ABSTRACT

Mapping at 1:2000 scale of the immediate Cobalt area provided initial data for a detailed interpretation of the glaciogenic deposystem during deposition of the basal 180 m of the Coleman Member of the Gowganda Formation. At Cobalt, deposition occurred on the subsiding inner shelf of the Huronian Supergroup passive margin. The unconformity surface that separates subhorizontal Coleman Member lithofacies from underlying, subvertical Archean strata exhibits a gentle paleotopography with less than 100 m relief. Evidence of plucking, lee-side quarrying and shaping of this surface support southerly movement of a grounded continental-scale ice sheet. Massive basal diamictites were deposited subglacially both as an extensive, primary basal till and restricted, lee-side tills that infilled paleotopographic lows and covered preglacial regolith. Coarsening-upward rhythmite/sandstone/clast-supported diamictite associations were deposited as prograding subaqueous outwash fans in front of a slowly retreating, wet-based, tidewater ice sheet grounded in 50-300 m of water. Rhythmite characteristics indicate a distal change from underflow to interflow/overflow sediment transport, supporting an ice-contact marine basin interpretation. Interfan areas received sediment from distal meltwater activity, and from abundant sediment gravity flows off oversteepened fan slopes and collapsing ice-marginal banks. An upper diamictite association contains dropstone diamictite, poorly laminated mudstones, diamictite with random clast orientations, and thick successions of diamictite characteristic of deposition from sediment gravity flows. These features suggest that a change from a grounded to a partially floating ice sheet occurred before deposition of the uppermost strata of the Coleman Member preserved at Cobalt.

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SEDIMENTOLOGY OF THE LOWER GOWGANDA FORMATION

COLEMAN MEMBER (EARLY PROTEROZOIC)

AT COBALT, ONTARIO

by

PETER STEELE MUSTARD, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Science

Department of Geology

Carleton University

Ottawa, Ontario

November, 1985

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(EARLY PROTEROZOIC) AT COBALT, ONTARIO
submitted by Peter Steele Mustard, B.Sc.
in partial fulfilment of the requirements for
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Thesis Supervisor

Chairman, Department of Geology

Carleton University

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CHAPTER I

INTRODUCTION

Significant advances in the understanding of the processes of glacial geology, especially glaciomarine sedimentology, have resulted from recent research (for summaries see Andrews and Matsch 1983; Eyles and Miall 1984; Molina 1983; Powell 1984). The interpretation of ancient glacial deposits has benefited greatly from this increased understanding. (see for example Anderson 1983; Andrews and Matsch 1983; Boulton and Deynoux 1972, 1981; Driemanis 1983; Hambrey and Harland 1981). Incorporating these new ideas and models, this thesis presents a reinterpretation of the lower part of the Gowganda Formation in the Cobalt area, Ontario, Canada.

The extensive early Proterozoic Gowganda Formation (Figure 1A) has been recognized to be the result of glacial deposition since Coleman (1907, 1908) described faceted and striated "boulders" in massive greywackes. The Gowganda Formation has been tentatively correlated with glacial deposits over a wide area in North America (Young 1973), Finland and the U.S.S.R. (Marmo and Ojakangas 1984). This vast extent suggests deposition by ice sheets during at least one or more major periods of Precambrian glaciation.

Early regional studies (Lindsey 1966, 1967, 1969, 1971; Ovenshine 1965) led to suggestions of terrestrial glacial deposition of the lower Gowganda Formation (except near Lake Huron where a glaciomarine environment was postulated). Recent studies in the Lake Huron and Elliott Lake areas (Young 1985; Miall 1985) confirm the glaciomarine (probably continental slope) interpretation previously suggested for southern exposures of the Gowganda Formation. Recent interpretations of

the northern part of the Gowganda Formation have been based on limited data (Miall 1983) or regional observations (Long and Leslie 1985). Although they agree that deposition was subaqueous, they differ on whether it occurred in deep marine water from a floating ice sheet (Miall), or in a relatively shallow lacustrine environment from a grounded ice sheet (Long and Leslie).

At Cobalt, Ontario (Figure 1A), the lower part of the Gowganda Formation (Coleman Member) is particularly suited for detailed study. In this area silver exploration and mining during the early 1900's resulted in extensive stripping of outcrops and creation of vertical walls in now-abandoned vein cuts and open pits. The work of Legun (1984) suggested that a more detailed sedimentological study was appropriate. Detailed mapping (1:2000 scale) of a nine km² area including the town of Cobalt (Figure 1B) was combined with section measurements, fabric studies and petrographic examination of representative lithologies. This work provided the basis for the interpretations presented here.

A lithofacies classification scheme based on that of Eyles et al. (1983) was used for mapping and section measurement (Table 1). As per Eyles et al., the non-genetic term diamictite is used in preference to conglomerate or tillite for rocks composed of poorly sorted or non-sorted gravel/sand/mud mixtures. Some minor modifications to the code based on field observation and features of the study area have been introduced here. The prefix "b" indicates a basal diamictite unit which could be mapped independently of other units. The prefix "p" for pebbly sandstones was also appropriate. Subdivision of nonbasal diamictites into clast-supported (D_{cm} or D_{cs}) and matrix-supported (D_m) map units proved to be feasible. Some of the clast-supported diamictites would be termed gravels (G_m, G_t etc.) according to other lithofacies codes

Figure 1 A. Regional Extent of the Huronian Supergroup and Location of Study Area. The extent of the Gowganda Formation is the same as that of the Huronian Supergroup. To the north of the dashed line, The Gowganda Formation directly overlies Archean rocks (approximate, based on Young 1985).

B. Study Area Showing Major Geological Features

COLEMAN MEMBER LITHOFACIES

Diamictite, (D): Lithified, poorly
sorted: mud-sand-gravel

Dm	matrix supported
Dc	clast supported
D-m	massive (<10% laminations)
D-s	stratified
D--gn	normally graded
D--gr	reverse graded
D---(r)	resedimented

bd---- basal: directly overlying
Archean unconformity

Sandstone, (S):

pS	pebbly (>5% gravel)
Sm	massive
Sh	horiz. lam./bedding
Sr	rippled
St	trough crossbedded
Sp	planar crossbedded
S-gn	graded, normal
S-gr	graded, reverse
S-d	dropstones

Fine-grained, (F): Mudstone, minor
very fine-grained
sandstone

Fr	rhythmically laminated
Fl	laminated (non-rhythmic)
Fm	massive (<10% laminations)
F-d	dropstones

Breccia, (Bx): Angular
fragments of subjacent
Archean rocks

Bx(r)	resedimented small occurrence
-------	-------------------------------------

OTHER LITHOLOGIES

N Nipissing Diabase
(Proterozoic)

I Mafic/ultramafic rocks
of Archean age

A	Archean, undifferentiated
Ap	mafic volc. rock - pillowed
Am	mafic volc. rock - massive
Af	felsic volcanic rock
Al	interflow sedimentary rock

~~Table 1: Lithofacies code for maps and sections (based on Eyles et al.~~
1983).

(Powell 1984; McCabe et al. 1984; Domack 1983). Because evidence of traction-current sedimentation is commonly lacking at Cobalt, the non-interpretative form (diamictite) was maintained. Further modifications include recognition of rhythmic layering in the fine-grained lithofacies (Fr_) and slightly different letter codes for some sedimentary structures (for example, gn and gr for normal and reverse grading).

1.1 Regional Setting of the Huronian Supergroup

*The Huronian Supergroup is an early Proterozoic (early Aphebian) sequence of siliclastic and minor volcanic rocks subdivided into four groups, each comprising an overall fining-upwards sequence (stratigraphy and formation nomenclature is summarized in Figure 2). The Huronian Supergroup occurs over an extensive area of northeastern Ontario (Figure 1) where only the Cobalt Group is present, unconformably overlying Archean rocks of the Superior Province. It also comprises most of the Southern Province near Lake Huron. Thicknesses generally increase southward to a cumulative maximum of over 10 km (Card et al. 1972). Radiometric dating of the underlying Archean granites and the cross-cutting Nipissing Diabase indicate that the sediments of the Huronian Supergroup were deposited between 2.6-2.5 and 2.1 Ga. (Fairbairn et al. 1969; Card and Pattison 1972). A whole-rock Rb-Sr age of approximately 2.3 Ga. has been obtained for quartzites and argillites of the Gowganda Formation near the town of Gowganda (Fairbairn et al. 1969).

The Huronian sediments appear to have been deposited on a continental margin, thought by Sims et al. (1980) and Zolnai et al. (1984) to resemble a divergent Atlantic-type plate margin. Young (1983) interpreted the lower Huronian sequences (those predating the Gowganda Formation) to have been deposited in an easterly-trending, fault-bounded

Figure 2 Generalised Stratigraphy of the Huronian Supergroup (based on Young 1981)

GENERALISED STRATIGRAPHY OF THE EARLY PROTEROZOIC HURONIAN SUPERGROUP

SOUTH
(Lake Huron
Region)

NORTH
(Timmins-
Kirkland Lake
Region)

Relative Location
of
Cobalt
Study Area

Nipissing
Dibase
≈ 2.1 Ga

FORMATION

GROUP

HURONIAN SUPERGROUP	
COBALT	BAR RIVER GORDON LAKE LORRAIN GOWGANDA SERPENT ESPANOLA BRUCE MISSISSAGI PECORS RAMSEY LAKE MCKIM MATINENDA
QUIRKE LAKE	
HOUGH LAKE	
ELLIOT LAKE	

ARCHEAN (> 2.5 Ga)

ARCHEAN
(> 2.5 Ga)

trough, whereas the more widespread upper Huronian strata were inferred to represent deposition during broad marginal downwarping. Slightly different tectonic settings have been proposed (see Young 1983 for a summary), but all have an ocean basin that opened to the south or southeast, with northern areas (including Cobalt) representing an inner shelf tectonic setting.

The Gowganda Formation, the basal unit of the upper Huronian Cobalt Group, is much more extensive than underlying Huronian strata (see Figure 2). It generally thickens southward, with the maximum thickness increases from 1300 m in the northwest to 1700 m near Lake Huron (Young 1981b). Thomson (1957) proposed subdividing the northern Gowganda Formation into upper Firstbrook and basal Coleman Formations. Subsequently however, these names have been used to designate members only, a practice continued in this report. The Firstbrook Member appears to be stratigraphically equivalent to the southern Upper Gowganda Formation of Young (1981a,b, 1985), termed the La Cloche Formation by Lindsey (1967, 1969, 1971). The Coleman Member is equivalent to the Lower Gowganda Formation of Young (1981a, b), termed simply the Gowganda Formation by Lindsey (1967, 1969, 1971).

The Firstbrook Member consists of a coarsening-upward sequence of laminated mudstones, siltstones and minor sandstones. This sequence, over 500 m thick in some areas, in most places conformably overlies the Coleman Member. The Firstbrook Formation is interpreted as a basin/prodelta/delta-slope transition, deposited in a nonglacial, probably marine environment (Rainbird, 1985).

3.2 Local Geologic Setting

In the Cobalt area Archean volcanic, sedimentary and minor

intrusive rocks of the Abitibi Greenstone Belt comprise the basement. A pronounced angular unconformity separates the subvertical Archean rocks from the overlying horizontal to shallowly dipping Coleman Member. The Firstbrook Member and Lorrain Formation crop out short distances to the east and west of the area. The Huronian rocks are at lower greenschist metamorphic grade. East of Cobalt, Archean and Huronian rocks are crosscut by the Nipissing Diabase. This diabase is a sheet-like intrusion, approximately 330 m thick, dipping gently to the east (Jambor 1971b). Economic concentrations of silver occur in steeply dipping veins which crosscut Archean, Huronian and Nipissing rocks. Berry (1971), Owsicki and Lovell (1984) and Goodz (1985) have provided detailed discussions of the silver veins and related economic geology of the Cobalt area.

1.3 Structure and Paleotopography of Study Area

Knight (1924) attempted the only major structural study of the Cobalt region. Within the study area, the only faults which significantly displace stratigraphy are the Cobalt Lake and Valley faults (Figures 1B, 18-21). Both are high-angle reverse faults which shallow at depth. Dip-separation displacements vary from a maximum of 170m at the south end of Cobalt Lake, and decrease to the northeast and southwest (Knight 1924). The Valley Fault is subparallel to the Cobalt Lake Fault and may join it to the northeast. Displacement of 20m has been documented in the northern part of the study area (Knight 1924). This displacement decreases southward, the fault is not present south of the Cobalt townsite. These major faults predate intrusion of the Nipissing Diabase (Knight 1924; Jambor 1971a), but evidence is lacking in the study area for faulting during deposition of the Coleman Member.

Minor faults and shear zones trending northeast, southeast, or east were mapped or have been reported (Wilson in prep.; Knight 1924; Thomson 1964a,b,c). None has a displacement of more than a few metres.

The dip of the Archean unconformity surface ranges from horizontal to approximately 30° and rarely exceeds 20° . Coleman Member strata are subparallel or slightly shallower dipping. Knight (1924) suggested that tectonic folding might account for some of the dip variations. This idea is supported by a paleomagnetic study of the Nipissing Diabase which concluded that broad, northeast-trending folds are superimposed on the gentle basin and dome emplacement configuration of the diabase (Symons 1970). Recent workers (Wood 1980; Kim 1979; Legun 1984) proposed that differential compaction over Archean paleotopographic highs accounts for changes in dip attitudes. In their model, present attitudes of the unconformity surface reflect the pre-Coleman Member topography with no subsequent folding. A maximum paleorelief exceeding 200m is apparent from examination of cross sections (Kim 1979; this study) and structure contour maps (Thomson 1961; Legun 1984).

The cross sections accompanying this study show that some lower units of the Coleman Member pinch-out against the Archean unconformity (figures 20, 21). Thickening of lower units in apparent lows and thinning over highs on the unconformity surface is also documented. These observations support the supratenuous folding models.

However, the upper units of the Coleman Member roughly parallel the Archean unconformity surface across areas of high and low topography. This suggests that some tectonic folding of the unconformity surface and the Coleman Member has occurred. When the effects of this folding are considered, the paleorelief in the Cobalt area is estimated to be $< 100\text{m}$ (generally tens of metres). The

paleotopography is envisioned as a series of broad, shallow troughs separated by low rises. Two major troughs, trending northeast, are recognized (see cross sections, Figures 20, 21). One is centred approximately over the present position of the Cobalt Lake Fault. The other is beneath Cart and Peterson Lakes. Minor east- to southeast-trending troughs connect the more extensive troughs in two places (cross sections B-B' and D-D', Figures 20, 21).

Although overall paleotopography of the unconformity is gentle, locally the surface is irregular and rugged. Slopes of 40-50° with ten to fifteen metres of relief were defined during mapping. These steep slopes delineate small-scale paleotopographic features, slight scarps and depressions rather than major ridges and cliffs.

Slightly higher relief probably existed southeast of the study area (Thomson 1957; Legun 1984), although the effects of later folding have not been estimated. Mountainous terrain as postulated by Schenk (1965a,b) for the Lake Temagami area to the southwest did not exist at Cobalt.

CHAPTER II

UNCONFORMITY SURFACE FEATURES AND BRECCIA

The Archean-Proterozoic unconformity surface is well exposed in the study area. It was closely examined for evidence of erosion by a Huronian ice body. Glacial striae have been reported in two other localities (Cooke 1922; Schenk 1965a,b), but were not observed in the study area. However, the unusual conditions required to preserve an exposed, striated paleosurface (such as protection by overhanging strata of the Coleman Member) were not encountered in the Cobalt area. Three previously unreported features suggesting the presence of grounded ice were discovered.

1. Angular, block-like depressions

Steep-sided angular depressions are common on the unconformity surface (Plate 1A), the sharply defined edges paralleling Archean joint sets. These depressions, less than one metre on their longest surface dimension, are infilled by unsorted, massive Coleman Member diamictite (Dmm or Dcm). The upper tens-of-centimetres of Archean rock and the unconformity surface are generally extensively jointed and fractured relative to typical Archean rock (Plate 1C). Ice-plucking of blocks from the highly fractured bedrock is the likely origin of the depressions.

2. Stepped unconformity contact

Several step-like contacts were observed in vertical exposures of the unconformity surface (Plate 1B). The steps are centimetres to tens-of-centimetres high and face approximately south. As for the plucked depressions, the vertical and horizontal contacts appear to be joint-controlled. These features probably originated by lee-side quarrying at the base of a moving ice mass.

3. Shaped stoss and lee feature

A stoss and lee feature three metres long and one metre high was discovered during the 1984 field season (Figure 3). Developed on Archean volcanic rocks, it displays a streamlined stoss (north) side, (smoothed and striated by Quaternary glaciation) that rises southward to a jagged, vertical, south-facing step-like contact with Coleman Member diamictite. On the lee side of this structure, the diamictite contains large angular clasts of the Archean volcanic rock, many of which can be visually restored to the unconformity surface. As for the stepped unconformity contacts, lee-side quarrying by moving ice is inferred, perhaps with some stoss-side shaping.

These features provide strong evidence for the presence of a grounded ice mass during at least initial deposition of the lower Gowganda Formation. Ice movement in a southerly direction is indicated.

Except in rare areas where special conditions existed, the unconformity surface was swept clean of any regolith which may have been present. This has resulted in the sharp Archean-Proterozoic contact commonly observed (Plate 1D) or occasional ice-plucked or stoss and lee structures with related fragments.

Occasionally, breccia derived from underlying or subjacent bedrock occurs at the unconformity. Most occurrences are thin (<20 cm) and rarely persist laterally for more than a few metres. Most occurrences of these breccias can be related to stoss and lee features discussed above (as in Plate 1B), or are preserved in slight lows on the irregular unconformity surface. The matrix of these breccias is similar to the matrix of the basal Coleman Member diamictite (Plate 1E).

Two rare examples of more extensive basal breccias are shown on

Figure 3. Lee-side plucking of the unconformity surface.

Southward (away from viewer) movement of the Pleistocene ice sheet has shaped this outcrop into a smoothed and plucked roche moutonnée that contains a segment of the Coleman-Archean contact. The Archean basement of felsic volcanic rock is stippled in the line drawing; Coleman Member diamictite is unpatterned, except for a few of the largest Archean clasts. The relationship of the irregular unconformity to these felsic clasts reveals that most of them were derived from the adjacent bedrock. At least one metre of paleorelief is apparent between the highest and lowest portions of the extensively jointed unconformity surface, indicating a southwesterly facing paleoscarp. In conjunction with the evidence for glacial deposition of the Coleman Member presented elsewhere in this thesis, an interpretation of joint-controlled, lee-side ice-plucking by an approximately southwest-moving grounded ice sheet is indicated for the illustrated relationship.

cross section D-D' (Figure 20). Both are lensoid bodies which are preserved in paleotopographic lows and thin up the Archean paleoslopes. The northern occurrence (previously studied by Rainbird 1980) consists of a continuous, upward gradation from fractured, but in situ Archean basement, to breccia of slightly rotated fragments, to increasingly displaced fragments which contain a higher matrix content (Plate 1F). A gradational contact with Coleman Member diamictite caps the sequence. Occasional exotic clasts are observed in the upper portion of the breccia (both in framework and matrix). Breccia fragments show little evidence of transport, except for a slight apparently northward movement of ultramafic dyke fragments near the base.

The southern breccia lens consists of angular fragments of felsic volcanic rock (70%) with exotic granitoid clasts (30%) (Plate 1G). It overlies Archean mafic volcanic rocks in a steep-sided paleodepression. A small, discontinuous lens of faintly-stratified Coleman Member diamictite (Dms) is also present beneath the breccia in one location. The southern breccia thins up a steep paleoslope where it is in contact with the parent felsic volcanic basement rock. The breccia matrix contains abundant (up to 30%) silt- and sand-sized quartz and feldspar grains identical to those in the Coleman Member basal diamictite matrix. However, most of the matrix in both breccias is extremely fine-grained chlorite and sericite.

Most previous studies have suggested a paleoregolith interpretation for breccia at Cobalt (Patterson 1979; Rainbird 1980; Donaldson and Munro 1982). A subglacial origin was postulated by Legun (1984). The southern occurrence was interpreted by Scammell (1984) as resedimented paleotalus.

The detailed work of this study suggests that most of the small,

isolated breccia occurrences preserved outside paleotopographic lows are related to ice-plucked or stoss and lee structures. The matrix appears to be composed of Coleman Member detritus. Sericite and chlorite is much less common than in the large breccia lenses. Such features suggest a subglacial origin for these breccias.

However, a paleoregolith interpretation does appear valid for the large breccia lenses. The in situ nature and preservation only in paleotopographic lows supports a pre-Coleman Member origin. The high percentage of fine-grained sericite and chlorite in the matrix may reflect a high original clay content. Frost heaving may have separated blocks to allow later Coleman Member sediments to infiltrate upper regions of the breccias. Slight solifluction could explain the northern movement of fragments at the base of the north breccia (Donaldson and Munro 1982). Much of the south breccia occurs north of its only possible bedrock source and must have moved downslope as Scammell (1984) suggested. However, this ~~must~~ have occurred during an early period of Coleman Member deposition, because the flow breccia rests on diamictite, and has incorporated matrix and framework material of Coleman Member origin.

The preservation of these breccias in depressions and the flow of the south breccia when the area was covered by an ice mass suggests that subglacial cavities existed at these sites. This interpretation is supported by the presence of a unique clast-supported diamictite overlying these breccias. Features and interpretation of this diamictite are presented in chapters 3 and 4 of this thesis.

CHAPTER III

LITHOFACIES DESCRIPTIONS

The following descriptions are composite summaries of the major features of the lithofacies. Detailed descriptions of individual units accompany the measured sections in Appendix 1. The framework-matrix boundary for diamictite descriptions was set at 2 mm; the classification proposed by Dott (1964) has been followed for both diamictite, matrix and sandstones.

Low-grade metamorphism has resulted in a common grey-green coloration of both fresh and weathered surfaces. For this reason colour is not included in descriptions of the lithologies. Most of the rocks contain dark, grey-green chlorite-rich 1-5 mm "spots" which resemble detrital clasts in photographs. These are contact-metamorphic alteration products related to intrusion of the Nipissing Diabase (Jambor 1971c), and have no relevance to Coleman Member deposition.

3.1 Basal Diamictite Association (bDmm)

An extensive basal diamictite is present throughout most of the study area. The observed thickness ranges from 1 to 12 m and averages 2-4 m, with a general thickening in the broad paleotopographic lows and thinning across paleohighs (see cross-sections, Figures 20,21, back-pocket).

The diamictite consists of 5-50% unsorted granule- to boulder-sized clasts dispersed in a feldspathic wacke matrix (Plate 2A). The framework consists of angular to subrounded clasts of varying composition. Exotic granitoid clasts generally predominate (40-80%); other components are mafic volcanic clasts (10-50%) and minor amounts of felsic volcanic, metamorphic, sedimentary and rare massive sulphide

clasts. Exposures are planar and two-dimensional due to Quaternary glacial smoothing. Within this restriction, the clasts display a diversity of shapes: granitoid clasts tend to have a higher apparent sphericity and tend to be more rounded than the volcanic clasts, which generally are angular to subangular. Pentagonal outlines were observed in this and other diamictites (Plate 2B). Coleman (1907, 1908) described and illustrated faceted and striated (in two or more directions) pebbles, and cobbles recovered from underground mine workings at Cobalt. From his descriptions, it appears that at least some of these clasts were located in the basal diamictite unit. Altered clast margins are locally abundant, and have been interpreted as predepositional weathering rinds (Kurt 1973).

Thin-sections reveal that the diamictite matrix is an immature, very poorly sorted, feldspathic wacke. Subequal amounts (30-40%) of subangular, commonly broken grains of quartz and feldspar with less abundant (10-25%) lithic clasts (mostly volcanic) are randomly dispersed in a chlorite-sericite matrix (Plate 2C). Silt-sized quartz and feldspar is common (10-20%). Most silt and sand-sized clasts appear to have been unaltered at the time of deposition, but some feldspar and rock fragments have been partially altered to chlorite and lesser amounts of sericite (Plate 2D). Diffuse Ti-oxide minerals also occur in the matrix as alteration products.

The bedding-parallel orientations of the apparent long-axes of elongate clasts were measured where feasible for this and other diamictites in the study area. Surfaces parallel to bedding planes (defined by adjacent stratification) were used and gravel-sized clasts with apparent axial ratios exceeding 2:1 were measured at each site. A

more detailed discussion of methods and statistical analysis is given in Appendix 2. Apparent long-axes of basal diamictite clasts are preferentially oriented approximately in a south-southwest azimuth (Figure 4B-J).

The diamictite generally appears massive in outcrops, polished slabs and thin-sections. Rare, thin, poorly sorted, massive sandstone lenses occur in upper sections of the diamictite (Plate 2E). These lenses are less than three cm thick and are traceable for a few metres at most. They are slightly irregular with diffuse contacts. Where the diamictite is overlain by a sandstone or finer-grained lithofacies, the upper contact commonly is gradational, with a faint, irregular lamination apparent in the upper 10-30 cm (Plate 2F).

Lateral variations in the basal diamictite are not apparent except for thickness changes and clast percent variations. However, different lithotypes occasionally are associated with the basal diamictite. Moderately-sorted, clast-supported diamictites (Dcs), in places interbedded with pebbly, graded sandstones (pSgn), occur rarely as isolated, channelized lenses at the base of, or cutting the massive diamictite.

In the two extensive breccia occurrences described previously (Chapter 2), the breccias are partially or completely overlain by an unusual clast-supported diamictite (Dcm) (Plate 2G,H). It appears to fill the remaining portion of the Archean depressions and rapidly pinches-out beyond these depressions (cross-section D-D', Figure 20, back-pocket). It is an unsorted massive composite of angular to subrounded volcanic clasts (50-70%) and subrounded granitoid clasts (20-30%) with a feldspathic wacke matrix (Rainbird 1980). Apparent long-axes of clasts in this diamictite are randomly oriented (Figure 4A).

