ O	1.09	4.02	3.97	4.38	5.07	3.87	4.09	3.36	4.24	3.71	4.22	3.07	2.56	3.72	4.13	4.52	4.63
P ₂ O ₅	0.10	0.23	0.26	0.26	0.18	0.28	0.16	0.26	0.31	0.38	0.48	0.24	0.28	0.18	0.25	0.24	0.22
S	0.01	0				0.01	0	0.01	0	0.01		0	0.01	0	0		0.01
L.O.I.	0.88	3.47	3.19	3.21	3.19	3.84	3.29	3.53	3.26	3.78	3.53	3.19	3.19	3.20	3.57	3.62	4.20
PPM																	
Ba	202	535	420	560	588	561	635	636	645	543	566	416	487	558	574	478	555
Cr																	
Zr	165	156	144	160	157	119	157	200	138	117	147	143	118	196	143	139	81
Sr	128	101	85	93	59	53	58	90	71	54	49	65	100	95	87	74	81
Rb	27	175	170	184	237	161	202	174	175	161	168	125	119	155	181	199	208
Y	48	19	17	17	22	21	17	21	21	25	26	16	28	27	26	22	22
Nb	6	12	7	6	11	8	5	7	11	12	12	7	16	13	14	14	11
Zn	50	73	71	58	57	93	97	81	64	94	39	57	174	94	103	78	87
Ni	16	67	60	61	65	69	62	51	64	65	61	65	58	58	67	71	64
V	0	66	115	128	136	177	78	103	141	162	92	113	169	116	127	106	157
B	21	58	62	49	51	55	67	34	73	56	39	41	64	52	79	50	37
Total	100.4	100.6	100.5	100.7	101.6	100.2	100.0	100.5	100.8	101.2	100.2	100.7	98.7	100.8	100.9	100.6	99.5
C.I.A.	53.0	66.4	69.5	67.8	68.0	72.0	68.5	63.1	66.0	72.9	67.8	68.4	77.5	67.7	70.6	71.1	67.1
K/Rb	314	191	194	198	177	199	168	161	201	191	207	203	180	200	189	188	185
Rb/Sr	0.2	1.7	2.0	2.0	4.1	3.1	3.5	1.9	2.5	3.0	3.4	1.9	1.2	1.6	2.1	2.7	2.6

Table 5.2 (cont.)

Sample No.	MB5	MB6	MB7	MB8	LSI	LAI	OM29	OMD4	OM83	MS1-F	MS5-B	CR27	CR28	CR35
Map Unit	3b	3b	3c	3c	2	2	2	2	2	2	2	5	5	6
Weight %	57.40	55.99	57.45	64.69	65.31	64.77	63.58	53.22	65.65	66.26	63.27	73.19	69.96	77.67
SiO ₂	0.60	0.73	0.71	0.58	0.60	0.67	0.46	1.10	0.58	0.54	0.59	0.30	0.40	0.32
TiO ₂	18.43	20.01	18.10	15.52	14.84	15.97	16.67	16.42	15.44	14.97	16.61	14.27	16.64	13.22
Al ₂ O ₃	9.79	11.13	9.60	6.23	7.11	5.65	5.22	13.52	4.85	5.48	6.30	2.34	3.05	2.16
Fe ₂ O ₃ (T)														
FeO	0.08	0.09	0.08	0.08	0.04	0.05	0.03	0.22	0.06	0.04	0.05	0.02	0.01	0.01
MnO	3.62	3.16	2.69	2.79	3.30	3.42	2.85	5.75	2.53	3.43	3.87	1.45	1.51	0.17
MgO	1.08	0.82	1.86	1.55	0.51	1.02	0.69	1.41	1.81	0.92	1.21	0.11	0.07	0.02
CaO	1.94	1.82	1.57	4.74	5.37	5.33	5.66	3.27	6.44	5.16	4.88	2.32	0.45	0
Na ₂ O	3.83	4.15	4.34	1.58	0.60	1.00	1.51	2.01	0.71	1.17	2.14	4.17	6.38	4.28
K ₂ O	0.17	0.30	0.23	0.13	0.20	0.12	0.19	0.17	0.14	0.19	0.19	0.04	0.06	0.07
P ₂ O ₅														
S														
L.O.I.	3.99	3.76	1.46	2.59	2.10	2.20	2.24	3.51	2.38	2.20	2.14	1.77	1.87	1.92
PPM	540	583	818	447	114	227	247	816	160	165	490	788	775	449
Ba							169	271	177	198	192	186	61	138
Cr	91	125	120	148	163	143	109	127	138	204	129	314	222	231
Zr	91	64	65	137	64	177	154	111	124	148	262	57	15	25
Sr	176	199	231	73	22	41	68	63	17	61	91	159	291	119
Rb	21	22	20	21	22	18	16	23	24	23	16	28	50	21
Y	10	12	8	7	7	6	6	1	5	5	7	6	14	3
Nb	109	88	72	79	39	60	23	197	24	35	38	33	13	6
Zn	76	63	58	47	49	52	34	52	34	32	37	12	7	11
NI	151	157	129	75	83	43	89	287	102	97	112	55	35	69
V	37	37	32	35	12	27	41	48	26	24	18	90	108	289
B														
Total	100.9	102.0	98.1	100.4	100.0	100.3	99.1	100.6	100.6	100.4	101.3	100.0	100.3	99.8
C.I.A.	69	71	64	56	60	59	58.7	62.8	51.9	57.7	58.9	62.9	68.5	74.1
K/Rb	181	173	156	180	223	201	187	270	346	160	198	216	179	293
Rb/Sr	1.9	3.1	3.6	0.5	0.4	0.2	0.4	0.4	0.1	0.4	0.4	2.9	20.8	5.0

Figure 5.9 Sample locations for Table 5.1 and Table 5.2 (Appendix 2).