Figure 4 Apparent long-axis orientations of diamictite clasts in the Basal Diamictite Association. Rose diagram A is for an unusual clast-supported diamictite which infills a paleodepression containing breccia. All other diagrams are for the bDmm unit which generally is the basal lithology of the Coleman Member in the study area. Sample sites are shown in Figure 13, Appendix 4.

This diamictite is gradationally overlain by the matrix-supported basal diamictite.

The basal diamictite is absent in a few places, where any of the other lithofacies rest directly on the Archean basement. The most common basal unit where the basal diamictite is absent is a fine-grained lithofacies (F). In the western portion of the study area a stratified diamictite (Dms) similar to some stratigraphically higher diamictites is exposed near the unexposed unconformity.

3.2 Fine-grained Lithofacies (F)

Fine-grained units vary greatly in thickness, lateral extent, texture and internal structure. The most extensive and thickest (up to 19 m) are well-laminated and spatially associated with the basal diamictite and/or current-sorted sandstones. These have a maximum lateral extent of more than 1000 metres (refer to Figures 18-21, back-pocket). Thinner, less extensive units occur stratigraphically higher, commonly in association with the heterolithic diamictite complex.

A regular, repetitive alternation of siltstone-claystone or fine-grained sandstone-mudstone couplets is discernable in many places (Plate 3A). By using the term rhythmite (Fr) for these units, the seasonal or time connotation associated with previously-used terms such as varve-like argillite (Lindsey 1967) is avoided. Well-laminated, but not obviously rhythmically interlaminated mudstones also occur as lateral equivalents of the rhythmites. Rare, irregularly laminated mudstones are discussed separately.

Well-laminated Units (Fr, Frd, Frd-Shd, minor Fl)

Rhythmites are most abundant in the lower portion of the Coleman Member, and commonly overlie the basal diamictite directly. Where this

occurs, the lower contact is sharp-to-gradational and the top 10-20 cm of the underlying diamictite also may be faintly laminated (Plate 2F). Most of these rhythmites are the basal component of coarsening-upward sequences that consist of a vertical rhythmite/sandstone/clast-supported diamictite transition. Reverse-order, fining-upward sequences also occur, but are less common and of smaller areal extent. Examination of the maps and cross-sections (Figures 18-21) reveals that these associations occur as fan-shaped bodies which individually cover a maximum area of a few square kilometres and are up to 40m thick. This fan shape is readily apparent in mid portions of cross-sections A-A' and B-B' (Figure 21) and in cross-section D-D' (Figure 22). The surface expression of these examples (Figures 18,19) allows an approximation of the areal extent of each fan (based on the extent of sandstone lithofacies of each sequence). For simplicity these sequences are subsequently termed fan associations.

Rhythmite lithofacies range in thickness to an approximate maximum of 19m. Typically, the basal section consists of silt-clay couplets with a thicker clay component (up to 5 mm). The coarse- to fine-grained quartz-feldspar silt component is sharp-based and normally graded or massive throughout. Micro-loading into the underlying clay is rare. The clay component generally has a sharp lower contact, but normally-graded fine silt is diffused through the lower half. The upper half usually appears massive. Gradational silt-clay contacts also occur. The clay is partially altered to a chlorite/sericite/Ti-oxide mass. Occasional microlaminations (one silt grain thick) occur within the clay (Plate 3B).

Silt laminations increase in abundance and thickness upwards. Higher in the sequence, composite graded silt layers are separated by thinner clay-silt layers. Sharp loaded basal contacts and complex internal grading patterns are common (eg. reverse-to-massive-to-

microlaminations. Fine-grained sand laminae (rarely thin beds), rare in the lower part of the sequence, are more common in mid-rhythmite sections. Many are discontinuous, with a lenticular to wavy (starved ripple) form (Plate 3D). Some contain faint cross-laminations and basal, deformed microflames, indicating southerly-directed flow.

In the upper part of the rhythmite section, the silt layers are thicker (up to 1 cm) and coarser grained. Sand-silt couplets are increasingly common and the clay component decreases in frequency and thickness. Clay layers are generally less than 5 mm thick and contain fine silt throughout, with a normally-graded silty base (Plate 3E).

Near the top of the rhythmite units, one to three cm thick, normally-graded, fine-grained sand to coarse-grained silt beds become common. Ripples and occasional climbing-ripple sets (A, B, and more abundant sinusoidal types of Jopling and Walker, 1968) are present (Plate 3F). Increasingly frequent fine-grained sand interbeds grade upward into a sandstone unit with no discrete clay laminae. Relatively thick (up to 30 cm), very fine- to fine-grained, massive to faintly laminated sandstones are interbedded in the upper 2-3 m of the rhythmites. These beds are deeply loaded into the rhythmites with associated rhythmite flames deformed and locally thrust to the south (Plate 3G,H). Dish and pillar dewatering structures occur in some of the massive sandstone interbeds (Plate 3I).

In the western part of the study area, the lower rhythmite units (cross-section E-E', west side, Figure 20) are unusually coarse-grained (Frd-Shd). The normal bottom component of the couplets is medium- to fine-grained sandstone grading into coarse siltstone. Many of the coarse layers comprise multiple laminations (both normal- and reverse-

graded), with microlaminated silt-clay units forming the upper component of the couplets. Much of this section contains composite subunits, although the upper clay-rich section is predominantly massive. Rarely, fragments of the underlying silt-clay laminae occur immediately above the sharp, loaded basal contact, indicating erosion during transport (Plate 4A).

Lonestones occur in all of the fine-grained lithofacies, but are most prevalent in the rhythmites. They range from sand-size to 80 cm in diameter. All lithologies that occur in the diamictites are represented. Surrounding laminae are depressed below, draped over, and/or pierced by the clasts (Plate 4B). The pierced laminae are typically contorted and thickened near the clasts. The contact relationships documented for Pliestocene dropstones (Thomas and Donnell 1985, fig. 2) were observed (Figure 5) and a dropstone origin for these clasts is inferred. In general, they are rare in the silt-clay rhythmites and common in the coarse-grained rhythmites. The coarse rhythmites in the west section of the study area contain an unusually high number of dropstones, (up to 10%). Some are concentrated in patches or small lenses parallel to the laminations, but the usual occurrence is as lonestones.

Suboval, sand-sized wacke clasts also occur, and are most abundant in the coarse, dropstone-rich rhythmites (Plate 3B,C). They exhibit diffuse margins, elongation parallel to the laminations and compositions similar to the matrix of the diamictites. These appear identical to the pelletoidal greywacke clasts described by Lindsey (1970). He proposed an origin as till pellets, partially consolidated by englacial ice pressure, freed by melting, deposited by ice-rafting and compacted into an ovoid form with elongation parallel to the enclosing laminae.

Figure 5. Contact relationships of dropstones in the study area.

[The terminology for dropstone contacts of Thomas and Connell (1985) are used here.]

A. (see also Plate 4b) Slight bending of laminae below clast accompanied by extreme thinning of subjacent laminae. Piercing of laminae and simple rucking (sharp, upward folding) of sediment against clast edges indicates initial penetration of approximately 3cm. Onlap of lamina above rucking is well-defined.

B. Extreme penetration of approximately 30-40cm by an unusually large clast. Displacement of sediment has caused pronounced rucking and convolute folding of individual strata. Sand beds are thickened on edges of clast due to lateral displacement, but the competency of individual strata was sufficient to prevent breakup.

C. Relatively sharp piercement accompanied by only minor rucking at clast edges and thinning below clast. May reflect greater competence of the clay-rich layers pierced as opposed to silt/sand layers of D.

D. Total penetration of layers by largest clast has caused rupture above the final position of the clast with some laminae extensively distorted (This may indicate a relatively water-rich sediment at the time of clast emplacement, in contrast to 5B,C).

E. Large clast has penetrated numerous laminae. Extreme rupture, convolute folding at clast edges, and break-up of some laminae may be the result of shock and displacement effects in a water-rich sediment.

F. A possible pseudo-dropstone: thinning beneath clast is minimal, downwarp of pierced laminae is limited to one side, rucking is not evident, and clast is not oversized with respect to the overlying layer. This pseudo-dropstone may have been transported as bedload, with later compaction resulting in piercement of lamina.

Deformation structures are evident in some of the rhythmites. The loaded bases of the massive sandstone interbeds rarely show evidence of extreme deformation, with sections of the underlying rhythmites decoupled and thrust southward several tens-of-centimetres (Plate 3H). In other areas, thin, short-displacement (<10 cm) thrusts of underlying laminae into the overlying (generally coarser) laminae also occur (Plate 4C). A few examples of convolutedly deformed sets of laminae (<1 cm - 40 cm thick) bounded by undeformed lamina were also observed. This style of deformation is not spatially associated with anomalous lithotypes, as is the first. Two clastic dykes of massive sand which cross-cut and deform the edges of rhythmite units were also discovered (Plate 4D).

Paleocurrents were estimated on the basis of cross-laminations in ripples, climbing ripple drift, asymmetry of ripple crests and deformation of flame structures. Exact measurements rarely could be obtained, because the best exposures occur on vertical faces, and three-dimensional exposures are rare. The paleocurrent directions generally range from southeast to southwest throughout the rhythmite sequences. In the middle to upper sections through the rhythmites, a few northerly directions were observed.

Poorly-laminated Units (Fl, Fm, Fl-Sh)

Massive fine-grained lithofacies are absent in the study area, but rare, thin units of faintly and irregularly laminated mudstones occur in higher stratigraphic positions and as the lateral equivalents of the well-laminated units. For both, a close spatial association with current-sorted sandstones is absent.

These units are composed of wavy to discontinuous silt and clay laminae of variable thickness (most laminae < 2 mm thick) (Plates 4E).

Contacts are generally diffuse and gradational. The silt-rich laminations are typically massive, but some are normally graded with dipot packing. The silt matrix and clay laminae consist of chlorite, minor sericite and patchy carbonate alteration.

Discontinuous, wavy, parallel, fine-grained sand laminations (.5-1 cm thick usually) are occasionally present. In one exposure, numerous isolated, fine-grained sandstone "clasts" from less than 1 cm to more than 30 cm diameter, "float" in irregularly laminated mudstone (Plate 4F). These irregularly shaped pseudonodules display convoluted laminations.

3.3 Sandstone Lithofacies (S)

Sandstones within the study area can be separated into two major subdivisions. Thickest and most extensive are sandstones of fan associations. Relatively thin sandstone sheets or lenses generally associated with the heterolithic diamictite complex are less extensive and will be described in the section dealing with this complex.

Units of sandstone in coarsening-upward sequences range in thickness from less than two metres to over nine metres. Their areal extent is less than the underlying rhythmite, but greater than the clast-supported diamictite that typically caps them (see cross-sections, Figures 20, 21, back-pocket). The lower contact of the sandstones is transitional with the previously described interbedded sandstone/coarse-grained rhythmite. A sharp, erosive contact is generally apparent at the base of a thicker continuous sandstone unit that overlies this interbedded zone. This was selected as the base of the sandstone for mapping and descriptive purposes. Rarely, sandstone directly overlies the basal diamictite (as in the northern portion of cross section D-D').

Figure 20). The contact is sharp and slightly erosive.

The sandstones are moderately-sorted feldspathic arenites or wackes with 10 to 40% matrix. The framework mineralogy consists of quartz and feldspar in subequal amounts and 10 to 25% lithic fragments, mostly volcanic. Packing ranges from condensed with numerous sutured grain contacts to dispersed with subangular to subround clasts. Clast alteration is limited to slight grain boundary alteration and incipient feldspar sericitization. The matrix consists of silt-sized clasts, abundant chlorite, minor amounts of sericite and Ti-oxide aggregates (sphene?) and rare patchy carbonate alteration. Plate 4G illustrates many of the above features. Kurt (1973) conducted a more detailed petrographic study of three of these sandstones.

In a typical sandstone unit, the basal, thin-bedded, fine- to medium-grained portion contains ripples or small-scale planar crossbedding. This coarsens upwards into medium- to coarse-grained tabular beds (10-50 cm thick), some of which exhibit low-angle planar crossbedding (Plate 4H). In other places, the beds comprise fining-upward coarse- to medium-grained cycles with rare pebbles at the base. Above this, trough crossbedding is occasionally present with overlapping, normally-graded, erosional trough sets containing pebbly lenses at the base. The troughs tend to be 1-2 metres long and less than 25 cm deep as seen in vertical exposures (Plate 5A). Above this, or where trough crossbedding is absent, the upper parts of the sandstone units are very coarse-grained, thin to medium bedded (<5-20cm) graded cycles of small pebble/granule to coarse-grained sands (Plate 5B,C). Normal, reverse or inverse-to-normal grading is present. Most cycles are normally graded with an unstratified pebble-granule component grading into a faintly laminated (rarely cross-laminated) coarse-grained

sand. In most areas these cycles are sharply overlain by a clast-supported diamictite.

Sandstones also occur in fining-upward sequences with units overlying clast-supported diamictites (Dcs, Dcm) and in places are overlain by rhythmites. These sequences are thinner and less extensive than the coarsening-upwards fan associations. The sandstones observed tend to be less than five metres thick. A gradational lower contact consists of sharp-based beds (up to 70 cm thick) of pebble-granule diamictite grading up into coarse-grained sandstones. In general the structures and textures are similar to those of the coarsening-upwards sequences, except for a lack of trough crossbedding.

Sharply bounded beds (30-60 cm thick) of massive to faintly-stratified, pebbled-sized, clast-supported diamictite (Dcm) occur rarely in the mid to upper portions of the sandstones. Rare lonestones up to 50 cm in diameter occur within these otherwise moderately-sorted sandstones (Plate 5D).

Paleocurrent measurement was hampered by the high induration and lack of three-dimensional exposures of relevant structures. However, a southeast to southwest trend similar to that of most rhythmite paleocurrents is apparent (Figure 6).

3.4. Clast-supported Diamictites (Dc)

Diamictites consisting of an intact framework of gravel-sized clasts (Dc) occur in three different facies relationships. Most are units within the fan association, but a few units occur as thin, isolated lenses within other lithofacies. Extensive tabular bodies of this lithofacies also form part of the heterolithic diamictite complex (discussed in the following section).

Figure 6. Paleocurrent rose diagrams from sandstone units within the study area. A-D are from individual sample sites, shown in Figure 14, Appendix 4. The lithofacies type is shown in the upper right corner (see Table 1 for lithofacies code). Diagram E is compiled from all paleocurrent data obtained during the study, including measurements not part of diagrams A-D. Statistical methods are as for diamictite apparent long-axis orientations, discussed in Appendix 2.

Clast-supported diamictites are the areally least-extensive unit of the fan association (see cross-sections, Figures 20,21, back-pocket). Diamictite thicknesses exceed 20 m in some coarsening-upwards sequences, but more commonly are less than 15 m. The basal contact may be sharp and erosional, but is commonly gradational with respect to the underlying sandstone. Where the diamictite directly overlies a rhythmite unit, the base is sharp, erosional and loaded.

The diamictite consists of a poorly-sorted, intact framework of 70-90% gravel-sized clasts (Plate 5E). Most are small-pebble to small-cobble size, but large cobbles and boulder clasts are common in some of the occurrences. Clast lithologies are diverse with volcanic (mafic > felsic) and granitic rocks accounting for over 90% of the total. Sedimentary, metamorphic and rarely sulphide clasts are also present. Clasts range from subangular to subrounded, with volcanic clasts more rounded than the igneous clasts in the planar, two-dimensional exposures examined. Most shapes appear to be equant to slightly ovoid.

The sand fraction of these diamictites is a moderately- to poorly-sorted, medium- to very coarse-grained feldspathic arenite (rarely a wacke). Sand and matrix characteristics are similar to those described previously. Many of the quartz and feldspar clasts appear to be derived from plutonic sources, a contrast to the high percentage of volcanic clasts in the gravel-sized fraction.

In a few places, a thick (up to 15 m) basal subunit can be differentiated within the diamictites of the coarsening-upwards associations. It appears massive and unsorted on most weathered surfaces and generally was mapped as Dcm or Dcm-Dcs (see maps, Figures 18,19, back-pocket). A crude stratification is apparent in good

exposures and in some cut slabs. In some exposures inverse grading can be seen in the lowest 20-50 cm. Above this (or where it is not present), a weak horizontal alignment of clast long-axes and poorly-developed graded cycles were commonly apparent (Plate 5F). Bedding could not be precisely defined. Rarely, thin (<15 cm), discontinuous pebbly-sandstone lenses occur in the upper portions. Apparent long-axes of clasts are preferentially oriented along south or southwest azimuths (Figure 7G-J). This is parallel to paleocurrent directions determined in the underlying sandstones (Figure 6A-D).

A moderately-sorted, obviously stratified diamictite (Dcs) occurs where this subunit is not present. It can also overlie this unit with a sharp or gradational contact. It usually consists of poorly defined, normally-graded beds tens-of-centimetres thick with pebble/cobble bases and granule- to coarse-grained sandstone tops (Plate 5G). In some areas, this upper subunit is well defined, with distinct graded cycles and faint planar (to trough?) cross-stratification visible in the pebbly-sandstone upper portion (Plate 5H). Rarely, a cycle grades up into asymmetrically-rippled fine-grained sandstone with a thin (<1 cm), laminated, siltstone top.

Clast-supported diamictites in fining-upward associations closely resemble the previous subunit. Poorly defined beds are up to 50 cm thick. The lower 10-30 cm consists of moderately-sorted, faintly graded pebble-to-small-pebble clasts. This grades sharply into a coarse-grained, pebbly-sandstone which also fines upward slightly (Plate 6A). In a few places a lower subunit of diamictite similar to the poorly-stratified lower unit described previously is also present. Apparent long-axes of clasts in these units are randomly oriented on bedding surfaces (Figure 7K,L).

Figure 7. Clast apparent long-axis orientations for diamictites of Fan and Interfan Associations. Sample sites are shown in Figure 15, Appendix 4. The lithofacies is shown in the upper right corner of each diagram (see Table 1 for lithofacies code). Explanation of symbols as for Figure 4.

Rarely, clast-supported diamictites occur as small, discontinuous bodies within the other lithofacies. These channelized, lens-like units decrease in thickness from a central few metres, pinching-out on both sides within tens of metres. They have a sharp, erosive base with the lithofacies containing them (most often Frd-Shd, bDmm, or Dms). Most consist of a moderately-sorted, small-cobble to small-pebble layer which grades into a thin sandstone. Some comprise repetitive beds of normally-graded, gravel- to sand-sized clasts. Faint horizontal bedding/lamination or rarely, planar cross-stratification are present in the sand-sized portion.

3.5 Heterolithic Diamictite Complex

This association comprises diamictites complexly intercalated with sandstones and fine-grained lithofacies. Lithotypes do not occur as stratigraphically confined units, as does the basal diamictite, or as members of a well-defined sequence of changing lithofacies as for fan associations. The prefix "upper" was used during mapping to distinguish this association from the basal diamictite.

This complex can be subdivided into units that occur at approximately the same stratigraphic position as the fan associations and overlying units that form the stratigraphically highest lithologies in the study area. The higher assemblage is approximately restricted to the area bounded by the Valley Fault on the west and the Cobalt Lake Fault on the east, plus the highest units west and north of the Valley Fault (Figure 48 and cross-sections C-C', E-E', F-F'; Figures 20, 21, back-pocket).

Lower Stratigraphic Assemblage

Lithologies of this assemblage generally overlie fine-grained or

sandstone lithofacies of the fan associations. Occasionally, this diamictite complex directly overlies the basal diamictite or the unconformity surface, making distinction of a bDmm unit difficult or impossible (eg. northwest side of cross-section C-C', Figure 20. back-pocket).

The most common lithology is matrix-supported diamictite, either stratified (Dms) or massive (Dmm): The former consists of units 0.5 - 15 m thick. The thick sections actually may be composite units, because contacts between separate Dms subunits are generally not distinguishable unless another lithology is interbedded (Plate 6B). Gravel-sized clasts typically form 10-70% of a unit and consist of angular to subrounded granules to boulders (largest observed: 140 cm). Some of these clasts appear faceted (Plate 6D). Framework clasts are dispersed in a very poorly sorted, feldspathic wacke similar to that of the basal diamictite, but with occasional faint stratification at thin-section scale. This consists of a subparallel alignment of elongate sand-sized clasts and rarely, the presence of faint, wavy laminations. A crude stratification is also apparent at outcrop scale, consisting of wavy laminations and/or a rough subhorizontal alignment of elongate, gravel-sized clasts. Rarely, a poorly-developed imbrication is apparent. Some clasts have deformed and/or pierced the faint, wavy laminae, suggesting a dropstone origin.

This lithology occurs interbedded with other diamictite, sandstone and fine-grained lithofacies. Where discernible, the lower contacts are sharp and in places erosive into the lower unit. This is especially noticeable where underlying laminated fine-grained units occur (Plate 6D). Upper contacts are generally indistinct with overlying diamictites, and sharp with non-diamictites. Rarely, dewatering has caused

intermixing of sands and diamicton, disrupting the contacts. Projecting clasts are occasionally present at the top contact.

Some diamictites appear to be massive (Dmm). These generally contain fewer gravel-sized clasts (<30%), but are otherwise identical to the stratified diamictites. Thin, discontinuous, contorted sandstone lenses are rarely present. The massive diamictite units can be thick (up to 15 m), but recognition of subunit contacts is difficult unless another lithology is interbedded.

The lateral extent of the matrix-supported diamictites is difficult to ascertain due to the subtle contacts between coincident units. In many areas, no definite change in diamictite type is apparent over hundreds of metres of exposure, suggesting relatively extensive sheets, although a composite of multiple, virtually identical subunits is suspected. In some places, thin discontinuous lenses of this diamictite can be mapped.

Unusual structures observed in the matrix-supported diamictites include a grooved surface on the top of a Dms unit. At the largest exposure (Plate 6E), linear, parallel grooves (2-20 mm amplitudes and 5-10mm wavelength) are oriented in a direction (135°) which roughly coincides with the local paleoslope. The grooves disappear beneath another Dms unit and have a thin, patchy, siltstone drape, eliminating the possibility of Pleistocene origin.

Two unusual sedimentary boulders were found in Dms units. Both consist of pebbles and cobbles with a wacke matrix and appear identical to Coleman Member clast-supported diamictites (Plate 6F). The irregular clast boundary is defined by complete, projecting cobbles or pebbles, supporting a synsedimentary source. The example in Plate 6F occurs in

faintly- to well-stratified transitional Dms-Frd. It both depresses and pierces faint laminations. This observation, supported by orientation of the boulder with its largest cobbles at the bottom, suggests final deposition as a dropstone.

A third unusual feature is the rare occurrence of isolated gravel-sized, intact-framework clusters (Dcm) in the generally dispersed-framework Dms units. These clusters tend to be ovoid in sections approximately parallel to bedding and are up to several metres in maximum diameter.

Other lithologies are interbedded with the matrix-supported diamictites. Clast-supported diamictites (Dcm or Dcs) occur as sheets or lenses, usually <2 m thick (rarely up to 5 m). Most of the lensoid units are channelized, moderately-sorted, and fining-upward as previously described (page 38). Sheet-like Dcm units are generally massive, with a sharp, slightly loaded, non-erosive lower contact, although erosional contacts were rarely observed (Plate 6G). These poorly-sorted units exhibit a wide range of grading patterns. Some are nongraded or have a crudely-defined, coarse central portion with nongraded, unsorted top and bottom sections. Some show vague normal grading, with projecting clasts at the top surface (Plate 6H). A thin, finer-grained, laminated or rippled bed drapes some of these units (Plate 7A). Inverse- to normal-graded sequences also occur.

An unusual Dcm unit of variable thickness (2-5 m) occurs in the southeastern part of the map area (cross-section A-A', east side, Figure 2b). It consists of an unsorted framework of gravel-sized clasts with an unusually large boulder fraction (>20%; largest: 2.7 m). Some of the large boulders are broken and the fragments are slightly separated (Plate 7B,C). The spaces between the fragments have been infilled by

the enclosing diamictite. Most of the broken fragments are not significantly dispersed, reflecting in situ fracturing of the clasts. The top contact of this unit is irregular, with some clasts projecting more than 10 cm. An overlying Fl-Sh unit covers and infills between the projecting clasts. Compaction may have accentuated, or even caused, such draping of the laminated unit around the uppermost clasts.

Apparent long-axis orientations of clasts in these diamictites (both massive and clast-supported) are preferentially oriented along a southeast to southwest azimuth (Figure 7A-F).

Sandstones occur as discontinuous sheets or lenses. These are generally coarse- to medium-grained feldspathic arenites or wackes, less than 2m thick and tens to a few hundred metres in extent where this could be determined. Most have sharp, loaded or erosive bases with underlying matrix-supported diamictites and conformable, draping contacts with clast-supported diamictites. Usually they consist of a single bed which is apparently massive or graded. Inverse to normal grading is common (Plate 7E), although normally-graded sequences also occur, some with a thin overlying faintly-laminated and locally rippled mudstone or fine-grained sandstone.

Two fine-grained lithofacies are associated with the lower portion of the diamictite complex. The most extensive are part of the fan association and occur below or are laterally transitional to the diamictite complex. Where a lateral progression from coarse-grained Frd-Shd lithofacies to stratified diamictites is observed, complex and abrupt lithologic variations are typical. A less abrupt and sharply intercalated lateral transition also occurs. In one area (cut by cross-section C-C', east side; Figure 21, back-pocket), a gradational

southward transition from Dms to Frd occurs over a few hundred metres. To the north, 10-15% pebble- to boulder-sized clasts are dispersed in a faintly and irregularly laminated fine-grained wacke which directly overlies the basal diamictite (see MS-5, Appendix 1). Southward, the matrix size decreases, laminations become more regular and gravel-sized clast percentage decreases. The stratigraphically equivalent unit to the south is a well-laminated rhythmite (Frd) that contains rare dropstones (Plate 3A). This rhythmite unit contains a thick (thinning from 7 m to 2 m over 200 m, shown on cross-section B-B' east side; Addition 4, back-pocket), tapered sheet of massive, clast-supported diamictite composed mostly of large pebbles, cobbles and sparse boulders. It occurs within the Frd unit with a sharp, loaded, lower contact and an irregular upper contact with projecting boulders, draped by Frd (similar to Plate 7D).

Irregularly laminated mudstones also occur in the lower stratigraphic assemblage. They are not obvious components of fan association sequences, although their stratigraphic position suggests that many are laterally equivalent to the rhythmites of other areas. These poorly-laminated units were described in detail in the previous section (Fine-grained Lithofacies).

Upper Stratigraphic Assemblage

The highest stratigraphic units in the study area consist of a complex series of diamictite bodies with minor occurrences of other lithologies. This portion of the Coleman Member at Cobalt is preserved in a relatively small area, and most exposures are restricted to isolated occurrences, with the exception of the ridge where a detailed section (MS-4) was measured (Appendix 1).

Matrix-supported diamictites within this upper portion occur as

thick (up to 10 m) tabular sheets, although, as for the lower assemblage, it is difficult to distinguish contacts between multiple Dms or Dmm units. Units include massive, unsorted Dmm with 10-50% granule- to boulder-sized clasts, most subangular to subrounded, dispersed in feldspathic wacke. Some Dm units are faintly stratified with irregular thin sandstone lenses. Others contain a wavy, nonrhythmically-laminated matrix of fine-grained sandstone and mudstone (Plate 7F). Apparent long-axes of clasts within these diamictites are randomly oriented (Figure 8A-D).

Clast-supported diamictites also occur. Some appear massive but have a reverse-graded base (up to 50 cm thick) that rests on a surface slightly eroded into the underlying unit (Plate 7G). A few discontinuous (<5 m), thin (<10 cm), F1 lenses appear to be interbedded with these thick (up to 17 m) units, suggesting that they actually consist of multiple subunits. Above these F1 interbeds a thin, reverse-graded zone is locally apparent. Rare stratified, clast-supported diamictite typically consist of a crudely stratified, poorly-sorted, intact-framework of granule- to boulder-sized clasts with a feldspathic wacke matrix. Stratification consists of a subhorizontal alignment of elongate clasts, a crude bedding defined by poorly developed size-sorting (poor normal- or reverse-graded cycles) and the rare occurrence of discontinuous pebbly-sandstone interbeds which show a poorly developed normal-grading. Apparent long-axes of clasts strongly trend along a southwest azimuth (Figure 8E-G).

Fine-grained units within the higher diamictite package tend to be nonrhythmic, poorly laminated mudstones similar to those described for the lower stratigraphic assemblage. Most occurrences are not associated with coarser-grained, stratified sequences as in the lower stratigraphic

Figure 8. Clast apparent long-axis orientations for diamictites of the Upper Diamictite Complex. Samples sites are shown in Figure 16, Appendix 4. The lithofacies is shown in the upper right corner of each diagram (see Table 1 for lithofacies code). Explanation of symbols as for Figure 4.

packages. In thin section, the nonrhythmic nature of the laminations and diffuse contacts between laminae are readily apparent (Plate 7H). A more regularly laminated and continuous, but nonrhythmic, unit exists in a few places. Diamictite lenses with erosional bases (Plate 7I), lonestones, and discontinuous beds of gravel-sized clasts, are present in a few places within these units.

CHAPTER IV

LITHOFACIES INTERPRETATIONS

4.1 Basal Diamictite Association

The characteristics and facies associations of the basal diamictite suggest an origin as a subglacially deposited, primary basal till (as defined by Boulton and Deynoux 1981; equivalent to the subglacial orthotill of Dreimanis 1983). Although definitions of till (and tillite, the lithified equivalent) vary, most authors agree that original transport and deposition by or from glacier ice is fundamental (see review in Dreimanis 1983). However, there is considerable disagreement on the amount of subsequent water-working or resedimentation a till can undergo and still be classified as a till. Opinions range from allowing no subsequent resedimentation (Lawson 1981), to minor resedimentation without disaggregation (Boulton 1972), or even significant penecontemporaneous resedimentation, including settling through a water column (Dreimanis 1979, 1983; Gravenor et al. 1984). For this study, the relatively restrictive definition of Boulton (1972) is used. The many diamictite units in the study area show a great range of features and facies associations, suggesting a complex depositional history. The discrimination of a tillite in the restrictive sense is regarded as more useful than inclusion of possible tillites that also display resedimentation features compatible with alternate modes of deposition.

Recent papers which summarize criteria for the identification of tillites vs. diamictites of non-till origin include Boulton and Deynoux (1981), Anderson (1983), Dreimanis (1983), and Gravenor et al. (1984). All of these authors stress that no one criterion uniquely

differentiates tillite. Only the association of several characteristics can be regarded as a reliable indication of till origin (*sensu stricto*).

The stratigraphic position of the basal diamictite and its relationship to other facies supports a subglacial tillite interpretation. It directly and sharply overlies a glacially scoured and shaped basement or, rarely, another diamictite which is interpreted to be a subglacial, lee-side tillite. The basal diamictite is sharply or gradationally overlain by dropstone-bearing rhythmites or other glacially-derived lithofacies. It is laterally persistent, occurring on paleotopographic slopes, highs and lows.

Lithologic characteristics of the basal diamictite also are typical of basal tills. It incorporates the immediate substratum (lee-side derived breccia). It also contains both far-travelled clasts (plutonics and high-grade metamorphics) and volcanic clasts similar to local lithologies (although most volcanic clasts are not diagnostic of distance of travel, because massive and pillowed volcanics are common throughout the Abitibi Subprovince). The apparent shapes of gravel-sized clasts correspond well to those shown by Boulton (1978) to indicate basal or low-englacial transport paths. The highly spherical and commonly subrounded granitoid clasts are the expected end-member of extensive transport in the basal traction zone of the glacier. Faceted clasts, an intermediate form according to Boulton, are relatively scarce at Cobalt; this may reflect extensive basal transport and/or the difficulty in recognizing this form in two-dimensional lithified exposures. The latter suggestion is supported by Coleman's (1907, 1908) description of faceted and striated (in two or more directions) pebbles and cobbles recovered from underground mine workings at Cobalt.

Both framework and matrix of the basal diamictite exhibit textural

features that are common to tills. The lack of sorting and the mineralogical immaturity (ie "fresh" feldspars and high lithic grain content) are typical of till matrix (Anderson 1983). The high percentage of silt-sized clasts and the subangular, broken appearance of many silt- and sand-sized clasts may reflect comminution in the basal traction zone (as described by Boulton 1978).

The generally massive nature of the basal diamictite is common in basal tills (Boulton and Deynoux 1981, Anderson 1983, Dreimanis 1983, Gravenor et al. 1984). The sporadically distributed and irregularly laminated, upper zone may represent englacially layered sediment. Such deposits have been observed in recent tills by Boulton 1970 and Lawson, 1981, but are rarely preserved within Pleistocene tills (Boulton 1970). A more likely explanation is reworking during deposition of the overlying lithofacies (usually rhythmite). The discontinuous sandstone lenses rarely observed in the basal diamictite also have a counterpart in Pleistocene and recent tills. Kruger (1979) cites thin, distorted, discontinuous sandstone lenses as indicative of basal till, and suggests an origin from local and temporary meltwater concentrations.

The apparent long axis orientations of large clasts within the basal diamictite show a strong northeast-southwest trend. This conforms with the dominant southwest direction of ice movement deduced from stoss and lee structures and derived breccia; similar ice movement has been proposed in other studies (Cooke 1922, Schenk 1965a,b, Lindsey 1967). Orientations of clast long axes parallel to the direction of ice movement is typical of subglacially derived tills (Holmes 1941; Boulton 1971; reviews by Andrews 1971; Domack and Lawson 1985). Up-ice imbrication of clasts is also common in basal tills (Boulton, 1978), but

the exposure type and high induration at Cobalt precludes this type of fabric study.

Rare discontinuous intrabeds of stratified, pebbly sandstone and clast-supported diamictite which occur at the lower contact, or within the basal diamictite, also have parallels in Pleistocene basal tills. Shaw (1977) describes similar units in a thick sequence of melt-out till, and interprets the stratified lenses as the accumulation from small subglacial and englacial meltwater channels. A similar origin is proposed for the stratified intrabeds of the basal diamictite.

The several lines of evidence presented above strongly support a till origin in the restricted sense and, more specifically, an interpretation as a subglacial, primary till. Primary till is commonly subdivided into two major types: lodgement and melt-out (Boulton and Deynoux, 1971; Dreimanis, 1983; Ashley et al. 1985). Lee-side till is a special type of lodgement till according to Boulton 1978. Many of the principal distinguishing criteria for lodgement till (reviewed by Eyles et al. 1982) are lacking in the basal diamictite, including fissility, shear lamination ("smudges" of Kruger 1979) and a systematic jointing pattern. However, it seems unlikely that these features would be preserved in the highly indurated, metamorphosed, post-lithification-jointed, basal diamictite. Most other criteria for the recognition of lodgement till also apply to basal melt-out till (clast orientation and shape for example). Although the presence of stratified intrabeds and thin discontinuous sandstone lenses in the basal diamictite supports a melt out genesis, the basal diamictite lacks sufficient features to conclusively select the appropriate subdivision.

The unusual clast-supported diamictite which overlies the unconformity surface regolith in two paleodepressions also appears to be

a subglacial deposit. The massive, non-sorted nature and occurrence directly below the basal tillite suggests a tillite interpretation.

However, preservation of the regolith in paleodepressions and restricted occurrence of the Dcm in paleodepressions suggests a unique mode of subglacial deposition in which subglacial cavities formed at a south-facing scarp. The unusual diamictite overlying these breccias is interpreted as a subglacial, lee-side deposit in these cavities.

Boulton (1971), Eyles and Menzies (1983) and Hillefors (1973) discussed possible mechanisms of deposition in lee-side cavities. Boulton (1978) termed these deposits lee-side tills. A possible model for the Cobalt occurrences is shown in Figure 9. Basal debris, much of it locally derived, is expelled from the overriding ice due to pressure-release and collects in the cavity. The random orientation of clast long-axes in this diamictite (Figure 4A) may reflect such subglacial expulsion of clasts into a cavity. Lack of stratification and sorting in the clast-supported diamictites or reworking of the north breccia implies that little meltwater was present. This suggests flow of the south breccia downslope may have been a slow, slope-creep event rather than a rapid water-saturated mass flow. The faintly-stratified, matrix-supported diamictite lens below the south breccia suggests some early subglacial meltwater activity.

Figure 9. Model for subglacial deposition in a lee-side cavity based on Hillefors 1971; Boulton 1971; Eyles and Menzies 1983).

4.2 Subaqueous Outwash Fans

The coarsening-upward fan associations are interpreted as deposits of subaqueous outwash fans as defined by Rust and Romanelli (1975), termed subaqueous esker-deltas by Thomas (1984). Many features suggest that deposition occurred in a subaqueous environment: sandstones within the fan associations contain dropstones; the fan lithofacies are at the same stratigraphic level as, and overlain by, diamictite-rhythmite-sandstone lithologies that also contain dropstones; sedimentary structures indicative of subaerial exposures are completely lacking from all lithofacies within the study area; regionally, the Coleman Member is conformably overlain by nonglacial, marine, prodeltaic mudstones deposited below wavebase (Rainbird 1985).

Rhythmites and the nonrhythmic, fine-grained lithofacies are interpreted as lower-fan and fan-distal deposits. Paleocurrent indicators and the lithologic distributions suggest that the southerly-directed meltwater discharges were the only significant current-source in this part of the basin. Laterally equivalent poorly laminated mudstones may represent distal areas where the direct effects of this meltwater input were rarely felt. Similar types of deposits are described from glaciolacustrine lakes by Smith (1978) and Gustavson (1975). Alternatively, if the basin was marine, the poorly-laminated mudstones could reflect normal marine sedimentation in relatively distal areas where the high sediment concentrations and lowered salinity due to high meltwater discharge do not strongly affect the sedimentation patterns (Mackiewicz and Powell 1982; Domack, 1984).

The thin, basal silt-clay rhythmites are interpreted as distal-fan deposits. Whereas a marine environment is possible (discussed in Chapter 5), the characteristics of these sediments are very similar to distal

rhythmites/varves described from glaciolacustrine lakes (Ashley 1975; Gustavson et al. 1975; Gustavson 1975; Ashley et al. 1985). The sharp, non-erosive couplet contacts, lack of current-structures, thicker clay than silt layers, and generally sharp silt-clay contacts are similar to features described from rhythmites formed by sediment-rich interflow/overflows (Ashley et al. 1985; Ashley 1975). These correspond to the distal varves of Bannerjee (1973), lake varves of Gustavson et al. (1975), and Group I varves of Ashley (1975). Ashley et al. (1985) provided a review of known processes of interflow/overflow formation and resultant deposits. They concluded that the differentiation of interflow from overflow deposition is impossible on the basis of sedimentary characteristics alone.

Some couplets in the lower rhythmites are continuous, normally-graded sequences without distinct silt-clay contacts. This is more typical of density-driven, turbid underflow deposits (Kuenen 1951; Bannerjee 1973; Ashley 1975), which can be a result of quasi-continuous distal meltwater underflows or short-lived, slump-generated surge-currents (Ashley 1975; Shaw and Archer 1977). The scarcity of microlaminae in the couplet layers and the transitional silt-clay contact is more consistent with single sudden-event deposition rather than irregular, long-term deposition from meltwater underflow (see discussion in Ashley et al. 1985; p. 197).

The intermediate rhythmites show an increase in multiple silt lamina, complex grading patterns and more evidence for basal currents (deformed flames, rare cross-lamination) in comparison to their distal equivalents. These features suggest deposition predominantly by density underflows as proposed for the Group II varves of Ashley (1975) or

intermediate varves of Bannerjee (1973). Sharp silt-clay contacts are still relatively common, and the silt layer microtextures (laminae, multiple grading) indicate underflow rather than overflow/interflow conditions in many cases. Multiple graded silt laminae within similar Pleistocene and recent rhythmites are commonly attributed to the unsteady nature of the quasi-continuous meltwater underflow or fluctuations in sediment content of the meltwater stream (Ashley 1975; Shaw 1975; Gustavson et al 1975; Smith 1978). Flow types were probably combined with underflows becoming increasingly important closer to the meltwater influx point, changing to overflows/interflows in more distal areas. Slump-generated surge currents also occurred. They best explain rare starved-ripple sequences and single, anomalously-coarse laminae or thin beds of sandstone or coarse siltstone, rarely cross-laminated.

Thicker rhythmites of the upper rhythmite sequences are interpreted as proximal basin deposits or fan bottomsets (delta varves of Gustavson et al 1975; Group III varves of Ashley 1975). Underflows appear to have been the dominant sediment transporting agent, as suggested by the presence of ripple cross-bedding, multiple normally-graded fine sand and silt lamina and local erosion of underlying rhythmites (producing scours and rip-ups). As with the intermediate rhythmites, the multiple coarse-grained laminae probably indicate velocity pulses in the quasi-continuous underflow. Fluctuating discharge velocities and sediment concentrations are well-documented in modern glacial meltwater currents (Smith 1978; Gustavson 1975). Rare, thin clay laminae within multiple sand-silt lamina may indicate pauses in the overall discharge pattern (Ashley et al. 1985). Thicker (up to 5 mm), normally-graded, silt-rich clay laminae are thought to represent periods of low sediment input, an interpretation proposed for similar Pleistocene sequences (Gustavson et

al 1975; Ashley 1975; Ashley et al 1985), These major discharge fluctuations could be seasonal, but the presence of other controls on discharge rates in modern environments makes such a conclusion tentative (see Smith 1978 for discussion). The grading and silt content of these clay laminae may indicate a lack of flocculation as has been proposed by Ashley (1975) for similar clays in her Group III varves.

The massive to faintly laminated sandstone beds which occur within upper rhythmite sections are interpreted as sediment gravity flows off prograding mid- to upper fan regions. The ~~generally~~ massive beds, occasional dish and pillar structures and lack of basal erosion are indicative of transitional grain flow/fluidized flow (Middleton and Hampton 1976), termed liquefied/fluidized flow by Lowe (1976b, 1979). The main grain support method for these flows was probably a combination of dispersive pressure and escaping pore fluid. Loading of these beds into the underlying rhythmites suggests that the entire bed flowed en masse onto the water-saturated muds. These sand accumulations are associated with some of the deformation features in the rhythmites. For example, thrusting of rhythmite layers into the sands (Plate 3H). ~~Where~~ thrusting has not occurred, the basal sandstone contact is deeply loaded with large asymmetric flames of rhythmite showing southward transport. This load and flame deformation of the water-saturated rhythmites was followed in some areas by the decoupling of flame structures on the south edge and downslope thrusting of rhythmite sections. Shear stress caused by the rapid deposition of the sand flow is thought to account for this deformation. Similar but less extensive downcurrent deformation occurs in other subaqueous fans, and was also related to loading by sediment flows (Rust and Romanelli 1975).

Minor, short-displacement, downslope thrusts of rhythmite laminae (Plate 4C) appear to be a result of downslope shear stress. Rare, convolutedly deformed packages of laminae seem to fit the generally postulated origin of liquefaction deformation as discussed by Lowe (1975), and Mills (1983). Convolute bedding and thrust faulting in rhythmites have been interpreted to be indicators of overriding by advancing/readvancing glaciers (Hansen et al. 1961; Moran 1971). However, relative rarity and localized occurrence of these features at Cobalt suggests that they instead reflect minor deformation, probably from downslope drag forces generated by slumps, sediment flows, sudden sediment loading, or normal compaction effects on a slope (as suggested for similar types of deformation by Mills 1983; Visser et al. 1984). Rare clastic dykes of massive sandstone that cut the rhythmites are considered to be dewatering structures where fluidized sands were injected upwards from underlying, overpressured sand units, a process discussed by Lowe (1975). The above methods also can trigger clastic intrusions (Lowe 1975).

A few isolated high-angle normal and reverse faults are probably due to compaction, as suggested for similar structures in the Dwyka Formation in South Africa (Visser et al. 1984). These do not resemble the paired high-angle fault systems seen in Pleistocene sequences and interpreted to be the result of the melting of buried ice blocks (McDonald and Shilts 1975; Boulton 1972; Shaw 1977). No features suggestive of buried ice masses were observed in the study area.

The transitional contact of rhythmite-sandstone units reflects the continuous distal to proximal variations in grain-size and sedimentary structures due to increased velocity and coarser sediment load closer to the site of meltwater influx. A proximal-distal pattern of sedimentary

structures and grain-size variations is a common characteristic of delta or fan deposition, both in glacial and nonglacial environments (Gustavson et al. 1975; Church and Gilbert 1975; Walker 1984).

The thinly-bedded, graded, fine-grained sandstones of the sandstone-rhythmite transition and the lower portions of the continuous sandstone bodies are interpreted to be more proximal equivalents of the finer-grained rhythmites. Deposition is again thought to have resulted from quasi-continuous underflows. The fluctuating nature of these flows is reflected in the grading, occasional ripple forms and small-scale planar cross-laminations that are preserved within these beds.

Climbing-ripple sequences are not abundant in the rhythmite-sandstone transition, in contrast to many Pleistocene and Recent deposits (Gustavson et al. 1975; Jopling and Walker 1968; Ashley et al. 1985).

Where poorly-developed climbing-ripple sequences are developed, the sinusoidal lamination form of Jopling and Walker (1968), termed draped lamination by Gustavson et al. (1975), are most abundant. Flume studies suggest that this structure results from suspension settling during the waning stages of short-period, lower-flow-regime pulses (Ashley et al. 1982). The relative scarcity of climbing-ripple structures at Cobalt must reflect flow strength and/or sediment concentration levels that preclude the formation of this structure.

Planar cross-bedded and occasional trough-crossbedded sandstone and pebbly sandstones of the upper sandstone bodies reflect higher current velocities in increasingly proximal areas. Graded cycles of pebble-granule-coarse sand beds reflect temporal flow fluctuations. Bannerjee and McDonald (1975) interpreted similar gravel-sand cycles in a Pleistocene esker-delta as representing annual flow variations. An

annual periodicity is possible for the Cobalt examples, but existence of non-seasonal controls on meltwater discharge rates makes such a specific interpretation impossible. Rare, isolated beds of massive to faintly stratified, non-graded, clast-supported pebble diamictite within the pebbly sandstones are interpreted to be debris flows from an apex diamictons. These coarse flows may initiate, or be proximal equivalents of, surge-current deposits and other sediment flows seen in the more distal facies.

Variations in the overall coarsening-upward sandstone-pebbly sandstone trend occur. An example is the sudden upward transition in MS-7 (Appendix 1) from coarse-grained sandstone to graded, gravel-pebbly sandstone, then to cross-bedded sandstones. This and similar sequences may reflect migration of discharge currents across mid- to upper-fan areas.

The clast-supported pebble-cobble-boulder diamictites which commonly cap the sandstone units are thought to be deposits at the fan apex, which roughly corresponds to the subglacial meltwater influx site. The proximal gravel facies of other subaqueous outwash fans have similar characteristics (Rust and Romanelli 1975; Rust 1977; Cheel and Rust 1982; Thomas 1984). The poor sorting, crude stratification and poorly-developed grading patterns suggest rapid deposition from meltwater streams suddenly exiting from confined subglacial/englacial tunnels. This interpretation is supported by the parallel-to-flow clast long-axis orientations characteristic of some of these diamictites (Figure 7G-J). These orientations can be due to saltation transport of high gravel concentrations near the bed (Rust 1977; Walker 1984). The high energy conditions required for saltation transport of cobbles and boulders is dissipated after exit of the meltwater from the tunnel into an unrestricted basin. Some bedload rolling of clasts is indicated by

the slight transverse-to-flow orientations. A lack of observed channels is common to the Cobalt deposits and to those of Rust and Romanelli (1975), a feature Rust (1977) felt could be due to the difficulty in distinguishing such forms in the very coarse-grained material.

In some sequences, cyclic, normally-graded pebble-granule-coarse-grained sand beds occur above the thick, crudely-stratified, clast-supported diamictite. Textures and sedimentary structures are similar to those in the graded cycles occurring below the diamictites. They could be due to lateral migration or waning flood-stage currents of the main meltwater flow in proximal areas of the fan, or might reflect a rapid retreat of the ice-front, causing overlap of more distal upper fan facies onto the fan apex gravels. Possible ice-front controls on sedimentation are discussed in more detail in Chapter 5.

The thinner, less extensive, fining-upward fan associations usually contain lithologies and sedimentary structures similar to those of the coarsening-upward fans. Similar overall proximal-distal trends are observed, but with a reverse order of vertical sequences. In the best exposed example (base of MS-1, Appendix 1); the crudely-stratified proximal gravels of the larger fans are not present. The lowest unit consists of cyclic, normally-graded clast-supported diamictite, pebbly-sandstone beds which grade vertically into thinly-bedded, dropstone-rich, proximal rhythmites. Fluctuation in flow strength of meltwater underflows again appears to be responsible for these cyclic deposits. The relative thinness of these associations and their fining-upward trends, suggest deposition during short periods of high meltwater activity, combined with rapid retreat of the ice front (discussed in Chapter 5). The random orientation of clast apparent long-axes in these

beds is unexpected. Possibly it reflects saltation and bedload rolling transport in a small channel combined with fluctuating (waning overall) currents. This could cause preferred orientations both parallel and perpendicular to the flow direction, in this case giving a seemingly random overall pattern. The possible bimodal trend of Figure 7L supports this hypothesis.

4.3 Lower Assemblage - Heterolithic Diamictite Complex

The diamictites, sandstones and minor fine-grained lithofacies of this assemblage occur in interfan areas where meltwater currents were not dominant depositional agents. Most of these lithologies are interpreted to be the deposits of sediment gravity flows, originating from prograding fans, ice-marginal banks or perhaps from flows off the ice sheet itself.

Sediment gravity flow (also called sediment flow or mass flow) is sediment transport in which movement parallel to the bed is due to gravity (Middleton and Hampton 1976). It encompasses a wide range of flow types and resultant depositional sequences. The classification scheme and nomenclature of Lowe (1979, 1982), used here, is based on the nature of the dominant sediment-support mechanism and the flow behaviour (plastic or fluid), and differs slightly from the Middleton and Hampton (1976) classification as shown in Table 2.

Rhythmite units are common at the base of, and intercalated within this heterolithic complex. These were interpreted earlier as distal fan interflow/overflow deposits. Poorly-laminated mudstones were interpreted as deposits in the most distal areas from the meltwater

Influx sites, but not necessarily distal with respect to the ice front.