APPENDIX 3

Individual X-ray diffractograms used in calculating average diffractograms shown in Figure 5.8. Samples were prepared as air-dried smear mounts of whole rock powders, and were scanned using Cu-K-alpha radiation.

E3047

E3320

E3457

E3597

E3622

E3672

E3709

E3842

E3948

E4511

E4771

1 OF/DE

80°17'
47°40'

20F/DE

79°25'
47°40'

PROTEROZOIC GEOLOGY OF THE EASTERN COBALT BASIN

WITH EMPHASIS ON DISTRIBUTION OF THE
FIRSTBROOK MEMBER (GOWGANDA FORMATION)

PALEOZOIC

ORDOVICIAN-SILURIAN

7 sandstone, shale, carbonate

MIDDLE TO LATE PROTEROZOIC

GRENVILLE PROVINCE

6 metasediments

EARLY PROTEROZOIC

SOUTHERN PROVINCE

5 NIPISSING DIABASE

HURONIAN SUPERGROUP (COBALT GROUP)

4 LORRAIN FORMATION: arkose.

3a FIRSTBROOK MEMBER: arkose, siltstone
(UPPER UNIT)

3b FIRSTBROOK MEMBER: siltstone, mudstone, arkose
(MIDDLE UNIT)

3c FIRSTBROOK MEMBER: mudstone, siltstone
(LOWER UNIT)

2 COLEMAN MEMBER: diamictite, sandstone, siltstone, mudstone

ARCHEAN

SUPERIOR PROVINCE

1 unsubdivided felsic and mafic volcanic rocks, metasediments, and granite

unconformity

fault contact

intrusive contact

GOWGANDA
FORMATION

unconformity

3 OF/DE

5
OF/DE

SYMBOLS

Bedding: horizontal

Bedding: inclined, vertical

Anticlinal axis

Motor road

SOURCES OF INFORMATION

Ontario Dept. of Mines

Map 34b, Matachewan Area, scale 1:63,360, 1925

Map 1968a, Township of Bucke, scale 1:15,640, 1956

Map 2050, 2051, 2052, Cobalt Silver Area, scale 1:12,000, 1963

Map 2957, Lake Huron, scale 1:63,360, 1925

SOURCES OF INFORMATION

6
OF/DT

SYMBOLS

	Bedding: horizontal		Anticlinal axis
	Bedding: inclined, vertical		Motor road
	Foliation: inclined, vertical		Township boundary
	Geological boundary, approximate		Mineral occurrence
	Geological boundary, assumed		Section location
	Fault (most inferred)		

SOURCES OF INFORMATION

Ontario, Dept. of Mines
Map 34b, Matabitchuan Area, scale 1:63,360, 1926
Map 1966a, Township of Bucke, scale 1:15,840, 1956
Map 2050,2051,2052, Cobalt Silver Area, scale 1:12,000, 1963
Map 2257, Makobe Lake, scale 1:63,360, 1973
Map 2259, Diamond Lake, scale 1:63,360, 1973
Ontario Geological Survey
Preliminary Map P2279, Firstbrook Lake Area, scale 1:15,840, 1980
Preliminary Map P2733, Lundy Township, scale 1:15,840, 1985
Map 2205, Timmins-Kirkland Lake, scale 1:253,440, 1973
Map 2361, Sudbury-Cobalt, 1:253,440, 1977
Can. Dept. of Mines and Resources
Map 387a, Ville Marie Area, scale 1:63,360, 1938

SCALE 1:100,000

47°00'
80°17'

70F/DE

? Localities referred to in text which are not on this map can be located on NTS maps 3

SOURCES OF INFORMATION

o Dept. of Mines.

o 34b, Matabitchuan Area, scale 1:63,360, 1925

o 1966a, Township of Bucke, scale 1:15,840, 1956

o 2050, 2051, 2052, Cobalt Silver Area, scale 1:12,000, 1963

o 2257, Makobe Lake, scale 1:63,360, 1973

o 2259, Diamond Lake, scale 1:63,360, 1973

o Geological Survey

o Preliminary Map P2279, Firstbrook Lake Area, scale 1:15,840, 1980

o Preliminary Map P2733, Lundy Township, scale 1:15,840, 1985

o 2205, Timmins-Kirkland Lake, scale 1:253,440, 1973

o 2361, Sudbury-Cobalt, 1:253,440, 1977

o Dept. of Mines and Resources

o 387a, Ville Marie Area, scale 1:63,360, 1938

: 1 0 0 , 0 0 0

5

10

15

ities referred to in text which are not on this map can be located on NTS maps 31M and 41P

80F/DE-8

END / FIN

3 04 87