Whereas most diamictites of the interfan complex overlie sandstones

or rhythmites of fan associations, some occur directly on basal diamictite or the unconformity surface. These matrix-supported units resemble the basal diamictite, but are irregularly-stratified with a faint, sometimes distorted lamination or bedding. Long-axis orientations of gravel-sized clasts within these stratified diamictites show a slight reorientation with respect to the basal diamictite (Figure 7E,F). The adjacent stratigraphic association and similarities in texture and composition to the basal diamictite suggests a similar till origin. However, the presence of distorted stratification and the pebble-fabric trends indicate that resedimentation has occurred. The poor sorting, lack of grading, non-erosive contacts and homogeneous appearance of these diamictites suggests debris flow transport. Their stratigraphic position and facies association supports an origin as ice-marginal debris, most likely as small morainal banks similar to those described by Powell (1981, 1984) that form at the margin of subaqueously-grounded ice sheets. These banks form from englacial and subglacial melt-out of debris, with debris possibly added from meltwater currents or flows off nearby fans. A slowly retreating or quasi-stable grounding line is implied, possibly coupled with minor (perhaps winter) advances of the ice sheet causing the push moraines described by Powell (1981, 1984) and May (1977). Clast shapes are similar to those of the basal diamictite, suggesting subglacial-englacial transport with little included supraglacial debris, based on studies of boulder-shape and ice-transport paths (Boulton 1978; Dowdeswell et al. 1985). This supports an origin as banks formed at the ice-sheet grounding line since

englacial layers are not thought to be significantly deformed or sheared upward in the front of large, subaqueously grounded ice sheets (Powell

FLOW TYPE		SEDIMENT SUPPORT MECHANISM
Turbidity Current Fluidized Flow Grain Flow Debris Flow		Fluid Turbulence
		Escaping Pore Fluid
		Dispersive Pressure
		Matrix Strength
FLOW BEHAVIOUR	FLOW TYPE	SEDIMENT SUPPORT MECHANISM
FLUID Flow	- High Density Turbidity Current - Low Density Fluidized Flow	Fluid Turbulence Escaping Pore Fluid (Full Support)
	D e n s i t y G r a i n f l o w L i q u e f i e d F l o w	Escaping Pore Fluid (Partial Support)
PLASTIC (Bingham) Flow	D e n s i t y G r a i n f l o w G r a i n F l o w	Dispersive Pressure
	M u d f l o w o r C o h e s i v e D e b r i s F l o w	Matrix Strength and Matrix Density

TABLE 2. Sediment gravity flow classification schemes of Middleton and Hampton 1976 (Top); and Lowe 1979 (Bottom).

1984; Anderson et al. 1984). These banks are highly unstable, with flows off the bank-slopes common and complete collapse possible when a previously stationary grounding-line retreats (Powell, 1984). Shock waves from ice-calving may also initiate flows off the unstable slopes of these banks and from the outwash fans (Rust 1977; Powell 1984). At Cobalt, these banks are interpreted to have collapsed by a series of debris flows. This term is used in the general sense of Lowe (1979) for plastically behaving flows with the sediment supported by a combination of dispersive pressures, matrix strength and minor escaping pore fluids.

The clast orientations at both sites show a weak secondary trend parallel to the underlying basal diamictite. This weak trend may reflect the original till orientation, with the main trend due to reorientation of clasts during mass flow off the banks. Lawson (1979, 1981) documented preferred orientations both parallel and perpendicular to flow in sediment flows of water-saturated tills in Alaska. Similar orientations were predicted by May (1977) and reported by Evenson et al. (1977) for subaqueously resedimented diamictons.

Similar remobilized subaqueous tills have been documented in Pleistocene or pre-Pleistocene deposits and termed flow tills (Evenson et al. 1977; Dreimanis 1982), lacustrotill (May 1977) or ice-marginal debris flows (De Jong and Rappol 1983; Vissor 1983). Facies associations and stratigraphic positions are major elements supporting a till origin. In isolation, features of these units reflect debris flow transport, but not necessarily a till origin. For this reason the terms "flow till" or "lacustrotill" are rejected in favour of subaqueous debris flow deposits (a convention supported by Gravenor et al. 1984; and Powell 1984).

Matrix-supported diamictites interbedded in higher levels of the

interfan complex are also interpreted as debris flows. These massive, poorly-sorted diamictites show a lack of lateral continuity, non-erosive basal contacts, and interbedding with other sediment gravity flows, indicating that these units are not tills deposited by readvances of the ice sheet. Instead, these features are typical of cohesive debris flows which travel downslope with grain support from matrix strength and density. They are deposited by mass emplacement when the gravity-caused shear stress drops below the yield strength of the moving material (Lowe 1982).

Rose diagrams for two of these units (Figure 7A,D) show strongly preferred orientations (NNE-SSW). Evidence for flow directions were not observed in these specific diamictites. Studies by Enos (1979), Lindsey (1968), Middleton and Hampton (1976) suggest that parallel to flow orientations of clasts might occur within debris flows. However, Lawson (1979, 1982) and Evenson et al. (1977) showed that both parallel- and transverse-to-flow orientations can be developed in water-saturated debris flows originating from glacier debris. Thus the use of fabric as the only means of flow direction indicator is not warranted. The strong central tendency of clast apparent long-axes in these diamictites argues against a dropstone diamictite interpretation with ice-rafting as the major source of the clasts. Domack (1983) and Domack and Lawson (1985) showed that ice-rafted diamictites have a very weak or random horizontal orientation of clasts. Anderson (1983) suggested that bottom currents might slightly realign ice-rafted clasts after deposition. The strength of the fabric patterns for these diamictites seems greater than could be attributed to bottom currents alone.

Crudely-stratified, rarely poorly-imbricated diamictites within the

interfan complex contain features similar to those of the massive diamictite, again suggesting debris flow transportation. However, the poor imbrication, slightly erosive lower contacts, and evidence of dewatering at upper contacts in some units suggests that grain-support mechanisms also included fluid effects and slight turbulence (Lowe 1976, 1979; Middleton and Hampton 1976). Similar features have been interpreted as the result of density-modified grain flows of gravels (Lowe 1982; Lash 1984), a transitional debris flow - high-density turbidity flow process (Lowe 1979). Enos (1977) showed that erosive turbulence can occur in initial stages of debris flow. This may account for the slightly erosive contacts in places observed at Cobalt. As initial flow velocities decrease, the turbulence changes quickly to more typical laminar conditions at the boundaries of the debris flow (Enos 1977; Middleton and Hampton 1976; Lowe 1979, 1982). Laminar conditions could cause the preferred clast-orientations noted on horizontal surfaces of some of these diamictites, as well as the observed subhorizontal orientation of many clasts in vertical sections. Similar orientations were predicted by Lindsey (1968) for debris flows and documented by Lash (1984) in gravelly, density-modified grain flows.

Dropstones within these flows indicate that ice-calving was occurring penecontemporaneously. Rare clusters of intact-framework gravel-sized clasts may also be related to ice-calving. Melt-out debris commonly accumulates on recent iceberg surfaces and, with overturning, a gravel mixture is deposited on the basin floor in localized concentrations (Powell 1981; Ovenshine 1970). Pleistocene occurrences of these dump structures were reported by Thomas and Connell (1985). The clast concentrations at Cobalt are exposed on smoothed horizontal surfaces, and thus the conical mound shape expected for these

structures could not be documented. The downslope oriented grooves uniquely preserved between two flows probably are due to clasts sliding at the base of the upper debris flow. This is a feature that Lowe (1979) suggested could be common at the base of debris flows. Middleton and Hampton (1976) interpreted similar bedding-plane grooves as slide marks formed when blocks of debris produced by tensile separation slid rigidly ahead of the main debris flow.

Clast-supported diamictites within the interfan areas are interpreted as high-density sediment gravity flows, probably originating from upper-fan meltwater deposits. Channelized, stratified diamictites could have originated as erosive high-density turbidity currents. Similar, discontinuous units were described by Walker (1984) and Hein (1982) as pebbly-sandstones and were related to suspension-sedimentation of gravels as turbulent flow begins to wane. Sandy upper layers form during continued deceleration of the flow. This is similar to the process proposed for the graded-stratified conglomerate model of Walker (1975). In cases where the channelized sequence contains multiple beds of graded clast-supported diamictite and pebbly sandstone, surging flows are suggested. Surging flows show an oscillating decline of velocity, competence and capacity. Each surge exhibits an abrupt velocity increase followed by a gradual deceleration, resulting in repetitive grading and structure divisions (cf. Lowe 1982).

These channelized sequences can resemble the cyclic, graded, gravel-to-pebbly sandstone beds in the upper fan areas. They may represent channels in lower fan areas which were formed by unusually strong meltwater underflow currents flowing down the fan slope. Such an underflow is technically not a sediment gravity flow, because the

sediment is being transported by the moving fluid. The scarcity of these sequences, and their association with other deposits of sediment gravity flow origin, supports the first interpretation presented.

More extensive clast-supported diamictites of interfan areas contain features typical of resedimented conglomerates as outlined by Walker (1975, 1984). The massive, non-graded, non-erosive, poorly-sorted lithotypes correspond to the disorganized-bed unit of Walker, and an origin as cohesive debris flows is suggested. Rodine and Johnson (1976) and Hampton (1979) demonstrated experimentally that, when clast densities are high (up to 95%), the matrix strength of the flow is unchanged, but the greatly increased buoyancy allows support of isolated large boulders for great distances on very low slopes. This may explain the irregular upper surface of some of these units, in which large clasts commonly project in to, and are draped by, the overlying unit. Projecting clasts have been cited as evidence for cohesive debris flows (Middleton and Hampton 1976; Lowe 1979, 1982; Nemec and Steel 1984).

Some massive diamictites have a vaguely-defined, coarser-grained central portion. This corresponds to the rigid plug zone thought to be a common feature of cohesive debris flows (Middleton and Hampton 1976). Enos (1977), Hampton (1975) and Middleton and Hampton (1976), demonstrated that in subaqueous debris flows, zones of shearing occur at the bottom and top of the flow, but the inner zone acts as a rigid plug. Hampton (1975) showed that competence is significantly greater in the rigid inner plug, and thus grain sizes should be coarser in this zone. Because the rigid plug migrates during flow, sharp intraflow boundaries are unlikely to form (Middleton and Hampton 1976).

Figure 7B shows the apparent long axis orientations of clasts in a clast-rich (partially clast-supported), diamictite which was deposited

over a slightly eroded sandstone (shown in Plate 6G). A poorly defined, nonsorted, internal plug of larger clasts, clasts projecting at the top, and its general lack of sorting all suggest a debris flow origin (cf. Middleton and Hampton 1976; Lowe 1982). The erosive lower contact is not typical of debris flows, and suggests some turbidity flow in initial stages at the base of the otherwise non-turbulent flow. The nature of the lower erosive contact, geometry of the diamictite body, and estimates of the local paleoslope all suggest that flow was roughly to the northwest. The strong preferred orientation thus is transverse to flow, probably reflecting clast-clast interactions or rolling of lower clasts as bedload. A slight parallel-to-flow orientation is also apparent, perhaps the result of laminar flow at flow edges during late stages of flow (Lindsey 1968).

The massive, clast-supported diamictite that contains fractured boulders (described in detail on pages 41-42) also appears to have formed as a cohesive debris flow. The massive nature, lack of sorting or grading, and presence of clasts projecting from an irregular upper surface, are, as discussed above, typical of cohesive debris flows. Although fractured boulders within cohesive debris flows are rare, Johnson (1970) documents recent cases of boulders fractured prior to flow, transported passively within subaerial debris flows and emplaced with the pieces only slightly separated. A similar (but subaqueous) origin is suggested for the fractured boulders at Cobalt. The original fracturing may have been a freeze-thaw or pressure effect related to subglacial or englacial transport. Alternatively, clast interactions within the flow could have caused the final separation of partially fractured boulders. The matrix density and strength of a cohesive debris flow could keep the pieces from separating widely, especially if

they were transported in a rigid plug zone. Infilling of the slight separations could occur either during flow or in the last stages of mass emplacement, perhaps due to a slight kinetic sieving mechanism similar to that proposed by Naylor (1980).

Inverse- to normally-graded and normally graded units, both with slightly erosive and/or loaded bases, are interpreted as high-density flows of the type described by Walker (1975) and Lowe (1982). The grading types suggest sediment-support mechanisms in addition to matrix strength and density. Bouyancy forces and dispersive pressure probably are major additional support mechanisms in these types of flows (Lowe 1976a, 1982; Lash 1984), termed density-modified grain flows. This is a type of flow transitional between cohesive debris flows and high-density turbidity flows as defined by Lowe (1976a, 1982; see Table 2). Inverse grading at the base of some units may reflect a sieving mechanism in which smaller grains displace larger grains upwards (Naylor 1980). Alternatively, a traction carpet layer can deposit a basal inversely-graded zone when intergranular dispersive pressure at the base of a slightly turbulent flow rapidly "freezes" as the velocity drops below the minimum necessary to maintain dispersive pressure (Lowe 1976a, 1982).

Occasionally observed inverse- to normally-graded sequences at Cobalt are interpreted according to the models of Walker (1975) and Lowe (1982). Inverse grading is formed from a highly-concentrated traction carpet layer, and normal grading represents direct suspension-sedimentation of coarser suspended gravel. In other units, extreme flow unsteadiness resulted in direct suspension-sedimentation without the development of a traction carpet, depositing a normally graded clast-supported diamictite. The last two diamictite types discussed correspond to the inverse- to normally-graded, and normally-graded

conglomerates of Walker (1975, 1984) and the R_2 and R_3 of Lowe's (1982) ideal gravelly flow sequence.

Both Walker and Lowe suggested that proximal to distal changes are apparent in flow deposits (disorganized to inverse- to normally-graded, to graded bed types in Walker's 1975 model). However, extreme flow separation is probably common, resulting in separated deposition sites without preserved lateral transitions (Lowe 1982). At Cobalt, these lateral transitions could not be documented within single units, suggesting that such flow separations occurred.

Some interfan clast-supported diamictites are directly overlain by thin sandstone or mudstone beds or laminae which are usually parallel or cross-laminated. These probably reflect winnowing of finer material from the gravelly, high-density flows. Hampton (1972) and Krause and Oldershaw (1979) discuss such a process where low-density turbulent clouds develop on the top of the main flow due to backward streaming of displaced water and sediment at the head of the flow. Deposition of the gravelly sedimentation wave is followed by deposition from a separate low-density turbidity current (shown in Figure 11). At Cobalt, these planar-laminated or thin-bedded sandstones and mudstones with ripple bedforms are interpreted as the B and C divisions of a Bouma sequence.

Coarse- to medium-grained interfan sandstone beds are interpreted as high-density sandy flows. These may be the residual portions of gravelly flows which continued downslope after deposition of the coarser gravel (Lowe 1982). This is a flow separation effect similar to that described previously. Grading sequences are similar to those seen in the clast-supported diamictites, and the processes probably were essentially the same, with density-modified grain flows and sandy, high-

density turbidity flows accounting for most of these isolated units. Some are overlain by thin, planar-laminated or rippled fine-grained sandstone or mudstone units. These are interpreted as B and C divisions of the Bouma turbidite model, reflecting waning turbulent flows velocities.

4.4 Upper Assemblage - Heterolithic Diamictite Complex

The restricted and in most places poorly-exposed occurrence of this assemblage hinders an extensive discussion of its origin. There is no direct evidence for a sudden change in depositional environment, or of an unconformity between the lower stratigraphic assemblage previously discussed and this complex. However, whereas the lower diamictite assemblage appears to occur in areas laterally equivalent to those of the subaqueous outwash fan associations, the upper package does not include well-developed rhythmite/sandstone/clast-supported diamictite associations. This suggests a significant change in the depositional environment of the upper assemblage.

Fine-grained lithofacies of this upper assemblage commonly consist of discontinuous silt and clay laminae of variable thickness with diffuse gradational contacts. These are in sharp contrast to the lower rhythmite units, interpreted to have been deposited by meltwater underflows and proximal interflows/overflows. The non-rhythmic laminae could reflect deposition in areas distal from the meltwater input sites. The diffuse contacts and discontinuous laminations are similar to features described by Mackiewicz et al. (1984) for distal laminated muds deposited by tidewater glacier meltwater in the Glacier Bay fjords of Alaska. Deposition is by suspension-settling of material transported by turbid overflows and/or interflows. Clay flocculation causes deposition of clay and silt at similar rates, resulting in a poorly-laminated

mudstone. The site of deposition is distal with respect to underflow deposits, but can still be within hundreds of metres to a few kilometres of the ice-front (Mackiewicz et al. 1984). This process has also been observed in Canadian Arctic fjords (Gilbert, 1983). Domack (1983) described similar mudstones (his pebbly-mud lithofacies) from a ice-proximal, Pleistocene glaciomarine environment. The similar features in the fine-grained lithofacies of the upper assemblage at Cobalt suggest comparable deposition in a glaciomarine environment, although not a fjord. This might reflect a significant change in the basin from lacustrine to marine conditions, or increased salinity effects in an ice-distal marine environment with deposition of the lower strata mimicking lacustrine conditions due to extreme meltwater input and sediment concentrations. These possibilities are discussed in detail in the next chapter. Single beds of diamictite or rarely, sandstone that occur within these mudstones are interpreted as sediment gravity flow deposits in areas of otherwise quiescent bottom conditions.

Dropstones are common within the upper assemblage mudstones, in contrast to underlying fan association rhythmite, where dropstones are relatively rare in the distal deposits. Some poorly-laminated mudstones contain abundant gravel-sized clasts; distributed randomly throughout the finer-grained matrix. Many of these clasts pierce mudstone laminae, implying a dropstone origin. These gravel-rich mudstones are a type of matrix-supported diamictite, apparently formed by introduction of the larger clasts into the mudstones. The term dropstone diamictite (Powell 1984) seems applicable to these units. Pebbly mudstones of similar origin were termed compound para-tills by Anderson et al. (1980), but use of the term "till" for these deposits is inappropriate in view of the definition of till used in this study.

Some matrix-supported diamictites are massive and unsorted. These appear to be more extensive than the similar diamictites of the lower assemblage. An origin as subglacial tills deposited during a readvance of the ice sheet is considered unlikely, because major glaciotectonic deformation features are absent in the underlying strata. Also, there is no evidence of erosion, shaping, or incorporation of the substratum. Clast apparent long-axis orientation data for these diamictites supports a non-till interpretation. The random patterns (Figure 8A-D) are in sharp contrast to the strong trends typical of subglacially deposited tills (Holmes 1941; Boulton 1971).

Possible alternative origins for these diamictites are as dropstone diamictites or cohesive debris flows. Direct evidence to discriminate between these two is lacking in the study area. The presence of the probable dropstone diamictite discussed previously supports a similar interpretation for the massive units. However, clast-supported diamictites within the upper assemblage contain evidence of sediment gravity flow origins (discussed below). Thus, a facies association approach is inconclusive. The random orientations of large clasts are characteristic of dropstone diamictites (Domack 1983; Lawson and Domack 1985; Anderson 1983), but can also occur in debris flows (Lindsay 1968).

Clast-supported diamictites of this upper assemblage are similar to those of the interfan areas. The inversely-graded zone at the base of otherwise massive units suggest traction-carpet deposition at the base of high-density flows, either as debris flows or as density-modified grain flows of the type discussed by Lowe (1982) and Lash (1984). The presence of a preferred long-axis orientation of gravel-sized clasts within these units supports this interpretation. Baker (1975) and Hein

(1982) suggested that unimodal orientations in similar resedimented conglomerates are parallel to the dominant flow direction. This could not be confirmed at Cobalt due to a lack of independent paleocurrent or paleoslope evidence for these or adjacent lithotypes. Fine-grained interbeds that occur between poorly-defined subunits of this clast-supported diamictite type probably reflect sedimentation between multiple flow events.

Clast-supported diamictite with crude-stratification and poorly-developed, normally-graded sequences are interpreted as deposits from high-density, surging flows of the type described by Hein (1982) and Lowe (1982). Extreme flow unsteadiness can cause crude, normally-graded sequences as flow velocities fluctuate due to flow separation effects (Hein 1982; Lowe 1982). Pebbly sandstone interbeds at the top of these units reflect deposition during the waning stages of transportation, as Walker (1975, 1984) suggested in his general model for graded-stratified, resedimented conglomerates. The strong unimodal trend of clast apparent long-axis orientations (Figure 8E-F) is typical of these types of gravity flows, and should parallel the main flow direction (Walker 1975; Hein 1982; Massari 1984). Independent paleocurrent evidence to confirm this interpretation is lacking in units of the upper assemblage.

CHAPTER V

CHARACTERISTICS AND SUMMARY OF THE GLACIOGENIC PALAEOENVIRONMENT AT COBALT

5.1 Regional Glacial Setting

The extensive glacial deposits of the lower Gowganda Formation reflect continental-scale glaciation (Lindsey 1969, 1971). Lindsey proposed an ice sheet model for this deposition, based mainly on pebble-fabric and paleocurrent studies. At Cobalt, the stratigraphic relationships and gentle paleotopography also suggest deposition beneath an ice sheet, as opposed to ice tongues or valley glaciers.

The lateral equivalence and intercalation of diamictites and sandstones with the dropstone-bearing fine-grained lithofacies indicates a subaqueous environment of deposition. Dropstones in the sandstones and the lack of sedimentary structures indicative of subaerial exposure also support this interpretation. Studies from regions to the north (Miall 1983; Long 1985) and south (Young 1981a, 1985; Miall 1985; Lindsey 1971), also suggest that lower Gowganda Formation deposition was subaqueous. Thus, all preserved parts of the formation appear to have been deposited in a subaqueous environment. The regional extent defines a basin of considerable size, and if correlations of this formation with other early Proterozoic glacial strata of interpreted subaqueous deposition are correct (Young 1973; Marmo and Ojakangas 1984), an even larger basin is implied. This large size does not require a marine basin, as glaciolacustrine environments of this scale existed during the Pleistocene Epoch. Consequently, in the continental margin tectonic setting proposed for upper Huronian Supergroup deposition, the Cobalt area would have occupied an inner shelf zone in the sense of Gravenor et al. (1984), where marine or lacustrine conditions are not specified.

5.2 Glaciomarine vs. Glaciolacustrine Deposition

The regolith on the unconformity surface indicates subaerial exposure before glaciation, and this could be used to support a glaciolacustrine interpretation for subsequent Coleman Member deposition. However, coupled with an already subsiding continental margin tectonic setting, isostatic loading due to initial ice sheet advance could have resulted in subsidence of the unconformity surface below sea level. Thus the unconformity surface regolith does not preclude a glaciomarine interpretation.

The observed lithofacies could form in either a freshwater or saline basin, with the possible exception of the fine-grained rhythmites. Lindsey (1966, 1969, 1971) considered this lithotype, which he interpreted as varves, to indicate a freshwater environment for the northern occurrences of the lower Gowganda Formation, including the Cobalt area. Legun (1981) also suggested a freshwater origin for the Cobalt strata based on this single criterion, although he later (1984) speculated that the basin may have been marine.

The rhythmites in the Cobalt area are very similar to some glaciolacustrine rhythmites in grading patterns, contact relationships and proximal-distal variations. The formation of the proximal rhythmites by meltwater underflow deposition also appears to support a glaciolacustrine interpretation. Modern observations document that where meltwater enters a marine environment, overflows or possibly interflows form due to freshwater-saltwater density contrasts (Gilbert 1983 presented a recent discussion of these processes). Suspended sediment increases the density of the meltwater, but probably not enough to overcome buoyancy effects except in unusual cases (Kuenen 1951;

Mackiewicz et al. 1984). However, Mackiewicz et al. (1984) documented underflow deposits of fine-grained sand/silt-clay couplets in ice-proximal (<0.5 km) areas of Glacier Bay, Alaska. They attributed formation of these underflows to the added density effects of a high bedload concentration of sediments in subglacial streams, and to the unique hydraulic conditions of subglacial streams (pipe-flow rather than open channel flow). These hydraulic differences suggest that suspension sedimentation may be more uniform and in higher concentrations in subglacial streams than in open channels. Sediment loads can also be increased after discharge by entraining morainal bank debris, or by turbulent mixing at the site of discharge due to the hydraulic jump effect (Mackiewicz et al. 1984). Domack (1984) cited similar processes to explain rhythmic interbedding of sands and muds and varve-like, laminated silts and muds in a Pleistocene glaciomarine sequence in the Puget Sound of Washington. He (and Gilbert 1983) also suggested that where large volumes of meltwater enter a marine environment, a dilution effect can occur, decreasing the salinity and, as a result, reducing the density contrast between inflowing meltwater and the sea water in proximal areas.

Both Mackiewicz et al. (1984) and Domack (1984) documented proximal to distal changes in predominant flow types with respect to deposition of fine-grained laminae (fine sand, silt and clay). They observed that underflows in proximal areas change distally to interflows/overflows as sedimentation concentration and perhaps salinity-dilution decreases. In the most distal areas, flocculation produces poorly-laminated mudstones rather than interlaminated silt-clay couplets. This general sequence corresponds well with the interpretation at Cobalt of underflow transport for proximal couplets and interflow-overflow transport for the

more distal couplets. The non-rhythmic, poorly-laminated mudstones at Cobalt correspond to areas of normal salinity and low sediment concentrations. Similar underflow to overflow/interflow changes can occur in glaciolacustrine sequences, but generally this applies only if the glacier is not present within the lake basin (Ashley 1975; Ashley et al. 1985). In ice-contact lakes, underflow deposition appears to dominate even in areas distal to the meltwater influx (Ashley et al. 1985; Gustavson 1975). The evidence for ice-contact, subaqueous deposition is abundant at Cobalt, therefore the previous discussion suggests a glaciomarine interpretation is warranted.

5.3 Ice Sheet Characteristics - Lower Stratigraphic Units

The upper assemblage of the heterolithic diamictite complex contains lithotypes and associations which are in some respects unlike those of the underlying strata. The lower strata (basal diamictite, subaqueous outwash fan and interfan [lower heterolithic diamictite complex] associations) form the bulk of the well-exposed areas in Cobalt, and this has resulted in a more thorough understanding of the depositional processes for the lower stratigraphic units at Cobalt. For this reason, the conclusions regarding ice sheet characteristics and its controls on sedimentation presented below apply only to the lower stratigraphic units. A brief discussion of possible ice sheet controls on the upper stratigraphic units is presented separately.

Grounded vs. Floating Ice Sheet Models

Presence of an extensive, subglacially deposited tillite, rare lee-side tillite, and a shaped and quarried unconformity surface indicate that the ice sheet was grounded during at least the initial advance. The presence of basal tillites at Cobalt is consistent with glaciomarine

deposition from a grounded ice sheet. Subglacial deposition beneath a grounded ice sheet should produce the same deposits whether the ice sheet is grounded subaqueously or subaerially (Powell 1984). Cenozoic age basal tills are recognized throughout the Antarctic continental shelf and probably reflect subglacial deposition hundreds of metres below sea level (Anderson et al. 1980a).

At Cobalt, the recognition of morainal banks and subaqueous fans also indicates deposition at the grounding line of a subaqueously-grounded ice sheet (Powell 1984, Rust and Romanelli 1975, Gravenor et al. 1984, Edwards 1984). This type of ice-proximal deposition can occur at the front of an ice-sheet that terminates at an ice cliff, termed a tidewater glacier by Powell (1981, 1984). Similar deposition can occur at the grounding line of an ice sheet where it has decoupled from the basin floor to form an ice shelf (Gravenor et al.; Powell 1984). At Cobalt, the distribution of dropstones provides strong evidence to support a tidewater glacier model. A rapid decrease in the abundance of dropstones is apparent in increasingly distal rhythmites of the subaqueous outwash fan associations. Proximal rhythmites in the western portion of the study area consist of >10% dropstones in some sequences. In contrast, dropstones make up <1% of the distal rhythmites. Drewry and Cooper (1981), Powell (1984), and Eyles and Miall (1984) cited evidence to show that ice shelves deposit basal and low englacial debris by undermelting and ice rain-out within a short distance of the grounding line (a few km according to Drewry and Cooper). This suggests that in an ice shelf environment, dropstones should occur in the distal rhythmites (still within 100's or a few thousand metres of the meltwater influx) in approximately similar quantities as in the proximal.

rhythmites. In contrast, Ovenshine (1970) observed that directly following ice-calving, icebergs in Glacier Bay undergo an initial period of fragmentation and rapid overturning before stabilization. Many icebergs calve from the base of subaqueously grounded ice fronts (Gustavson 1975, Anderson *et al.* 1980b; Powell 1983) and contain significant debris. This initial fragmentation thus should yield abundant ice-rafted debris in ice-proximal positions. Boulton and Deynoux (1981) suggested that in open marine conditions, icebergs are rapidly swept out of the ice-proximal zone. A combination of initial instability and rapid transport of icebergs could account for the variations in dropstone abundances at Cobalt. The interpretation of rare clast-clusters in the Cobalt strata as having resulted from iceberg overturns also supports a tidewater glacier model. This type of feature could not occur beneath an ice shelf (Powell 1984).

Tidewater glaciers can be grounded in considerable depths of water. Powell (1984) cites a theoretical limiting depth of approximately 250 m, although ice sheets ground below 310 m in Antarctica (Robin 1979). Whereas the abundance of dropstones at Cobalt indicates that ice-calving was common, no iceberg-contact features are preserved within the strata. These could include grounding structures such as those documented by Thomas and Connell (1985), impact marks (Powell, 1983) and ice-scour gouges (as in Dredge, 1982). Anderson *et al.* (1984) observed tabular icebergs with drafts exceeding 200 m, but these were calved from ice shelves and probably exceed the size of icebergs originating from tidewater glaciers. Observations at tidewater ice fronts suggests that ice calving impact rarely occurs below 100 m (Powell 1983). Based on the preceding discussion, a conservative estimate of water depth at Cobalt during deposition is 50-300 m.

Retreat Rate of Ice Sheet

The lack of deformation or erosion features normally associated with overriding of proglacial sediments by an advancing glacier suggests that deposition occurred during overall retreat of the ice sheet. However, the coarsening-upward nature of the fan associations suggest that retreat rates were sufficiently slow to allow progradation to occur. A rapid retreat should cause deposition of fining-upward subaqueous fan associations (Rust and Romanelli 1975); minor advance and quasi-stationary periods in ice-front position could have occurred without significantly changing the patterns of deposition. A slow retreat rate is also compatible with the formation of morainal banks at the grounding line (Powell 1981, 1984).

Basal Thermal Regime

The basal thermal regimes of glaciers have been generalised into wet-based (temperate, free water at base) and dry-based (cold, frozen to bed) types (Edwards 1978). However, the actual regimes are complex, with wet- and dry-based sections present within the same glacier and conditions at a single position varying over daily, seasonal, or longer time periods (Powell 1984; Eyles et al. 1983). At Cobalt, the abundance of meltwater deposits suggests that wet-based conditions predominated near the grounding-line during deposition of these sediments. The data provided by this study do not allow a more detailed interpretation of the basal thermal regime at Cobalt.

5.4 Ice Sheet Characteristics - Upper Assemblage of the Heterolithic

Diamictite Complex

A tidewater ice sheet model is proposed for deposition of the subglacial sediments, subaqueous fans, and the interfan deposits (most of the strata exposed at Cobalt). In the overlying assemblage of the heterolithic diamictite complex, a lateral variation in frequencies of dropstones, and the presence of clast concentrations suggestive of iceberg overturn deposits, were not observed. This can be attributed to less extensive exposure, but the presence of dropstone diamictite, and of massive diamictite with random clast orientations, suggests a change in ice-sheet characteristics.

The absence of glaciotectonic deformation structures, or evidence of erosion and incorporation of underlying material in this sequence, indicates that readvance did not involve a grounded ice sheet. The lack of such features has been cited in studies of Pleistocene deposits to support ice shelf depositional models (Eyles and Eyles 1983, McCabe et al. 1984). Ice shelf deposition at Cobalt would account for the random long-axis orientations observed in the massive diamictite, and also for the presence of dropstone diamictite. The non-rhythmic nature of the poorly laminated mudstones and the lack of fan associations suggests little direct deposition by meltwater currents. However, there is no evidence of a major retreat of the grounded ice sheet prior to deposition of this upper assemblage. Thick associations of dropstone-poor, non-rhythmically laminated mudstones would be expected if normal marine conditions developed due to a significant retreat of the ice sheet prior to the readvance. Such a lithotype is not present at Cobalt. A more likely possibility is that partial decoupling of the ice sheet occurred to the north of the study area so that the readvance was

of a partially floating ice sheet. This type of ice-sheet decoupling has been proposed elsewhere to explain similar rapid changes in Pleistocene age lithotypes suggesting both grounded ice and ice shelf deposition (McCabe et al. 1984; Dreimanis 1982). These authors suggested that ice sheet thinning or sea-level rises could have caused the partial decoupling. At Cobalt, no evidence was observed to indicate a cause for this possible decoupling of the ice sheet.

A partially floating ice shelf model would be expected to deposit large morainal banks at the grounding line zone due to rapid undermelting of basal and low englacial debris, accompanied by ice-push effects (Powell 1984; Gravenor et al. 1984). These large accumulations of diamicton (a subtype of undermelt diamicton in the classification of Gravenor et al. 1984) should have been a major source of sediment gravity flows into distal areas. These flows are initiated on bank slopes due to initial slope instability and oversteepening from advance of the grounding line (Powell 1984). This process could account for the thick resedimented diamictites which form a major component of the upper assemblage at Cobalt. Sandstones intercalated with these diamictites may reflect secondary flow initiation at the head of the high-density flows, a process discussed previously.

Whether this readvance of the ice sheet was part of a major readvance, or merely a large-scale fluctuation in the overall retreat, has not been established. The Coleman Member at Cobalt is incompletely preserved, with perhaps >100m of the uppermost strata missing (based on regional correlations). For this reason, the importance of the evolution of the glacial depositional environment for the upper assemblage at Cobalt cannot be ascertained.

5.5 Summary of Depositional Sequence at Cobalt

The simplified summary diagrams of Figures 11 and 12 illustrate the glaciogenic depositional environments envisioned for the Cobalt area:

1. The local setting was an area of low to moderate relief on the inner shelf of a slowly subsiding continental margin. A regolith was developed on part of the subaerially exposed (at least initially) Archean unconformity surface.
2. Continental-scale glaciation involved southerly advance of an ice sheet, perhaps inducing isostatic loading to below sea level.
3. Subglacial processes caused plucking, brecciation and shaping of the unconformity surface. The regolith was incorporated by the advancing ice sheet, except where cavitation occurred over paleotopographic lows. Lee-side till was deposited into these subglacial cavities, covering the remaining regolith. A primary basal till was deposited over much of the unconformity surface.
4. Deposition during retreat was from a wet-based tidewater glacier grounded approximately 50-300 m below sea level.
5. Slow retreat rates resulted in deposition of prograding subaqueous outwash fans where subglacial/englacial meltwater channels entered the basin. Deposition from underflows induced by proximal meltwater changed distally to deposition from interflows and/or overflows.
6. Morainal banks formed at the grounding line in interfan areas due to englacial/subglacial melt-out and fluctuations in ice-sheet retreat rates.
7. Oversteepening of fan and morainal bank slopes, bank collapse during retreat, and perhaps the shock effects of ice-calving, initiated sediment gravity flows into interfan areas. Numerous sediment-support

mechanisms resulted in a variety of intercalated flow types.

8. Ice-calving caused deposition of IRD in areas near the ice front. Rapid iceberg transport caused less dropstone deposition in relatively distal areas.

9. The upper strata of the Coleman Member probably were deposited by readvance of a floating or partially-floating ice sheet. Undermelt diamictos were initially deposited near the grounding line (north of the study area) and were redeposited as sediment gravity flows within the study area. Ice-rafted debris from melt-out beneath the shelf was in part deposited as dropstone diamicton.

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Figure 10. Depositional model for the lower part of the Coleman Member at Cobalt.

Figure 11. Depositional model for the upper part of the Coleman Member at Cobalt.

PHOTOGRAPHIC PLATES

(Location of photographs is shown on Figure 23, back-pocket)

Plate 1. Unconformity surface and basal breccia.

- A. Oblique view of joint-bounded depression in unconformity surface infilled with Coleman Member diamictite.
 - B. Vertical face (south to the right) showing south-facing step on unconformity surface, and locally derived breccia.
 - C. Horizontal exposure of extensively jointed unconformity surface. Dark infillings of angular depressions are Coleman Member diamictite.
 - D. Vertical exposure of sharp unconformity contact between Archean felsic volcanic and overlying Coleman Member diamictite.
 - E. Thin section of breccia derived from lee-side erosion of unconformity. Breccia fragments "float" in a sandstone matrix similar to that of the Coleman Member basal diamictite.
 - F. Basal breccia preserved in a paleodepression. Extensively fractured Archean mafic volcanic rock at base of photo is in place, and grades upward to increasingly displaced breccia fragments. White rounded clasts at upper right are in the basal part of a Coleman Member clast-supported diamictite which overlies the breccia and infills the remaining portion of the paleodepression (also shown in Plate 2G,H).
 - G. Felsic volcanic clasts of the southern breccia lens.
-

Plate 2. Basal diamictite association.

- A. Typical basal diamictite with gravel-sized clasts floating in a sandstone matrix.
- B. Horizontal surface showing possible faceted clasts in the basal diamictite. Some clasts margins are outlined by concentrations of chlorite, a metamorphic alteration product.
- C. Thin section of basal diamictite matrix showing poor sorting and angularity of many grains. Note high percentage of angular silt-sized grains.
- D. Thin section of basal diamictite matrix showing lack of alteration of most grains. Quartz grains generally are pristine, with only slight edge alteration. Many feldspar grains are essentially unaltered, especially in cores. Large grain at bottom centre is untwinned K-feldspar.
- E. A vertical exposure of basal diamictite containing irregular, thin, slightly distorted sandstone lenses.
- F. Irregular laminations at a gradational contact between basal diamictite and an overlying rhythmite unit.
- G. Clast-supported diamictite (upper third of photo) overlying basal breccia in a paleodepression on the unconformity (same outcrop as in Plate 1F).
- H. Vertical exposure of the clast-supported diamictite of Plate 2G. Note poor sorting and lack of obvious fabric.

Plate 3. Fan association: rhythmite and sandstone units

- A. Well-developed rhythmic alternation of siltstone (dark-coloured) and claystone laminae. A thin bed of siltstone near top of photo has loaded into the underlying claystone; associated flames have been thrust to the right (southeast, approximately equal to the local paleoslope).
- B. Distal rhythmites showing multiple graded silt-clay couplets and two coarse silt laminae, one of which is normally graded. Ovoid mass of silt and clay near right centre is interpreted as a till pellet. Scale = .5mm.
- C. Rhythmites with silt laminae generally thicker than clay, a variety of grading patterns, and common microlaminations of silt in the clay laminae. Central ovoid mass is interpreted as a till pellet.
- D. Lenticular to wavy fine-grained sandstone interbeds in rhythmites. Some ripple bedforms are apparent. Some lenses are slightly deformed (especially lenses below scale card).
- E. Proximal rhythmites (top to left in photo) with graded or massive sandstone to siltstone thin beds relatively common and multiple silt-clay laminations separating coarser-grained layers.
- F. Sinusoidal climbing ripples, some transitional to "type B" of Jopling and Walker (1968). Correspond to "draped lamination" of Gustavson et al. (1975).
- G. Thick beds of massive sandstone within upper portion of rhythmite sequence. Bases of some sandstone beds are loaded into rhythmites.
- H. Rhythmite laminae below a massive sandstone interbed with well-developed loading and flame structures plus decoupling and thrusting of a portion of the rhythmites. Thrusting and deformation of flames is to the south (right of photo).
- I. Sandstone interbed in rhythmites showing breached convolute lamination. Massive vertical zones separating the concave-up laminated zones probably were the result of early dewatering.

Plate 4. Fan association: rhythmite and sandstone units.

- A. Proximal rhythmites with graded sandstone bases, some containing fragments of finer-grained rhythmite. Loading of sandstone bases into the underlying laminae is common.
- B. Dropstone in rhythmites - see Figure 5A for discussion of the contact relationships of this dropstone.
- C. Deformation structures in rhythmites (top to left of photo). Light-coloured clay-rich laminae in layer 1 cm left of scale have been thrust to the right (southeast), approximately down the paleoslope. Laminae in centre of rock slab are deformed and broken, perhaps due to a combination of thrusting and dewatering.
- D. Massive clastic dyke of fine-grained sandstone that has intruded and deformed rhythmites. Top of tape measure is at top contact of sandstone.
- E. Thin section of poorly laminated mudstone. Laminae are wavy, discontinuous and of variable thickness.
- F. Fine-grained sandstone pseudonodules in a poorly laminated mudstone. Pseudonodules display distorted internal lamination, and appear to be the result of the complete foundering of a laminated sandstone bed in a water-saturated mudstone.
- G. Thin section of a fan-association medium-grained sandstone (modal grain size in photo = .4-.5mm) Condensed packing (sutured grain boundaries) is typical of these sandstones. Feldspar grains are only slightly altered, supporting a cold climate hypothesis for weathering and transport.
- H. Low-angle planar cross-bedding in the mid portion of a sandstone unit. Current transport to the right (approximately south).

Plate 5. Fan association: sandstones and clast-supported diamictites

- A. Upper portion of a sandstone unit. Pebbly coarse-grained sandstone with poorly defined trough crossbedding (curved erosion surface parallels a trough outline).
- B. Upper portion of a sandstone unit (top to left). Repetitive cycles of pebbly sandstone (to granule conglomerate) and planar laminated coarse-grained sandstone. Some cycles show normal grading between the coarser base and finer top.
- C. Pebbly sandstone/granule conglomerate cycles at the top of a sandstone unit. Transitional to a clast-supported diamictite above.
- D. Dropstone near the base of a sandstone unit.
- E. Typical clast-supported diamictite showing poor sorting and apparent lack of stratification.
- F. Crude stratification in a clast-supported diamictite.
Stratification defined by horizontal alignment of clasts and poorly defined graded cycles.
- G. Stratified, clast-supported diamictite with moderate sorting and relatively well-developed graded cycles.
- H. Upper subunit of a clast-supported diamictite with moderately sorted beds of pebbles (some graded) and sharply defined normally graded beds of small pebble to very coarse-grained sandstone.
Planar crossbedding dips southward (left in photo).

Plate 6 Heterolithic diamictite association: lower stratigraphic assemblage (interfan association)

- A. Cyclically repeated clast-supported diamictite and pebbly sandstone beds of a fining upward fan association.
- B. Matrix-supported stratified diamictites in an interfan area. Irregular beds and lenses of mudstone and sandstone occur within and between individual diamictites.
- C. Pentagonal outline of a clast in an interfan diamictite. Similar clast outlines are moderately common and suggest a faceted shape.
- D. Two units of matrix-supported diamictite and interbedded rhythmities. The lower contact of the upper diamictite is sharp and erosive into the underlying rhythmite.
- E. Grooved surface on the top of a matrix-supported diamictite. A thin veneer of siltstone partially fills some grooves (linear light grey zones above, and to the left of hammer). Pleistocene striations are faintly visible, oriented approximately 90° to the grooves.
- F. Boulder of clast-supported diamictite in a matrix-supported diamictite. Clasts at edge of boulder are not truncated and some protrude. Largest cobbles are at base of boulder. Faint laminae in host diamictite are depressed beneath and at lower edges of boulder, and some are pierced by boulder.
- G. Erosive contact between a generally clast-supported, very poorly sorted diamictite and a bedded sandstone unit. Both units occur as discontinuous sheet-like bodies in an interfan area.
- H. Normally graded clast-supported sheet-like diamictite with clasts projecting into overlying sandstone (top right corner shows best example). Overlying sandstone unit is shown in Plate 7a.

Plate 7. Heterolithic diamictite complex: lower and upper
stratigraphic assemblage

- A. Detail of sandstone overlying the diamictite shown in Plate 6H. Unit fines upward overall from a normally graded coarse-grained sandstone to a rippled (some climbing) fine- to medium-grained sandstone. Planar laminated siltstone caps the sequence, and coarse-grained sandstone sharply overlies the siltstone.
- B. Boulder-rich massive diamictite with in situ fractured and separated boulder fragments.
- C. Close-up of separated fragments of a boulder shown in Plate 7B. Spaces between fragments have been infilled by the enclosing diamictite.
- D. Bedding-parallel view of laminated mudstone draped around a clast of the underlying diamictite shown in Plate 7B.C.
- E. Sandstone which occurs as a discontinuous sheet-like body in an interfan area. Inverse-to-normal grading is apparent in the bed shown (base of bed 1 cm below scale, top not shown; dark areas in top left and above scale are weathered surfaces).
- F. Upper stratigraphic assemblage showing nonrhythmically laminated fine-grained sandstone and mudstone that contains abundant clasts. Many (perhaps all) of the large clasts are dropstones.
- G. Clast-supported diamictite of the upper assemblage, showing a well-defined inversely graded zone above its lower contact. The contact appears to be slightly erosive with respect to the underlying mudstone.
- H. Thin section of poorly laminated mudstone of the upper assemblage. Laminae are nonrhythmic, discontinuous and contacts are diffuse.
- I. Erosive contact between a matrix-supported diamictite and a laminated mudstone. A fragment of the underlying mudstone (right of scale) has been incorporated into the diamictite.

APPENDICES

APPENDIX 1

Measured Sections

These nine measured sections are abbreviated versions of the original section descriptions, plus interpretations of the units based on knowledge gained through this study. Localities of the measured sections are shown in Figure 12. Table 1 (page 5) shows the lithofacies code used during this study; Table 3 is a legend of symbols used in the graphic logs. Tables 1 and 3 have been combined in a single removable back-pocket addition (Figure 23) to facilitate examination of these sections. Vertical distances shown on the left of the sections are in metres.

Figure 12 Localities of Measured Sections. Lines indicate sections partially measured along the topographic surface. Diamonds indicate sections measured vertically on an exposed face of an abandoned pit or vein cut.

LEGEND - MEASURED SECTIONS

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LITHOLOGIES-

Nipissing Diabase, N

DIAMICTITES, D

Clast-Supported

Matrix-supported,
stratified

Matrix-supported,
massive

SANDSTONES, S

Pebbly

Fine to Coarse-Grained

FINE-GRAINED LITHOLOGIES, F

Silt > Clay

Clay > Silt

BRECCIA, Bx

ARCHEAN ROCKS, A

COVERED INTERVAL

CONTACTS

Sharp

Erosional

Deformed

Gradational

Lateral Gradational

STRUCTURES

Ripple Marks

Climbing Ripples

Planar Crossbedding

Trough Crossbedding

Discontinuous Interbed

Dropstone

Deformed Laminations

Rip-up Clasts

VERTICAL SCALE

Metres

SECTION WIDTH VS. GRAIN SIZE

Table 3

MS-1 CONIAGAS-TRETHIEWAY PIT

OBSERVATIONS

INTERPRETATIONS

Dmm 10-15% clasts in fg sand matrix; largest clast 40cm, mode 2-4cm, most granitic, non-sorted, no app. orient. laterally extensive, 100's - 1000's of metres; rare discont. fg Sh of Fl lenses, 10's cm thick, <10m length

Upper Complex Probably series of debris flows with lenses of Sh and Fl as interflow deposits; dropstone diamictite origin possible but evidence lacking due to massive nature of rocks

Dms-pShd-pSpd 20-50% clasts in poorly bedded sand-sized matrix, poorly sorted, some beds/lenses w. crude subhor. align. of peb. long axes; largest clast 1m, mode 2-6cm; most granitic but 10% blk. chert peb., some dropstones in pSh-pSp, Dcs-pSh unit to north appears equivalent

Interfan Complex Pro-fan flows from fan assoc. to north, combined turb. and lam. flow-types plus high IRD component

Frd-Shd couplets of fg sandst., siltst., mudst.; most <1cm thick, some to 2cm, thicker and coarser to top of unit; sharp contacts between couplets, occ. microloads into mudst.; occ. thin beds (2-4cm) of fine-cse grained massive sandst., loads into Frd, rare beds (to 30cm.) of pebble-sized Dcm, dropstones common (to 10%) esp. in top 5m, some occur in poorly defined lenses

Fan Association Relatively prox. mudst. underflow rhythmites of fan prograding from the north. Sm and Dcm beds rep. grain flows and debris flows from more proximal areas; high dropstone content reflects proximal position to ice-front; dropstone lenses may be iceberg overturn deposits. Lack of overlying sandst.-Dcs units of fan suggests shifting of outlet location or cutoff of subglacial meltwater channel prior to complete progradation of fan at this point.

Sm med.-grained; thins from 35cm to <5cm N.; slightly erodes into underlying Dmm base

Interfan Complex sediment gravity flow, thickness and erosive contact suggest density-modified grain flow

Dmm 10-20% clasts in fine to med.-grained sandst. matrix, 20-25% clasts in top 2m; largest clast 120cm; random sizes and orient. non-sorted; clasts 85% granitic, 15% volc.

Interfan Complex Debris flow or flows, perhaps from morainal banks formed at ice front in interfan area to north.

Dcs-pShgn peb./cse-grained sandst. w. eros. base into Frd; peb. base, crude norm. graded med/cse grained sandst. (p; unit thins over 20m from >2m to <50cm (then covered), not present on pit wall 20 m. to Nth.

Interfan/Fan Association Channelized turbulent flows from proximal fan area; perhaps result of short-lived, extreme meltwater influx event?

Frd-Shd couplets fg sandst., siltst., mudst.; most <1cm thick. sandst. based couplets to 3cm couplets coarser/thicker to top, sharp couplet contacts, occ. microloaded bases, rare rip-ups Fr in basal Sh, rare ripples in Sh; <5% dropst.

Fan Association proximal-underflow-deposited rhythmites; perhaps part of meltwater system which deposited underlying units, but increase up of lam. thickness and grain-size suggests renewed meltwater input.

Dcs-pShgn interbedded 10-35cm mod-sorted pebble bases grade to <20cm of pebbly, cse-grained, thin-bedded (2-4cm) sandst., Dcs lower contact sharp, occ. erosive w. pShgn below; poorly defined ripples in pShgn

Fan Association Proximal deposition to meltwater outlet in ice sheet. Initial fining-up trend suggests waning current strength due to ice retreat, lower ice-melt rates, or fan migration

bDmm <10% pebble-cobble clasts, random in a fg sandst. matrix; exposed in S.W. corner of till, unconformably very poorly exposed

Basal Tillite subglacial, primary till

A mass. volcanic; exposed in S.W. corner pit

MS-2 VEIN 64' PIT

OBSERVATIONS

INTERPRETATIONS

Dca-pShgn 20-50cm beds w. peb.-cob. base (10-35cm) and med-cse grained norm. graded sandst. top; largest clast 25cm, mode 2-4cm. mod. sort.; <5% random peb. in sandst.

Sh? inaccessible on cliff face, appears med-cse grained, med. bedded

Dcm-Dca 75-85% pebbles-cobbles in a cse-grained sandst. matrix; largest clast 40cm, mode 2-4cm; poor sort.; rare crude stratif. w. slight conc. of similar sizes in poorly defined beds; clasts >50% granitic, <50% felsic volc. > mafic volc. > sed.

Dmm 10-15% pebbles-cobbles in a vfg sandst. matrix; faintly laminated, non-rhythmic, no obv. grading or grain-size variations in matrix, rest of unit as for Dmm below

Dmm 10-15% pebbles-cobbles in vfg sandst. matrix; nonsorted, no obv. clast orient.; granitic, <20% volc.

Fan Association Upper fan high energy deposition, related to underlying deposits, reflecting rapid changes in meltwater influx and lateral fan migration

Fan Association upper to mid fan, distal vs. overlying Dca-pShgn

Fan/Interfan Association one or several debris flows into interfan area from prox. upper fan Dca source, perhaps reflects initial fan migration into interfan area

Interfan Association debris flow or flows? perhaps from moraine banks at ice sheet edge, laminae might reflect distal meltwater or other currents

Interfan Association Similar origin to above unit, ind. flows not appar. of basal tillite, but Archean not found in pit.

Archean volcs. exposed to west of pit and overlain by thin (<2m) bDmm. Projection and information from mine reports suggest base of section is within 5m of Archean contact.

MS-3 LITTLE SILVER VEIN CLIFF

OBSERVATIONS

INTERPRETATIONS

Dcs-Dcm >80% pebbles-boulders in a cse-grained sandst. matrix; largest clast 90 cm, mode 4-6cm, poor sorting, crude strat. with subhor. clast align., poorly-defined thick beds of similar clast sizes; rare discont. contorted cse-grained sandst. lenses >30cm. thick and 5m exposed length

pStgn-Design trough crossbedded units; up to 1.5m long overlapping troughs w. erosion of trough below., approx. basal 25cm of each trough preserved; small pebb. granule basal lenses grade up to granule, coe-grained sandst. w. rare pebbles; paleocurrents towards SW

Sp med/cse-grained feldspathic arenite
planar crossbedded beds up to 1m thick,
most <50cm; crossbeds dip approx. 20o
towards Sth/SW

Sh-Sr med-grained feld. arenite; faintly bedded (3-20cm); rare ripplés w. internal x-strat.; rare dropstones up to 15cm dia.

Fr-Sm intercalated med-grained Sm beds (15-40cm) in Fr; Sm bases loaded w. flames of Fr distorted to Stch.; poas, dewatering pillars in some Sm beds; Fr lams 1cm thick w. fg sandst. bases and rare 1-2cm Sr beds w. ripples asym. to sth.

Fr. complete of siltst., mudst. vfg sandst. coarser-grained and thicker (to 1cm) upward; bases sharp w. occ. microlenses; occ. single beds (1-3cm) (g x-lam. sandst.; occ. ripples w. internal x-lam. most show 4th. transport, occ. nth. directed; occ. poorly dev. climbing-ripples near top (4th climbing)).

Covered Interval - inaccessible vein cuts, drillhole data, and scattered outcrops indicate all of interval consists of Fr.

Frd couplets of siltst., mudst.; lams 1-3mm thick; sharp bases, occ. definite dropstones

bdm 20-30% pebbles-cobbles in a vfg sandst./
mudst. matrix; largest clast 30cm, mode 2-4cm;
rare fg discont. contorted sandst. lenses <5cm
thick, 1m length; non-sorted, no obv. clast
orient.; top 20cm lam., grad. change to Fr.

Dca-pShgn 20-30cm peh.-cob. base w. 10-20cm
poorly graded med/cse-grained sandst. top;
mod. sort; discont., not present 20m nth.

A pillow v. l. uncon. poorly exposed in vein-cut W. of cliff, well-exposed SW of vein-cut.

Fan Association Proximal upper fan deposition at influx site of subglacial/englacial meltwater channel into basin. Sandst. lenses may reflect fluctuations in input & current strength.

Fan Association Upper/mid fan.
Continual change upward in grain
size and sed. structures reflects
increasing current strength towards
influx site, progradation of fan
into basin and temporal fluctuations
in current strength (graded upper
beds)

Fan Association transition from lower fan Fr to mid-fan S. Sm as density modified grain flows from southward prograding mid-fan

Fan Association lower fan, deposition by density underflows (proximal) and interflow/overflows (distal); Thicker and coarser-grained lams. reflect southward fan progradation.

Basal Tillite Association primary subglacial till; sand lenses may indicate melt-out origin; faint lams. in upper part due to reworking, by currents depositing overlying Frd

Basal Tillite Association
small subglacial meltwater
channel

MS-4 RIDGE EAST OF VALLEY FAULT, COBALT TOWNSHIP

OBSERVATIONS

INTERPRETATIONS

pShgn patchy o/c of med-rse sandst., med-poor sort.; occ. peb. bases; poorly exposed

Upper Complex gravelly turb. sed. grav. flow? related to Dcm below?

Dcm-Dcm 80-85% peb.-cob. clasts in cse-grained sandst. matrix; largest clast 30cm, mode 3-4cm, poor sorting, crude strat. as occ. poorly defined thick beds; discont. lenses med/cse-grained massive sandst., <5cm thick, <10m length

Upper Complex Gravelly debris flows with rare lam. flow giving crude beds. Sm may define flow boundaries and be density-modified grain flows from backstreaming in gravel flows.

Dmm 30-50% peb.-cob. clasts in med-cse-grained sandst. matrix; non-sorted, no obv. clast orient.; clasts >60% gran., <40% volc.; rare discont. lenses vfg sandst./mudst., <10cm thick, <5m length

Upper Complex debris flows or drop stone diamictite; Sm-lm lenses may be interflow beds or low-current deposition when little IRD input

Fld midst./ vfg sandst; non-rhythmic laminations, many wavy and discont.; lam 5mm-1cm thick; rare 2-3cm fg massive sandst. beds; basal lam drape projecting clasts of Dmm-Dcm below

Upper Complex ice-distal deposition in quiet environ., seds from distal meltwater input or IRD; currents distal meltwater or normal basinal currents

Dmm-Dcm 35-65% peb.-cob. clasts in fine to cse-grain sandst. matrix; non-sorted, no obv. clast orient., clasts 60-70% gran., 30-40% volc., <5% sed; projecting clasts at top into Fld

Upper Complex debris flow or flows, poss. dropstone diamictite but prob. clasts supports debris flow interp.

Dcm-Dcm 70-85% peb.-cob. clasts in med/cse-grain sandst. matrix; largest clast 25cm, mode 4cm, poorly sort., crude 1-2m thick beds sep. by discont. Fl-Sh lenses <10cm thick, <5m length; most beds mass., poor subhor. clast align. in spots, occ. poor inv. grading at base, norm. grading at top; clasts 50-60% gran., 40-50% volc. Dcmgr part of above unit but massive except basal 30 cm inv. graded; basal cont. sharp, undulatory (loaded?) and erodes Sm

Upper Complex gravelly sed. grav. flows; high density debris flows and fluidized flows; traction carpet deposition at bases gives inv. grading, slight lam. flow gives crude beds and norm. grading. Fl-Sh lenses mark flow contacts, form as den. mod. grain flows, perhaps seds. from backstreaming effects in gravel flows.

Shd-Smd poorly exposed vfg to fg sandst. perhaps faint bedding? no obv. structures; rare limestones (pebble size)

Upper Complex density-modified grain flow or flows? limestones as dropstones? poor exp. hinders int.

Covered bushy zone at base of cliff, possible location of Valley Fault (but may be just west of unit blow)

Dmm-Fld o/c approx. 15m. of cliff; 25-30% peb.-cob. clasts in vfg sandst./siltst. matrix largest clast 60cm, mode 2-3cm; non-sorted, no obv. clast orient.; matrix gen. faintly lam., esp at top, occ. mass., lam gen. <5mm thick, non-rhythmic, some clasts definite dropstones

Upper Complex combined debris flows and dropstone diamictite, lamina suggest ice-distal currents, clasts as IRD plus reworked debris flows?

SECTION APPROX. 120M ABOVE UNCONFORMITY (based on assessment reports, mine plans and cross-sections drawn for this thesis)

MS-5 WEST SIDE PETERSON LAKE

OBSERVATIONS

INTERPRETATIONS

Fan Association upper fan portion smaller and better sorting vs. other fans in area; boulders as dropstones? (doesn't explain linear trend)

Fan Association as above; seq. of structures and coarsening-up ind. increased energy due to sth. fan progradation; dropstones support subaqueous fan interpretation.

Fan/Interfan Association fan-distal meltwater dep.; sug. fan above from rapid migration into interfan area.

Interfan Complex Combined debris flows and high IRD input into area of fan-distal meltwater input. Sth. transition to Frd and grad. contact w. bDmm suggests ice-prox. deposits, perhaps collapsed morainal banks.

Basal Tillite Association primary subglacial till; unusually high % volc. clasts and position on SE side major Archean paleohigh (Nipissing Hill) suggests local source for many of these clasts.

MS-6 McDONALD VEIN PIT

OBSERVATIONS

INTERPRETATION

Fan Association Upper fan, prox. meltwater underflows, fluctuating (seasonal?) input causes grading and changes in sed. structures, less prox. than Dcm-Dcm below due to lat. fan migration, ice sheet retreat and/or changing subglacial meltwater paths

Fan Association Proximal fan deposition at influx site of subglac./englac. meltwater channel into basin. Some remobilization as high-density sed. grav. flows poss. w. traction carpet dep. at base giving inv. grading.

Fan Association Lower fan, deposition by meltwater underflows and perhaps interflows/overflows (lower section); Sm as density modified grain flows from sth. prograding mid-fan; increased grain size and lam. thickness upward reflect prograd. of fan;

Interfan Association debris flow or flows; very similar to basal tillite, may be flows from interfan morainal banks at edge of ice sheet

Fan Association small (short-lived?) fan deposit; fining-up sequence and lack of major gravel units suggests relatively lower energy (vs. other fans in study) and waning meltwater input

Archean not seen at base, present approximately 200m to S.E. where massive volcanics are sharply overlain by bDmm. Map and cross-section information suggest unconformity is within 5m of base of section.

MS-7 RAINBIRD TIERIS AREA

OBSERVATIONS

INTERPRETATION

Fan Association Upper and mid fan. Continual change upward in grain size and sed. structures reflects increasing current strength towards influx site (where Dcs deposited), progradation of fan into basin and temporal fluctuations in input current strength (causing grading). Dcm from debris flow off of upper fan.

Basal Tillite Association subglacial, primary till; sand lenses may indicate melt-out origin; faint lams in upper part due to reworking by meltwater currents (Frd overlies unit to south)

Basal Tillite Association subglacial, primary till; location in paleodep. covering regolith suggests origin as lee-side infill of a subglacial cavity, high % volc. clasts may reflect basal transport and local source

Regolith pre-Coleman Member deposition, perhaps periglacial cold climate weathering; only preserved in small paleodepressions w. sth.-facing scarps causing initial subglacial cavities

Glacially Shaped Uncon. Surface fracturing periglacial or subglacial freeze/thaw effect; angular depressions are subglacial plucked blocks, infilled by subglacial till

MS-8 SCAMMELL THESIS AREA (WEST)

OBSERVATIONS

INTERPRETATION

Interfan Association series of debris flows, density-modified grain flows, high-density turb. flows into interfan area from sth. prograding fan and moraine banks; prob. IRD component but difficult to recognize due to massive or poorly laminated nature

Fan Association Relatively complete but condensed (vs MS-1) fan succession. Sth extension of MS-7 units. Coarsening-up and fan progradation. Sm beds in Frd thick density-modified grain flows off of mid fan. Sudden loading by Sm caused thrust flame structures and convolute laminations. High sedimentation rates may account for unusual thickness and number of grain flows into lower Frd.

Basal Tillite Association subglac. primary till; lamina in upper part may reflect reworking by meltwater currents during dep. of tid

Glacially Shaped Uncon. Surface ang. depressions from subglacial plucking of frac. uncon. surface, sth-facing scarps stagnation plucking effect (similar to rock mountain), indicates sth-west ice sheet movement

MS-9 SCARPELL THESIS AREA (CENTRAL)

OBSERVATIONS

INTERPRETATION

Dms-Dms 30-60% clasts in fg sandst. matrix; poor sorted, no obv. clast orient. largest clast 40cm, mode 4-5cm; clasts 50-60% gran., 35-45% volc., <5% sed., occ. faint lams.; occ. discont. lenses Flid, Shgr/gn, Sr, <30cm thick, most <10m length, some cont. over 30m; well-developed grooves on top of Dms in one area, grooves infilled by <2cm thick vfg Sh; base of unit erosional into pShgn below

Interfan Association series of debris flows from upper fan and morainal banks; sep. flows recog. where interflow deposits pres.; grooves from drag and flow separation at debris flow base; Sh dep. as dens. mid. grain flows and sandy turbidity flows; Fl as distal meltwater deposits between flow events

pShgn-Dcs 10-60cm beds w. 2-50cm thick peb. bases grading to 5-30cm thick med/cse-grain. sandst. mod. sort., largest clast 2cm, mode 1cm, base of Dcs sharp; base of unit sharp, possibly erosive into Dms below

Fan/Interfan Association Typical of upper fan deposits from strong, fluctuating meltwater underflows, but adj. units sug. interfan area? Perhaps from short-lived period of extreme meltwater input?

Dms 10-35% peb-cob clasts in fg sandst./siltst. matrix, non-sorted, no obv. clast orientation; largest clast 15cm, mode 3cm; clasts 60-70% gran., 25-35% volc., <5% sed.,

Interfan/Basal Tillite Association poss. debris flow or flows from interfan morainal banks, may be subglacial primary till; evidence inconclusive for either interp.

Archean not seen at base, cross-sections from this study suggest unconformity is within ten metres of base of section.

APPENDIX 2

Apparent Long-Axis Orientations of Diamictite Clasts

Surfaces approximately parallel to bedding (defined by adjacent or nearby stratification) were selected for measurement of apparent long-axis orientations of clasts with apparent a:b ratios of 2:1 or greater. Large clasts (pebbles and cobbles) were measured for ease of sampling and because they should show the least variable fabrics (Boulton and Deynoux 1981). As recommended by Rust (1975), who observed that in glaciofluvial gravels small pebbles showed more scattered orientations, clasts with apparent long axes greater than 3 cm were measured. Azimuths of apparent long-axes were measured using a Brunton compass. A minimum of 40 clasts were measured per site. To obtain this minimum number of measurements no size restrictions were placed on the area of the sample site.

As recommended by Andrews (1971) for the statistical analysis of till fabrics where three-dimensional orientations cannot be measured, the two-dimensional vector method of Curray (1956) was applied. This method is summarized in Table 3. The BASIC programs in Table 4 were used to compute all statistics. The significance of the resultant vectors was measured by the Rayleigh significance test which Curray (1956) showed gave values similar (or slightly higher) than chi-square tests. Orientation rose diagrams were plotted in the form suggested by Andrews (1971), with 20° class intervals.

For each 20° class interval:

$$\text{Resultant Vector } \phi = \frac{1}{2} \arctan \frac{A}{B}$$

$$\text{where } A = \sum_{i=1}^n \sin 2\theta \quad n = \text{number of observations in interval}$$

$$B = \sum_{i=1}^n \cos 2\theta \quad \theta = \text{azimuth of each observation}$$

$$\text{Vector Strength } R = (A^2 + B^2)^{0.5}$$

$$\text{Vector Magnitude } L\% = \frac{R}{n} 100$$

For total sample site:

Total Resultant Vector

$$\phi = \frac{1}{2} \arctan \frac{A_T}{B_T}$$

$$\text{where } A_T = \sum_{i=1}^K A$$

K = number of intervals
= 9 for this study

$$B_T = \sum_{i=1}^K B$$

Total Vector Strength

$$R_T = (A_T^2 + B_T^2)^{0.5}$$

Total Vector Magnitude

$$L\% = \frac{R_T}{N} 100$$

N = total number of observations

Significance (Rayleigh test of probability)

$$S = \text{from graph in Curaray 1956 (Figure 4)}$$

Table 3. Formulae used in the statistical analysis of two-dimensional orientation data (based on Curaray 1956; Andrews 1971).

Calculation of Vector Mean and Magnatude for Each Interval

```

5   CLS
10  PRINT "INPUT NUMBER IN SET"
15  INPUT "NUMBER IN SET"; N%
20  PRINT "INPUT DATA FOR INTERVAL"
23  INPUT "NUMBER IN INTERVAL"; T%
25  DIM THETA!(T%), T2!(T%), ST2!(T%), CT2!(T%), RTH!(T%)
30  ASUM! = 0.00
35  BSUM! = 0.00
40  FOR J% = 1 TO T%
50      INPUT "ANGLE"; THETA!(J%)
60      T2!(J%) = THETA!(J%) * 2
70      RTH!(J%) = T2!(J%) * 0.01745 'VERT TO RAD
80      ST2!(J%) = SIN(RTH!(J%))
90      ASUM! = ASUM! + ST2!(J%)
100     CT2!(J%) = COS(RTH!(J%))
110     BSUM! = BSUM! + CT2!(J%)
120     NEXT
130     ACT! = ATN(ASUM!/BSUM!) * 0.5
140     ACT! = ACT! * 57.29578
145     VM! = (SQR(ASUM!^2 + BSUM!^2)/N%) * 100
150     PRINT "SUMA, SUMB, ARCTAN, VMAG"
155     PRINT ASUM!; BSUM!; ACT!; VM!
160     END

```

Calculation of Total Vector Mean, Strength, Magnatude

```

5   CLS
10  PRINT "VECTOR MEAN - STRENGTH - MAGNATUDE"
15  INPUT "NUMBER IN SET"; N%
20  PRINT "INPUT DATA FOR INTERVAL, A FIRST THEN B"
25  DIM A!(9), B!(9)
30  ASUM! = 0.00 : BSUM! = 0.00
40  FOR J% = 1 TO 9
50      INPUT "A"; A!(J%)
60      ASUM! = ASUM! + A!(J%)
65      NEXT
70  FOR J% = 1 TO 9
75      INPUT "B"; B!(J%)
80      BSUM! = BSUM! + B!(J%)
90      NEXT
100  VM! = ATN(ASUM!/BSUM!) * 0.5 * 57.2958
110  VS! = SQR(ASUM!^2 + BSUM!^2)
115  VW! = (SQR(ASUM!^2 + BSUM!^2)/N%) * 100
120  PRINT "SUMA, SUMB, VMEAN, VSTREN, VMAG"
130  PRINT ASUM!; BSUM!; VM!; VS!; VW!
140  END

```

Table 4. BASIC programs for statistical analysis of two-dimensional

orientation data using formulae in Table 3. (BASIC for Radio Shack TRS

Model 100. Programs written by J. Richardson, Ottawa-Carleton Centre for

Geoscience Studies.)

APPENDIX 3

PALEOPLACER GOLD POTENTIAL AT COBALT

Previous studies of the lower Gowganda Formation Coleman Member indicated that there is little potential for paleoplacer gold concentration (Long 1981, 1982; Mossman and Harron 1983, 1984). However, none of these studies specifically examined the immediate Cobalt area.

A major component of Coleman Member deposition at Cobalt is interpreted to comprise prograding subaqueous outwash fans (of the type documented by Rust and Romanelli, 1975) resulting from subglacial and/or englacial meltwater streams entering a proglacial body of water. Preserved parts of these small fans (areas of less than $2-3 \text{ km}^2$ in the Cobalt region) consist of a coarsening upward sequence of siltstone-mudstone rhythmites overlain by horizontal- and planar-crossbedded fine- to medium-grained sands, less-common trough-crossbedded sands, and pebbly sands with sparse pebble lags, all capped by moderately to poorly sorted orthoconglomerates.

On the basis of pebble-cobble long-axis orientations, Lindsey (1967) suggested SSW-directed movement of the Gowganda ice sheet. This was confirmed by the discovery during this study of lee-side glacial quarrying features on the unconformity surface at Cobalt and the strong northeast/southwest trend of clast long-axes in the basal diamictite (interpreted as a primary subglacial tillite). The combination of an excellent gold source area to the north (the Abitibi Greenstone Belt) and the abundance of current-worked sands and gravels at Cobalt, suggested that sampling and analysis was justified.

The results of this sampling program are shown in Table 4.

The general locations of sample sites are shown in Figure 17. Some high values were obtained in the initial analyses. However, analysis of the retained portions of these samples resulted in trace values at best, suggesting lab error or perhaps the presence of isolated gold-rich volcanic or sulphide clasts (D. Long, pers. com. 1984). One repeat of sample A8 was slightly anomalous (0.012 oz./ton), but a second analysis of the retained portion of the same sample preparation yielded only 0.003 oz./ton, again suggesting that no real anomaly exists. Additional sampling resulted in more low values. Thus, in spite of the sedimentologically promising setting, results from the Cobalt area complement those obtained from other areas, and suggest that the Coleman Member contains little paleoplacer gold potential.

Sample	Gold Value oz/ton		Lithology	Interpretation
	Initial	Repeat		
Fan A				
A1	nil(2)	nil(2)	top of granule-pebble orthocgl.	Upper (Proximal) Fan
A2	trace(2)	nil(2)	upper zone, A1 unit	
A3	0.019 0.001(2)	nil	mid A1 unit	
A4	trace	-	med-cse pebbly sandstone	Mid to
A5	nil(3)	-	med-cse sandstone	
A6	nil	nil	base of graded trough peb. SS	
A7	nil 0.012	-	med sandstone	
A8	0.112	0.003 nil	peb. lag of trough, x-bedded SS	
A9	nil(2)	-	graded granule cgl-cse SS	Fan
A10	nil(2)	nil	cse, pebbly, hor. bedded SS	
A11	0.006	nil	graded cse-med sandstone	
A12	nil	-	cse sandstone	
Fan B				
B1	0.004	0.002	pebble-cobble orthocgl.	Upper
B2	0.002	-	base: same as B1	Fan
B3	0.006	nil	top: med-cse peb.	Mid to
B4	0.004	nil	base: troughed SS	Upper Fan
Fan C				
C1	nil	-	med-large peb. orthocgl.	Upper Fan
C2	trace	-	small peb. orthocgl.	Mid to
C3	nil	-	peb. lag, graded trough SS.	Upper Fan
Fan D				
D1	trace	-	med-cse, graded peb. SS.	Mid
D2	trace	-	med-grained pebbly SS.	Fan
Misc.				
M1	trace	-	small peb orthocgl. on Archean uncon. surface	Subglacial Meltwater
M2	nil	-	similar to M1	Channel
M3	nil	-	graded hor. bed peb cse SS.	Mass Flow
M4	nil	-	small peb. orthocgl lense in diamictite (matrix sup)	Mass Flow in interfan zone

Table 4 Assay results from Coleman Member of the lower Gowganda

Formation in the Cobalt study area. Assays are grouped within fan complexes and in correct relative stratigraphic position where possible. Bracketted numbers after assay values indicate multiple samples from the same unit. The general location of sample sites are shown in Figure 17.

APPENDIX 4**Locality Maps Showing Data Collection Sites**

Figure 13 Sample sites - Orientations of apparent long axes of clasts in diamictites of the Basal Diamictite Association (see Figure 4)

Figure 14 Sample sites - Paleocurrent measurements (see Figure 6A-D)

Figure 15 Sample sites - Orientations of apparent long axes of clasts in diamictites of the Fan and Interfan Associations (see Figure 7).

Figure 16 Sample Sites - Orientation of apparent long axes of clasts in diamictites of the Upper Diamictite Complex (see Fig. 8).

Figure 17 Sample Sites - Gold Assays of Table 6

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79°41'40"

79°41'30"

88

GOWGANDA FORMATION

COLEMAN MEMBER

COBALT ONTARIO

Northern Sheet

Contour Interval: 1 Metre

Scale: 1:2000

LEGEND*

PROTEROZOIC

Basic Intrusive Sill: Nipissing Diabase

Intrusive Contact

HURONIAN SUPERGROUP

COBALT GROUP

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES**

Upper Heterolithic Diamictite Complex***

- UD upper Diamictite
- UDm matrix-supported
- UDc clast-supported (rare)
- UD-m massive (<10% irregular stratification)
- UD-s stratified
- UD--(r) resedimented

Diamictite, clast supported

Magnetic declination approximately 10° west

SYMBOLS

Geologic contact: defined, approximate, assumed

Boundary of rock outcrop

Small outcrop

Strike and dip of bedding: inclined, horizontal, vertical

Strike, tops of pillowed volcanic rock: dip known, unknown

Q8

4
OF/DE

UD-m massive (<10% stringers of stratification)
UD-s stratified
UD--(r) resedimented

Diamictite, clast supported

Dcm massive
Dcs stratified

Sandstone

pS pebbly sandstone (>5% gravel-sized grains)
Sm massive
Sh horizontal lamination
Sr rippled
St trough cross bedded
Sp planar cross bedded
S-gn graded, normal
S-gr graded, reverse

Fine-grained Facies (mudstone, minor very fine-grained sandstone)

Fr rhythmically laminated (sand-silt and/or silt-clay alterations)

Fl laminated (non-rhythmic)
Fm massive (<10% laminations)
F-d dropstones

Basal Diamictite (Tillite)

bdmm matrix-supported, massive

-other symbols as for Upper Diamictite Complex

Breccia

Bx(r) resedimented

▲ small occurrences

Angular Unconformity

ARCHEAN

Basic/Ultrabasic Intrusions

Intrusive Contact

A undifferentiated Archean
Ap basic volcanic rock - pillowed
Am basic volcanic rock - massive
Af felsic volcanic rock
Ai interflow sedimentary rock

Strike and dip of bedding: inclined, horizontal, vertical

Strike, tops of pillowed volcanic rock: dip known, unknown

Paleocurrent indicator: direction known, unknown

Dyke attitude: inclined, vertical

Major fault: dip, upthrown (U), downthrown (D) sides

Minor fault or shear zone (little displacement)

Open pit or quarry

Mined vein or exploration trench: > 2 m wide, < 2 m wide

Ditch

Portal of tunnel or adit

Cross-section location

Topographic contour: one metre intervals

SOURCES OF INFORMATION

* Outcrops are shown in dark colour. Inferred extension of units are shown in light tone of same colour.

Geology, 1984: P. Mustard, R. Scammell, B. Wilson, R. Rainbird

1985: P. Mustard, E. Dodd

** Lithofacies code used for mapping adapted from Eyles et al. (1983) and Powell, (1984). In some areas, units are missing or not in sequence shown in legend.

Geology compiled by P. Mustard to accompany Mustard, P.S. 1985. Sedimentology of the Coleman Member, Gowganda Formation, at Cobalt, Ontario. Unpublished M.Sc. thesis, Carleton University, Ottawa, Ontario.

*** Contains sandstone and rare mudstone interbeds, mapped where thick and traceable.

Major Fault Locations: Thomson R. 1964a. Cobalt silver area, northern sheet, Timiskaming district. Ontario Department of Mines, Map 2050.

Topographic Base Map: Ontario Ministry of Natural Resources, Urban Topographic Series, 1:2000 scale

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30F/DE

79°40'20"

79°40'10"

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79°39'50"

50,000mE

Peterson Lake

4 OF/DE

50F/DE

GOWGANDA FORMATION

COLEMAN MEMBER

COBALT - ONTARIO

Southern Sheet

Contour Interval: 1 Metre

Scale: 1:2000

LEGEND*

PROTEROZOIC

Basic Intrusive Sill: Nipissing Diabase

Intrusive Contact

HURONTIAN SUPERGROUP

COBALT GROUP

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES

Upper Heterolithic Diamictite Complex***

UD upper Diamictite
UDm matrix-supported
UDc clast-supported (rare)
UD-m massive (<10% irregular stratification)
UD-s stratified
UD--(r) resedimented

Diamictite, clast supported

Dcm massive
Dcs stratified

7
OF/DE

Peterson Lake

GOWGANDA FORMATION

COLEMAN MEMBER

COBALT ONTARIO

Southern Sheet

Contour Interval: 1 Metre

Scale: 1:2000

LEGEND

PROTEROZOIC

Basic Intrusive Sill: Nipissing Diabase

Intrusive Contact

HURONIAN SUPERGROUP

COBALT GROUP

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES

Upper Heterolithic Diamictite Complex ***

- UD upper Diamictite
- UDm matrix-supported
- UDc clast-supported (rare)
- UD-m massive (<10% irregular stratification)
- UD-s stratified
- UD--(r) resedimented

Diamictite, clast supported

- DCm massive
- DCs stratified

Magnetic declination
approximately 11° west

SYMBOLS

Geologic contact: defined, approximate, assumed

Boundary of rock outcrop

Small outcrop

Strike and dip of bedding: inclined, horizontal, vertical

Strike, tops of pillowed volcanic rock: dip known, unknown

Paleocurrent indicator: direction known, unknown

Dike attitude: inclined, vertical

80F/DE

3 OF/DE 3

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LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

Canada

Short Lake

90F/DE

LAKE

COBALT

scattered outcrop in dense bush

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52°48'00"N

79°42'00"

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83

79°41'50"

84

85

79°41'40"

86

87

79°41'30"

88

10
OF/DE

Diamictite, clast supported

Dcm massive
Dcs stratified

Sandstone

ps pebbly sandstone (>5% gravel-sized grains)
Sm massive
Sh horizontal lamination
Sr rippled
St trough cross bedded
Sp planar cross bedded
S-gn graded, normal
S-gr graded, reverse

Fine-grained Facies (mudstone, minor very fine-grained sandstone)

Fr rhythmically laminated (sand-silt and/or silt-clay alterations)
Fl laminated (non-rhythmic)
Fm massive (<10% laminations)
F-d dropstones

Basal Diamictite (Tillite)

bDm matrix-supported; massive

-other symbols as for Upper Diamictite Complex

Breccia

Bx(r) resedimented

▲ small occurrences

Angular Unconformity

ARCHEAN

Basic/Ultrabasic Intrusions

Intrusive Contact

A undifferentiated Archean
Ap basic volcanic rock - pillowed
Am basic volcanic rock - massive
Af felsic volcanic rock
Ai interflow sedimentary rock

Strike, tops of pillowed volcanic rock: dip known, unknown

Paleocurrent indicator: direction known, unknown

Dyke attitude: inclined, vertical

Major fault: dip, upthrown (U), downthrown (D) sides

Minor fault or shear zone (little displacement)

Open pit or quarry

Mined vein or exploration trench: > 2 m wide, < 2 m wide

Ditch

Portal of tunnel or adit

Cross-section location

Topographic contour: one metre intervals

SOURCES OF INFORMATION

Geology, 1984: P. Mustard, R. Scammell,
B. Wilson, R. Rainbird

1985: P. Mustard, E. Dodd

Geology compiled by P. Mustard to accompany
Mustard, P.S. 1985. Sedimentology of the
Coleman Member, Gowganda Formation, at
Cobalt, Ontario. Unpublished M.Sc.
thesis, Carleton University, Ottawa,
Ontario.

Major Fault Locations: Thomson R. 1964a.
Cobalt silver area, northern sheet,
Timiskaming district, Ontario
Department of Mines, Map 2050.

Topographic Base Map: Ontario Ministry
of Natural Resources, Urban
Topographic Series, 1:2000 scale

* Outcrops are shown in dark
colour. Inferred extension
of units are shown in light
tone of same colour.

** Lithofacies code used for
mapping adapted from Eyles
et al. (1983) and Powell,
(1984). In some areas,
units are missing or not
in sequence shown in legend.

*** Contains sandstone and rare
mudstone interbeds, mapped
where thick and traceable.

120F/DE12

C

20F/DE

Cross-section
Azimuth
308° 15'

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CHAPTER I

INTRODUCTION

Significant advances in the understanding of the processes of glacial geology, especially glaciomarine sedimentology, have resulted from recent research (for summaries see Andrews and Matsch 1983; Eyles and Miall 1984; Molina 1983; Powell 1984). The interpretation of ancient glacial deposits has benefited greatly from this increased understanding. (see for example Anderson 1983; Andrews and Matsch 1983; Boulton and Deynoux 1972, 1981; Driemanis 1983; Hambrey and Harland 1981). Incorporating these new ideas and models, this thesis presents a reinterpretation of the lower part of the Gowganda Formation in the Cobalt area, Ontario, Canada.

The extensive early Proterozoic Gowganda Formation (Figure 1A) has been recognized to be the result of glacial deposition since Coleman (1907, 1908) described faceted and striated "boulders" in massive greywackes. The Gowganda Formation has been tentatively correlated with glacial deposits over a wide area in North America (Young 1973), Finland and the U.S.S.R. (Marmo and Ojakangas 1984). This vast extent suggests deposition by ice sheets during at least one or more major periods of Precambrian glaciation.

Early regional studies (Lindsey 1966, 1967, 1969, 1971; Ovenshine 1965) led to suggestions of terrestrial glacial deposition of the lower Gowganda Formation (except near Lake Huron where a glaciomarine environment was postulated). Recent studies in the Lake Huron and Elliott Lake areas (Young 1985; Miall 1985) confirm the glaciomarine (probably continental slope) interpretation previously suggested for southern exposures of the Gowganda Formation. Recent interpretations of

the northern part of the Gowganda Formation have been based on limited data (Miall 1983) or regional observations (Long and Leslie 1985). Although they agree that deposition was subaqueous, they differ on whether it occurred in deep marine water from a floating ice sheet (Miall), or in a relatively shallow lacustrine environment from a grounded ice sheet (Long and Leslie).

At Cobalt, Ontario (Figure 1A), the lower part of the Gowganda Formation (Coleman Member) is particularly suited for detailed study. In this area silver exploration and mining during the early 1900's resulted in extensive stripping of outcrops and creation of vertical walls in now-abandoned vein cuts and open pits. The work of Legun (1984) suggested that a more detailed sedimentological study was appropriate. Detailed mapping (1:2000 scale) of a nine km² area including the town of Cobalt (Figure 1B) was combined with section measurements, fabric studies and petrographic examination of representative lithologies. This work provided the basis for the interpretations presented here.

A lithofacies classification scheme based on that of Eyles et al. (1983) was used for mapping and section measurement (Table 1). As per Eyles et al., the non-genetic term diamictite is used in preference to conglomerate or tillite for rocks composed of poorly sorted or non-sorted gravel/sand/mud mixtures. Some minor modifications to the code based on field observation and features of the study area have been introduced here. The prefix "b" indicates a basal diamictite unit which could be mapped independently of other units. The prefix "p" for pebbly sandstones was also appropriate. Subdivision of nonbasal diamictites into clast-supported (D_{cm} or D_{cs}) and matrix-supported (D_m) map units proved to be feasible. Some of the clast-supported diamictites would be termed gravels (G_m, G_t etc.) according to other lithofacies codes

CROSS-SECTIONS South Map

C'

3
OF/DE

B'

SCALE: 1:2000

VERTICAL = HORIZONTAL

LEGEND

PROTEROZOIC

N Basic intrusive to the Nipissing Diabase
Intensive Contact

Huronian Supergroup - Cobalt Group

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES

D Upper detritalitic Diamictite-Complex

Dc diamictite, clay supported

S sandstone

F fine-grained facies

bd Basal Diamictite (Billed)

Bx Breccia

Angular discontinuity

ARCHEAN

I dykes/dike-like intrusions
Intensive Contact

A Archean volcanic and sedimentary rocks

* See legend on accompanying map for detailed lithofacies codes.

SYMBOLS

Archean-Proterozoic unconformity surface,
Nipissing Diabase lower contact

Coleman Lithofacies Contacts:

B

A

40F/DE

5 OF/DE

B'

340 metres
320
300
280
260
240
220
200
180
140

SYMBOLS

Archean-Proterozoic unconformity surface,
Nipissing Diabase lower contact

Coleman Lithofacies Contacts:

Defined: Based on surface mapping and projected
short distances into section.

Approximate: Based on projection of surface contacts
or information from subsurface sources.

Very approximate or inferred: Based on imprecise
subsurface information.

Major fault: arrows indicate direction of movement

Minor fault or shear zone (little displacement)

SOURCES OF INFORMATION

Archean Unconformity Surface:

Thomson, R. 1961. Part of underground workings and approximate structural contours, Coleman Tp., Concessions V & VI - Lots 1 to 6, District of Timiskaming, Ontario Department of Mines, Provisional Map P-97A.

Legun, A. 1984. Basement contour map: Cobalt area, in Stratigraphy and sedimentation in the Cobalt area, Ontario Geological Survey, Open File Report 5508, 60p.

Knight, C.W. 1924. Geology of the mine workings of Cobalt and South Lorrain silver areas, Ontario Department of Mines, Annual Report for 1922, 31, 356p.

Nipissing Diabase Lower Surface:

Thomson, R. 1961. as above

Knight, C.W. 1924. as above

Coleman Member Subsurface Geology:

Knight, C.W. 1924. as above

Mine plans, assessment files and drillhole data covering the period 1906 to approximately 1950. On file in the Ontario Geological Survey Resident Geologist's office, Cobalt, Ontario.

Field notes and underground observations of Robert Thomson, O.G.S. Resident Geologist, Cobalt, 1947 - 1967. On file in the O.G.S. Resident Geologist's office, Cobalt, Ontario.

6 OF/DE

7 OF/DE 7

SYMBOLS

- Archean-Proterozoic unconformity surface;
Nipissing Diabase lower contact
- Coleman Lithofacies Contacts:
 - Defined: Based on surface mapping and projected short distances into section,
 - - - Approximate: Based on projection of surface contacts or information from subsurface sources.
 - - - Very approximate or inferred: Based on imprecise subsurface information.
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Field notes and underground observations of Robert Thomson. O.G.S. Resident Geologist, Cobalt, 1947 - 1967. On file in the O.G.S. Resident Geologist's office, Cobalt, Ontario.

F

Minor faults and shear zones trending northeast, southeast, or east were mapped or have been reported (Wilson in prep.; Knight 1924; Thomson 1964a,b,c). None has a displacement of more than a few metres.

The dip of the Archean unconformity surface ranges from horizontal to approximately 30° and rarely exceeds 20° . Coleman Member strata are subparallel or slightly shallower dipping. Knight (1924) suggested that tectonic folding might account for some of the dip variations. This idea is supported by a paleomagnetic study of the Nipissing Diabase which concluded that broad, northeast-trending folds are superimposed on the gentle basin and dome emplacement configuration of the diabase (Symons 1970). Recent workers (Wood 1980; Kim 1979; Legun 1984) proposed that differential compaction over Archean paleotopographic highs accounts for changes in dip attitudes. In their model, present attitudes of the unconformity surface reflect the pre-Coleman Member topography with no subsequent folding. A maximum paleorelief exceeding 200m is apparent from examination of cross sections (Kim 1979; this study) and structure contour maps (Thomson 1961; Legun 1984).

The cross sections accompanying this study show that some lower units of the Coleman Member pinch-out against the Archean unconformity (figures 20, 21). Thickening of lower units in apparent lows and thinning over highs on the unconformity surface is also documented. These observations support the supratenuous folding models.

However, the upper units of the Coleman Member roughly parallel the Archean unconformity surface across areas of high and low topography. This suggests that some tectonic folding of the unconformity surface and the Coleman Member has occurred. When the effects of this folding are considered, the paleorelief in the Cobalt area is estimated to be $< 100\text{m}$ (generally tens of metres). The

paleotopography is envisioned as a series of broad, shallow troughs separated by low rises. Two major troughs, trending northeast, are recognized (see cross sections, Figures 20, 21). One is centred approximately over the present position of the Cobalt Lake Fault. The other is beneath Cart and Peterson Lakes. Minor east- to southeast-trending troughs connect the more extensive troughs in two places (cross sections B-B' and D-D', Figures 20, 21).

Although overall paleotopography of the unconformity is gentle, locally the surface is irregular and rugged. Slopes of $40-50^{\circ}$ with ten to fifteen metres of relief were defined during mapping. These steep slopes delineate small-scale paleotopographic features, slight scarps and depressions rather than major ridges and cliffs.

Slightly higher relief probably existed southeast of the study area (Thomson 1957; Legun 1984), although the effects of later folding have not been estimated. Mountainous terrain as postulated by Schenk (1965a,b) for the Lake Temagami area to the southwest did not exist at Cobalt.

CHAPTER II

UNCONFORMITY SURFACE FEATURES AND BRECCIA

The Archean-Proterozoic unconformity surface is well exposed in the study area. It was closely examined for evidence of erosion by a Huronian ice body. Glacial striae have been reported in two other localities (Cooke 1922; Schenk 1965a,b), but were not observed in the study area. However, the unusual conditions required to preserve an exposed, striated paleosurface (such as protection by overhanging strata of the Coleman Member) were not encountered in the Cobalt area. Three previously unreported features suggesting the presence of grounded ice were discovered.

1. Angular, block-like depressions

Steep-sided angular depressions are common on the unconformity surface (Plate 1A), the sharply defined edges paralleling Archean joint sets. These depressions, less than one metre on their longest surface dimension, are infilled by unsorted, massive Coleman Member diamictite (Dmm or Dcm). The upper tens-of-centimetres of Archean rock and the unconformity surface are generally extensively jointed and fractured relative to typical Archean rock (Plate 1C). Ice-plucking of blocks from the highly fractured bedrock is the likely origin of the depressions.

2. Stepped unconformity contact

Several step-like contacts were observed in vertical exposures of the unconformity surface (Plate 1B). The steps are centimetres to tens-of-centimetres high and face approximately south. As for the plucked depressions, the vertical and horizontal contacts appear to be joint-controlled. These features probably originated by lee-side quarrying at the base of a moving ice mass.

3. Shaped stoss and lee feature

A stoss and lee feature three metres long and one metre high was discovered during the 1984 field season (Figure 3). Developed on Archean volcanic rocks, it displays a streamlined stoss (north) side, (smoothed and striated by Quaternary glaciation) that rises southward to a jagged, vertical, south-facing step-like contact with Coleman Member diamictite. On the lee side of this structure, the diamictite contains large angular clasts of the Archean volcanic rock, many of which can be visually restored to the unconformity surface. As for the stepped unconformity contacts, lee-side quarrying by moving ice is inferred, perhaps with some stoss-side shaping.

These features provide strong evidence for the presence of a grounded ice mass during at least initial deposition of the lower Gowganda Formation. Ice movement in a southerly direction is indicated.

Except in rare areas where special conditions existed, the unconformity surface was swept clean of any regolith which may have been present. This has resulted in the sharp Archean-Proterozoic contact commonly observed (Plate 1D) or occasional ice-plucked or stoss and lee structures with related fragments.

Occasionally, breccia derived from underlying or subjacent bedrock occurs at the unconformity. Most occurrences are thin (<20 cm) and rarely persist laterally for more than a few metres. Most occurrences of these breccias can be related to stoss and lee features discussed above (as in Plate 1B), or are preserved in slight lows on the irregular unconformity surface. The matrix of these breccias is similar to the matrix of the basal Coleman Member diamictite (Plate 1E).

Two rare examples of more extensive basal breccias are shown on

Figure 3. Lee-side plucking of the unconformity surface.

Southward (away from viewer) movement of the Pleistocene ice sheet has shaped this outcrop into a smoothed and plucked rock moutonnee that contains a segment of the Coleman-Archean contact. The Archean basement of felsic volcanic rock is stippled in the line drawing; Coleman Member diamictite is unpatterned, except for a few of the largest Archean clasts. The relationship of the irregular unconformity to these felsic clasts reveals that most of them were derived from the adjacent bedrock. At least one metre of paleorelief is apparent between the highest and lowest portions of the extensively jointed unconformity surface, indicating a southwesterly facing paleoscarp. In conjunction with the evidence for glacial deposition of the Coleman Member presented elsewhere in this thesis, an interpretation of joint-controlled, lee-side ice-plucking by an approximately southwest-moving grounded ice sheet is indicated for the illustrated relationship.

CROSS-SECTIONS North Map

3 OF/DE

SCALE: 1:2000

VERTICAL HORIZONTAL

metres 100 80 60 40 20 0 100 200 metres

LEGEND

PROTEROZOIC

HURONIAN SUPERGROUP CORAL T Group

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES

Upper part of the Gowganda Formation

Gowganda Formation, lower part

Sandstone

Stratified Breccia

Basal Breccia (bD)

Breccia

Angular Unconformity

ARCHEAN

Basic/Ultrabasic Intrusion

Intrusive Contact

Archean volcanic and sedimentary rocks

See legend on accompanying map for detailed lithological code

SYMBOLS

Archean-Proterozoic unconformity surface,
Nipissing Diabase lower contact

Coleman Lithofacies Contacts:

Defined: based on surface mapping and profile

isolated breccia occurrences preserved outside paleotopographic lows are related to ice-plucked or stoss and lee structures. The matrix appears to be composed of Coleman Member detritus. Sericite and chlorite is much less common than in the large breccia lenses. Such features suggest a subglacial origin for these breccias.

However, a paleoregolith interpretation does appear valid for the large breccia lenses. The in situ nature and preservation only in paleotopographic lows supports a pre-Coleman Member origin. The high percentage of fine-grained sericite and chlorite in the matrix may reflect a high original clay content. Frost heaving may have separated blocks to allow later Coleman Member sediments to infiltrate upper regions of the breccias. Slight solifluction could explain the northern movement of fragments at the base of the north breccia (Donaldson and Munro 1982). Much of the south breccia occurs north of its only possible bedrock source and must have moved downslope, as Scammell (1984) suggested. However, this ~~must~~ have occurred during an early period of Coleman Member deposition, because the flow breccia rests on diamictite, and has incorporated matrix and framework material of Coleman Member origin.

The preservation of these breccias in depressions and the flow of the south breccia when the area was covered by an ice mass suggests that subglacial cavities existed at these sites. This interpretation is supported by the presence of a unique clast-supported diamictite overlying these breccias. Features and interpretation of this diamictite are presented in chapters 3 and 4 of this thesis.

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Knight, C.W.
South, Lorr
Report 40
Nipissing Dia
Thomson, R. 1986
Knight, C.W.
Coleman Membr
Knight, C.W.
Mine plans,
1906 to appo
Survey Reside
Field notes
Resident Geol
Resident Geol

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V = H
0 5 metres

SYMBOLS

— Archean-Proterozoic unconformity surface,
Nipissing Diabase lower contact

Coleman Lithofacies Contacts:

- Defined: Based on surface mapping and projected short distances into section.
- Approximate: Based on projection of surface contacts or information from subsurface sources.
- - - Very approximate or inferred: Based on imprecise subsurface information.

Major fault: arrows indicate direction of movement

Minor fault or shear zone (little displacement)

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LEGEND - MEASURED SECTIONS

LITHOLOGIES

Nipissing Diabase, N

DIAMICTITES, D

Clast-Supported

Matrix-supported, stratified

Matrix-supported, massive

SANDSTONES, S

Pebbly

Fine to Coarse-Grained

FINE-GRAINED LITHOFACIES, F

Silt > Clay

Clay > Silt

BRECCIA, Bx

ARCHEAN ROCKS, A

COVERED INTERVAL

CONTACTS

Sharp

Erosional

Deformed

Gradational

Lateral Gradational

STRUCTURES

Ripple Marks

Climbing Ripples

Planar Crossbedding

Trough Crossbedding

Discontinuous Interbed

Dropstone

Deformed Laminations

Rip-up Clasts

VERTICAL SCALE

SECTION WIDTH VS. GRAIN SIZE

COLEMAN NUMBER LITHOFACIES

Diamictite, (D): Lithified, poorly sorted mud-sand-gravel admixture

Dm matrix supported

Dc clast supported

Sandstone, (S):

pS pebbly (>5% gravel)

Sm massive

Sh horiz. lam./bedding

1
OF/DE

Clay > Silt

BRECCIA, Bx

ARCHEAN ROCKS, A

COVERED INTERVAL

Interbedded interval

Dropstone

Deformed Laminations

Rip-up Clasts

VERTICAL SCALE

SECTION WIDTH VS. GRAIN SIZE

COLEMAN MEMBER LITHOFACIES

Diamictite, (D): Lithified, poorly sorted mud-sand-gravel admixture		Sandstone, (S):	
Dm	matrix supported	pS	pebbly (>5% gravel)
Dc	clast supported	Sm	massive
D-m	massive (<10% laminations)	Sh	horiz. lam./bedding
D-s	stratified	Sr	rippled
D-gn	normally graded	St	trough crossbedded
D-gr	reverse graded	Sp	planar crossbedded
D---(r)	resedimented	S-gn	graded, normal
		S-gr	graded, reverse
		S-d	dropstones
bd----	basal: directly overlying Archean unconformity		

Fine-grained, (F): Mudstone, minor very fine-grained sandstone		Breccia, (Bx): Angular fragments of subjacent Archean rocks	
Fr	rhythmically laminated		
Fl	laminated (non-rhythmic)	Bx(r)	resedimented
Fm	massive (<10% laminations)		small
F-d	dropstones		occurrence

OTHER LITHOLOGIES

N	Nipissing Diabase (Proterozoic)	A	Archean, undifferentiated
		Ap	basic volc. rock - pillowed
		Am	basic volc. rock - massive
I	Basic/ultrabasic rocks of Archean age	Af	felsic volcanic rock
		Al	interflow sedimentary rock

Table 1: Lithofacies code used for mapping and section measurement

(based on Eyles et al. 1983).

2
OF/DE
2

occurs, the lower contact is sharp-to-gradational, and the top 10-20 cm of the underlying diamictite also may be faintly laminated (Plate 2F). Most of these rhythmites are the basal component of coarsening-upward sequences that consist of a vertical rhytmite/sandstone/clast-supported diamictite transition. Reverse-order, fining-upward sequences also occur, but are less common and of smaller areal extent. Examination of the maps and cross-sections (Figures 18-21) reveals that these associations occur as fan-shaped bodies which individually cover a maximum area of a few square kilometres and are up to 40m thick. This fan shape is readily apparent in mid portions of cross-sections A-A' and B-B' (Figure 21) and in cross-section D-D' (Figure 22). The surface expression of these examples (Figures 18,19) allows an approximation of the areal extent of each fan (based on the extent of sandstone lithofacies of each sequence). For simplicity these sequences are subsequently termed fan associations.

Rhytmite lithofacies range in thickness to a approximate maximum of 19m. Typically, the basal section consists of silt-clay couplets with a thicker clay component (up to 5 mm). The coarse- to fine-grained quartz-feldspar silt component is sharp-based and normally graded or massive throughout. Micro-loading into the underlying clay is rare. The clay component generally has a sharp lower contact, but normally-graded fine silt is diffused through the lower half. The upper half usually appears massive. Gradational silt-clay contacts also occur. The clay is partially altered to a chlorite/sericite/Ti-oxide mass. Occasional microlaminations, (one silt grain thick) occur within the clay (Plate 3B).

Silt laminations increase in abundance and thickness upwards. Higher in the sequence, composite graded silt layers are separated by thinner clay-silt layers. Sharp loaded basal contacts and complex internal grading patterns are common (eg. reverse-to-massive-to-

microlaminations. Fine-grained sand laminae (rarely thin beds), rare in the lower part of the sequence, are more common in mid-rhythmite sections. Many are discontinuous, with a lenticular to wavy (starved ripple) form (Plate 3D). Some contain faint cross-laminations and basal, deformed microflames, indicating southerly-directed flow.

In the upper part of the rhythmite section, the silt layers are thicker (up to 1 cm) and coarser grained. Sand-silt couplets are increasingly common and the clay component decreases in frequency and thickness. Clay layers are generally less than 5 mm thick and contain fine silt throughout, with a normally-graded silty base (Plate 3E).

Near the top of the rhythmite units, one to three cm thick, normally-graded, fine-grained sand to coarse-grained silt beds become common. Ripples and occasional climbing-ripple sets (A, B, and more abundant sinusoidal types of Jopling and Walker, 1968) are present (Plate 3F). Increasingly frequent fine-grained sand interbeds grade upward into a sandstone unit with no discrete clay laminae. Relatively thick (up to 30 cm), very fine- to fine-grained, massive to faintly laminated sandstones are interbedded in the upper 2-3 m of the rhythmites. These beds are deeply loaded into the rhythmites with associated rhythmite flames deformed and locally thrust to the south (Plate 3G,H). Dish and pillar dewatering structures occur in some of the massive sandstone interbeds (Plate 3I).

In the western part of the study area, the lower rhythmite units (cross-section E-E', west side, Figure 20) are unusually coarse-grained (Frd-Shd). The normal bottom component of the couplets is medium- to fine-grained sandstone grading into coarse siltstone. Many of the coarse layers comprise multiple laminations (both normal- and reverse-

graded), with microlaminated silt-clay units forming the upper component of the couplets. Much of this section contains composite subunits, although the upper clay-rich section is predominantly massive. Rarely, fragments of the underlying silt-clay laminae occur immediately above the sharp, loaded basal contact, indicating erosion during transport (Plate 4A).

Lonestones occur in all of the fine-grained lithofacies, but are most prevalent in the rhythmites. They range from sand-size to 80 cm in diameter. All lithologies that occur in the diamictites are represented. Surrounding laminae are depressed below, draped over, and/or pierced by the clasts (Plate 4B). The pierced laminae are typically contorted and thickened near the clasts. The contact relationships documented for Pliocene dropstones (Thomas and Donnell 1985, fig. 2) were observed (Figure 5) and a dropstone origin for these clasts is inferred. In general, they are rare in the silt-clay rhythmites and common in the coarse-grained rhythmites. The coarse rhythmites in the west section of the study area contain an unusually high number of dropstones, (up to 10%). Some are concentrated in patches or small lenses parallel to the laminations, but the usual occurrence is as lonestones.

Suboval, sand-sized wacke clasts also occur, and are most abundant in the coarse, dropstone-rich rhythmites (Plate 3B,C). They exhibit diffuse margins, elongation parallel to the laminations and compositions similar to the matrix of the diamictites. These appear identical to the pelletoidal greywacke clasts described by Lindsey (1970). He proposed an origin as till pellets, partially consolidated by englacial ice pressure, freed by melting, deposited by ice-rafting and compacted into an ovoid form with elongation parallel to the enclosing laminae.

Figure 5. Contact relationships of dropstones in the study area.

[The terminology for dropstone contacts of Thomas and Connell (1985) are used here.]

A. (see also Plate 4b) Slight bending of laminae below clast accompanied by extreme thinning of subjacent laminae. Piercing of laminae and simple rucking (sharp, upward folding) of sediment against clast edges indicates initial penetration of approximately 3cm. Onlap of laminae above rucking is well-defined.

B. Extreme penetration of approximately 30-40cm by an unusually large clast. Displacement of sediment has caused pronounced rucking and convolute folding of individual strata. Sand beds are thickened on edges of clast due to lateral displacement, but the competency of individual strata was sufficient to prevent breakup.

C. Relatively sharp piercement accompanied by only minor rucking at clast edges and thinning below clast. May reflect greater competence of the clay-rich layers pierced as opposed to silt/sand layers of D.

D. Total penetration of layers by largest clast has caused rupture above the final position of the clast with some laminae extensively distorted (This may indicate a relatively water-rich sediment at the time of clast emplacement, in contrast to 5B,C.

E. Large clast has penetrated numerous laminae. Extreme rupture, convolute folding at clast edges, and break-up of some laminae may be the result of shock and displacement effects in a water-rich sediment.

F. A possible pseudo-dropstone: thinning beneath clast is minimal, downwarp of pierced laminae is limited to one side, rucking is not evident, and clast is not oversized with respect to the overlying

layer. This pseudo-dropstone may have been transported as bedload, with later compaction resulting in piercement of lamina.

Deformation structures are evident in some of the rhythmites. The loaded bases of the massive sandstone interbeds rarely show evidence of extreme deformation, with sections of the underlying rhythmites decoupled and thrust southward several tens-of-centimetres (Plate 3H). In other areas, thin, short-displacement ($<10^4$ cm) thrusts of underlying laminae into the overlying (generally coarser) laminae also occur (Plate 4C). A few examples of convolutedly deformed sets of laminae (<1 cm - 40 cm thick) bounded by undeformed lamina were also observed. This style of deformation is not spatially associated with anomalous lithotypes, as is the first. Two clastic dykes of massive sand which cross-cut and deform the edges of rhythmite units were also discovered (Plate 4D).

Paleocurrents were estimated on the basis of cross-laminations in ripples, climbing ripple drift, asymmetry of ripple crests and deformation of flame structures. Exact measurements rarely could be obtained, because the best exposures occur on vertical faces, and three-dimensional exposures are rare. The paleocurrent directions generally range from southeast to southwest throughout the rhythmite sequences. In the middle to upper sections through the rhythmites, a few northerly directions were observed.

Poorly-laminated Units (Fl, Fm, Fl-Sh)

Massive fine-grained lithofacies are absent in the study area, but rare, thin units of faintly and irregularly laminated mudstones occur in higher stratigraphic positions and as the lateral equivalents of the well-laminated units. For both, a close spatial association with current-sorted sandstones is absent.

These units are composed of wavy to discontinuous silt and clay laminae of variable thickness (most laminae <2 mm thick) (Plates 4E).

10F/DE

Figure 20). The contact is sharp and slightly erosive.

The sandstones are moderately-sorted feldspathic arenites or wackes with 10 to 40% matrix. The framework mineralogy consists of quartz and feldspar in subequal amounts and 10 to 25% lithic fragments, mostly volcanic. Packing ranges from condensed with numerous sutured grain contacts to dispersed with subangular to subround clasts. Clast alteration is limited to slight grain boundary alteration and incipient feldspar sericitization. The matrix consists of silt-sized clasts, abundant chlorite, minor amounts of sericite and Ti-oxide aggregates (sphene?) and rare patchy carbonate alteration. Plate 4G illustrates many of the above features. Kurt (1973) conducted a more detailed petrographic study of three of these sandstones.

In a typical sandstone unit, the basal, thin-bedded, fine- to medium-grained portion contains ripples or small-scale planar crossbedding. This coarsens upwards into medium- to coarse-grained tabular beds (10-50 cm thick), some of which exhibit low-angle planar crossbedding (Plate 4H). In other places, the beds comprise fining-upward coarse- to medium-grained cycles with rare pebbles at the base. Above this, trough crossbedding is occasionally present with overlapping, normally-graded, erosional trough sets containing pebbly lenses at the base. The troughs tend to be 1-2 metres long and less than 25 cm deep as seen in vertical exposures (Plate 5A). Above this, or where trough crossbedding is absent, the upper parts of the sandstone units are very coarse-grained, thin to medium bedded (<5-20cm) graded cycles of small pebble/granule to coarse-grained sands (Plate 5B,C). Normal, reverse or inverse-to-normal grading is present. Most cycles are normally graded with an unstratified pebble-granule component grading into a faintly laminated (rarely cross-laminated) coarse-grained

Figure 23. Locality Map for Photographs

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Clast-supported diamictites are the areally least extensive unit of the fan association (see cross-sections, Figures 20,21, back-pocket). Diamictite thicknesses exceed 20 m in some coarsening-upwards sequences, but more commonly are less than 15 m. The basal contact may be sharp and erosional, but is commonly gradational with respect to the underlying sandstone. Where the diamictite directly overlies a rhythmite unit, the base is sharp, erosional and loaded.

The diamictite consists of a poorly-sorted, intact framework of 70-90% gravel-sized clasts (Plate 5E). Most are small-pebble to small-cobble size, but large cobbles and boulder clasts are common in some of the occurrences. Clast lithologies are diverse with volcanic (mafic > felsic) and granitic rocks accounting for over 90% of the total. Sedimentary, metamorphic and rarely sulphide clasts are also present. Clasts range from subangular to subrounded, with volcanic clasts more rounded than the igneous clasts in the planar, two-dimensional exposures examined. Most shapes appear to be equant to slightly ovoid.

The sand fraction of these diamictites is a moderately- to poorly-sorted, medium- to very coarse-grained feldspathic arenite (rarely a wacke). Sand and matrix characteristics are similar to those described previously. Many of the quartz and feldspar clasts appear to be derived from plutonic sources, a contrast to the high percentage of volcanic clasts in the gravel-sized fraction.

In a few places, a thick (up to 15 m) basal subunit can be differentiated within the diamictites of the coarsening-upwards associations. It appears massive and unsorted on most weathered surfaces and generally was mapped as Dcm or Dcm-Dcs (see maps, Figures 18,19, back-pocket). A crude stratification is apparent in good

exposures and in some cut slabs. In some exposures inverse grading can be seen in the lowest 20-50 cm. Above this (or where it is not present), a weak horizontal alignment of clast long-axes and poorly-developed graded cycles were commonly apparent (Plate 5F). Bedding could not be precisely defined. Rarely, thin (<15 cm), discontinuous pebbly-sandstone lenses occur in the upper portions. Apparent long-axes of clasts are preferentially oriented along south or southwest azimuths (Figure 7G-J). This is parallel to paleocurrent directions determined in the underlying sandstones (Figure 6A-D).

A moderately-sorted, obviously stratified diamictite (Dcs) occurs where this subunit is not present. It can also overlie this unit with a sharp or gradational contact. It usually consists of poorly defined, normally-graded beds tens of centimetres thick with pebble/cobble bases and granule- to coarse-grained sandstone tops (Plate 5G). In some areas, this upper subunit is well defined, with distinct graded cycles and faint planar (to trough?) cross-stratification visible in the pebbly-sandstone upper portion (Plate 5H). Rarely, a cycle grades up into asymmetrically-rippled fine-grained sandstone with a thin (<1 cm), laminated, siltstone top.

Clast-supported diamictites in fining-upward associations closely resemble the previous subunit. Poorly defined beds are up to 50 cm thick. The lower 10-30 cm consists of, moderately-sorted, faintly graded pebble-to-small-pebble clasts. This grades sharply into a coarse-grained, pebbly-sandstone which also fines upward slightly (Plate 6A). In a few places a lower subunit of diamictite similar to the poorly stratified lower unit described previously is also present. Apparent long-axes of clasts in these units are randomly oriented on bedding surfaces (Figure 7K,L).

Figure 7. Clast apparent long-axis orientations for diamictites of Fan and Interfan Associations. Sample sites are shown in Figure 15, Appendix 4. The lithofacies is shown in the upper right corner of each diagram (see Table 1 for lithofacies code). Explanation of symbols as for Figure 4.

Rarely, clast-supported diamictites occur as small, discontinuous bodies within the other lithofacies. These channelized, lens-like units decrease in thickness from a central few metres, pinching-out on both sides within tens of metres. They have a sharp, erosive base with the lithofacies containing them (most often Frd-Shd, bDmm, or Dms). Most consist of a moderately-sorted, small-cobble to small-pebble layer which grades into a thin sandstone. Some comprise repetitive beds of normally-graded, gravel- to sand-sized clasts. Faint horizontal bedding/lamination or rarely, planar cross-stratification are present in the sand-sized portion.

3.5 Heterolithic Diamictite Complex

This association comprises diamictites complexly intercalated with sandstones and fine-grained lithofacies. Lithotypes do not occur as stratigraphically confined units, as does the basal diamictite, or as members of a well-defined sequence of changing lithofacies as for fan associations. The prefix "upper" was used during mapping to distinguish this association from the basal diamictite.

This complex can be subdivided into units that occur at approximately the same stratigraphic position as the fan associations and overlying units that form the stratigraphically highest lithologies in the study area. The higher assemblage is approximately restricted to the area bounded by the Valley Fault on the west and the Cobalt Lake Fault on the east, plus the highest units west and north of the Valley Fault (Figure 18 and cross-sections C-C', E-E', F-F'; Figures 20,21, back-pocket).

Lower Stratigraphic Assemblage

Lithologies of this assemblage generally overlie fine-grained or

sandstone lithofacies of the fan associations. Occasionally, this diamictite complex directly overlies the basal diamictite or the unconformity surface, making distinction of a bDmm unit difficult or impossible (eg. northwest side of cross-section C-C', Figure 20. back-pocket).

The most common lithology is matrix-supported diamictite, either stratified (Dms) or massive (Dmm). The former consists of units 0.5 - 15 m thick. The thick sections actually may be composite units, because contacts between separate Dms subunits are generally not distinguishable unless another lithology is interbedded (Plate 6B). Gravel-sized clasts typically form 10-70% of a unit and consist of angular to subrounded granules to boulders (largest observed: 140 cm). Some of these clasts appear faceted (Plate 6D). Framework clasts are dispersed in a very poorly sorted, feldspathic wacke similar to that of the basal diamictite, but with occasional faint stratification at thin-section scale. This consists of a subparallel alignment of elongate sand-sized clasts and rarely, the presence of faint, wavy laminations. A crude stratification is also apparent at outcrop scale, consisting of wavy laminations and/or a rough subhorizontal alignment of elongate, gravel-sized clasts. Rarely, a poorly-developed imbrication is apparent. Some clasts have deformed and/or pierced the faint, wavy laminae, suggesting a dropstone origin.

This lithology occurs interbedded with other diamictite, sandstone and fine-grained lithofacies. Where discernible, the lower contacts are sharp and in places erosive into the lower unit. This is especially noticeable where underlying laminated fine-grained units occur (Plate 6D). Upper contacts are generally indistinct with overlying diamictites, and sharp with non-diamictites. Rarely, dewatering has caused

intermixing of sands and diamicton, disrupting the contacts. Projecting clasts are occasionally present at the top contact.

Some diamictites appear to be massive (Dmm). These generally contain fewer gravel-sized clasts (<30%), but are otherwise identical to the stratified diamictites. Thin, discontinuous, contorted sandstone lenses are rarely present. The massive diamictite units can be thick (up to 15 m), but recognition of subunit contacts is difficult unless another lithology is interbedded.

The lateral extent of the matrix-supported diamictites is difficult to ascertain due to the subtle contacts between coincident units. In many areas, no definite change in diamictite type is apparent over hundreds of metres of exposure, suggesting relatively extensive sheets, although a composite of multiple, virtually identical subunits is suspected. In some places, thin discontinuous lenses of this diamictite can be mapped.

Unusual structures observed in the matrix-supported diamictites include a grooved surface on the top of a Dms unit. At the largest exposure (Plate 6E), linear, parallel grooves (2-20 mm amplitudes and 5-10mm wavelength) are oriented in a direction (135°) which roughly coincides with the local paleoslope. The grooves disappear beneath another Dms unit and have a thin, patchy, siltstone drape, eliminating the possibility of Pleistocene origin.

Two unusual sedimentary boulders were found in Dms units. Both consist of pebbles and cobbles with a wacke matrix and appear identical to Coleman Member clast-supported diamictites (Plate 6F). The irregular clast boundary is defined by complete, projecting cobbles or pebbles, supporting a synsedimentary source. The example in Plate 6F occurs in

faintly- to well-stratified transitional Dms-Frd. It both depresses and pierces faint laminations. This observation, supported by orientation of the boulder with its largest cobbles at the bottom, suggests final deposition as a dropstone.

A third unusual feature is the rare occurrence of isolated gravel-sized, intact-framework clusters (Dcm) in the generally dispersed-framework Dms units. These clusters tend to be ovoid in sections approximately parallel to bedding and are up to several metres in maximum diameter.

Other lithologies are interbedded with the matrix-supported diamictites. Clast-supported diamictites (Dcm or Dcs) occur as sheets or lenses, usually <2 m thick (rarely up to 5 m). Most of the lensoid units are channelized, moderately-sorted, and fining-upward as previously described (page 38). Sheet-like Dcm units are generally massive, with a sharp, slightly loaded, non-erosive lower contact, although erosional contacts were rarely observed (Plate 6G). These poorly-sorted units exhibit a wide range of grading patterns. Some are nongraded or have a crudely-defined, coarse central portion with nongraded, unsorted top and bottom sections. Some show vague normal grading, with projecting clasts at the top surface (Plate 6H). A thin, finer-grained, laminated or rippled bed drapes some of these units (Plate 7A). Inverse- to normal-graded sequences also occur.

An unusual Dcm unit of variable thickness (2-5 m) occurs in the southeastern part of the map area (cross-section A-A'; east side, Figure 21). It consists of an unsorted framework of gravel-sized clasts with an unusually large boulder fraction (>20%; largest: 2.7 m). Some of the large boulders are broken and the fragments are slightly separated (Plate 7B,C). The spaces between the fragments have been infilled by

the enclosing diamictite. Most of the broken fragments are not significantly dispersed, reflecting in situ fracturing of the clasts. The top contact of this unit is irregular, with some clasts projecting more than 10 cm. An overlying Fl-Sh unit covers and infills between the projecting clasts. Compaction may have accentuated, or even caused, such draping of the laminated unit around the uppermost clasts.

Apparent long-axis orientations of clasts in these diamictites (both massive and clast-supported) are preferentially oriented along a southeast to southwest azimuth (Figure 7A-F).

Sandstones occur as discontinuous sheets or lenses. These are generally coarse- to medium-grained feldspathic arenites or wackes, less than 2m thick and tens to a few hundred metres in extent where this could be determined. Most have sharp, loaded or erosive bases with underlying matrix-supported diamictites and conformable, draping contacts with clast-supported diamictites. Usually they consist of a single bed which is apparently massive or graded. Inverse to normal grading is common (Plate 7E), although normally-graded sequences also occur, some with a thin overlying faintly-laminated and locally rippled mudstone or fine-grained sandstone.

Two fine-grained lithofacies are associated with the lower portion of the diamictite complex. The most extensive are part of the fan association and occur below or are laterally transitional to the diamictite complex. Where a lateral progression from coarse-grained Frd-Shd lithofacies to stratified diamictites is observed, complex and abrupt lithologic variations are typical. A less abrupt and sharply intercalated lateral transition also occurs. In one area (cut by cross-section C-C', east side; Figure 21, back-pocket), a gradational

southward transition from Dms to Frd occurs over a few hundred metres. To the north, 10-15% pebble- to boulder-sized clasts are dispersed in a faintly and irregularly laminated fine-grained wacke which directly overlies the basal diamictite (see MS-5, Appendix 1). Southward, the matrix size decreases, laminations become more regular and gravel-sized clast percentage decreases. The stratigraphically equivalent unit to the south is a well-laminated rhythmite (Frd) that contains rare dropstones (Plate 3A). This rhythmite unit contains a thick (thinning from 7 m to 2 m over 200 m, shown on cross-section B-B' east side; Addition 4, back-pocket), tapered sheet of massive, clast-supported diamictite composed mostly of large pebbles, cobbles and sparse boulders. It occurs within the Frd unit with a sharp, loaded, lower contact and an irregular upper contact with projecting boulders, draped by Frd (similar to Plate 7D).

Irregularly laminated mudstones also occur in the lower stratigraphic assemblage. They are not obvious components of fan association sequences, although their stratigraphic position suggests that many are laterally equivalent to the rhythmites of other areas. These poorly-laminated units were described in detail in the previous section (Fine-grained Lithofacies).

Upper Stratigraphic Assemblage

The highest stratigraphic units in the study area consist of a complex series of diamictite bodies with minor occurrences of other lithologies. This portion of the Coleman Member at Cobalt is preserved in a relatively small area, and most exposures are restricted to isolated occurrences, with the exception of the ridge where a detailed section (MS-4) was measured (Appendix 1).

Matrix-supported diamictites within this upper portion occur as

thick (up to 10 m) tabular sheets, although, as for the lower assemblage, it is difficult to distinguish contacts between multiple Dms or Dmm units. Units include massive, unsorted Dmm with 10-50% granule- to boulder-sized clasts, most subangular to subrounded, dispersed in feldspathic wacke. Some Dm units are faintly stratified with irregular thin sandstone lenses. Others contain a wavy, nonrhythmically-laminated matrix of fine-grained sandstone and mudstone (Plate 7F). Apparent long-axes of clasts within these diamictites are randomly oriented (Figure 8A-D).

Clast-supported diamictites also occur. Some appear massive but have a reverse-graded base (up to 50 cm thick) that rests on a surface slightly eroded into the underlying unit (Plate 7G). A few discontinuous (<5 m), thin (<10 cm), Fl lenses appear to be interbedded with these thick (up to 17 m) units, suggesting that they actually consist of multiple subunits. Above these Fl interbeds a thin, reverse-graded zone is locally apparent. Rare stratified, clast-supported diamictite typically consist of a crudely stratified, poorly-sorted, intact-framework of granule- to boulder-sized clasts with a feldspathic wacke matrix. Stratification consists of a subhorizontal alignment of elongate clasts, a crude bedding defined by poorly developed size-sorting (poor normal- or reverse-graded cycles) and the rare occurrence of discontinuous pebbly-sandstone interbeds which show a poorly developed normal-grading. Apparent long-axes of clasts strongly trend along a southwest azimuth (Figure 8E-G).

Fine-grained units within the higher diamictite package tend to be nonrhythmic, poorly laminated mudstones similar to those described for the lower stratigraphic assemblage. Most occurrences are not associated with coarser-grained, stratified sequences as in the lower stratigraphic

Figure 8. Clast apparent long-axis orientations for diamictites of the Upper Diamictite Complex. Samples sites are shown in Figure 16, Appendix 4. The lithofacies is shown in the upper right corner of each diagram (see Table 1 for lithofacies code). Explanation of symbols as for Figure 4.

packages. In thin section, the nonrhythmic nature of the laminations and diffuse contacts between laminae are readily apparent (Plate 7H). A more regularly laminated and continuous, but nonrhythmic, unit exists in a few places. Diamictite lenses with erosional bases (Plate 7I), lonestones, and discontinuous beds of gravel-sized clasts, are present in a few places within these units.

CHAPTER IV

LITHOFACIES INTERPRETATIONS

4.1 Basal Diamictite Association

The characteristics and facies associations of the basal diamictite suggest an origin as a subglacially deposited, primary basal till (as defined by Boulton and Deynoux 1981; equivalent to the subglacial orthotill of Dreimanis 1983). Although definitions of till (and tillite, the lithified equivalent) vary, most authors agree that original transport and deposition by or from glacier ice is fundamental (see review in Dreimanis 1983). However, there is considerable disagreement on the amount of subsequent water-working or resedimentation a till can undergo and still be classified as a till. Opinions range from allowing no subsequent resedimentation (Lawson 1981), to minor resedimentation without disaggregation (Boulton 1972), or even significant penecontemporaneous resedimentation, including settling through a water column (Dreimanis 1979, 1983; Gravenor et al. 1984). For this study, the relatively restrictive definition of Boulton (1972) is used. The many diamictite units in the study area show a great range of features and facies associations, suggesting a complex depositional history. The discrimination of a tillite in the restrictive sense is regarded as more useful than inclusion of possible tillites that also display resedimentation features compatible with alternate modes of deposition.

Recent papers which summarize criteria for the identification of tillites vs. diamictites of non-till origin include Boulton and Deynoux (1981), Anderson (1983), Dreimanis (1983) and Gravenor et al. (1984). All of these authors stress that no one criterion uniquely

differentiates tillite. Only the association of several characteristics can be regarded as a reliable indication of till origin (*sensu stricto*).

The stratigraphic position of the basal diamictite and its relationship to other facies supports a subglacial tillite interpretation. It directly and sharply overlies a glacially scoured and shaped basement or, rarely, another diamictite which is interpreted to be a subglacial, lee-side tillite. The basal diamictite is sharply or gradationally overlain by dropstone-bearing rhythmites or other glacially-derived lithofacies. It is laterally persistent, occurring on paleotopographic slopes, highs and lows.

Lithologic characteristics of the basal diamictite also are typical of basal tills. It incorporates the immediate substratum (lee-side derived breccia). It also contains both far-travelled clasts (plutonics and high-grade metamorphics) and volcanic clasts similar to local lithologies (although most volcanic clasts are not diagnostic of distance of travel, because massive and pillowed volcanics are common throughout the Abitibi Subprovince). The apparent shapes of gravel-sized clasts correspond well to those shown by Boulton (1978) to indicate basal or low-englacial transport paths. The highly spherical and commonly subrounded granitoid clasts are the expected end-member of extensive transport in the basal traction zone of the glacier. Faceted clasts, an intermediate form according to Boulton, are relatively scarce at Cobalt; this may reflect extensive basal transport and/or the difficulty in recognizing this form in two-dimensional lithified exposures. The latter suggestion is supported by Coleman's (1907, 1908) description of faceted and striated (in two or more directions) pebbles and cobbles recovered from underground mine workings at Cobalt. Both framework and matrix of the basal diamictite exhibit textural

features that are common to tills. The lack of sorting and the mineralogical immaturity (ie "fresh" feldspars and high lithic grain content) are typical of till matrix (Anderson 1983). The high percentage of silt-sized clasts and the subangular, broken appearance of many silt- and sand-sized clasts may reflect comminution in the basal traction zone (as described by Boulton 1978).

The generally massive nature of the basal diamictite is common in basal tills (Boulton and Deynoux 1981, Anderson 1983, Dreimanis 1983, Gravenor et al. 1984). The sporadically distributed and irregularly laminated, upper zone may represent englacially layered sediment. Such deposits have been observed in recent tills by Boulton 1970 and Lawson, 1981, but are rarely preserved within Pleistocene tills (Boulton 1970). A more likely explanation is reworking during deposition of the overlying lithofacies (usually rhythmite). The discontinuous sandstone lenses rarely observed in the basal diamictite also have a counterpart in Pleistocene and recent tills. Kruger (1979) cites thin, distorted, discontinuous sandstone lenses as indicative of basal till, and suggests an origin from local and temporary meltwater concentrations.

The apparent long axis orientations of large clasts within the basal diamictite show a strong northeast-southwest trend. This conforms with the dominant southwest direction of ice movement deduced from stoss and lee structures and derived breccia; similar ice movement has been proposed in other studies (Cooke 1922, Schenk 1965a,b, Lindsey 1967). Orientations of clast long axes parallel to the direction of ice movement is typical of subglacially derived tills (Holmes 1941; Boulton 1971; reviews by Andrews 1971; Domack and Lawson 1985). Up-ice imbrication of clasts is also common in basal tills (Boulton, 1978), but

the exposure type and high induration at Cobalt precludes this type of fabric study.

Rare discontinuous intrabeds of stratified, pebbly sandstone and clast-supported diamictite which occur at the lower contact, or within the basal diamictite, also have parallels in Pleistocene basal tills. Shaw (1977) describes similar units in a thick sequence of melt-out till, and interprets the stratified lenses as the accumulation from small subglacial and englacial meltwater channels. A similar origin is proposed for the stratified intrabeds of the basal diamictite.

The several lines of evidence presented above strongly support a till origin in the restricted sense and, more specifically, an interpretation as a subglacial, primary till. Primary till is commonly subdivided into two major types: lodgement and melt-out (Boulton and Deynoux, 1971; Dreimanis, 1983; Ashley et al. 1985). ~~Lee~~-side till is a special type of lodgement till according to Boulton 1978. Many of the principal distinguishing criteria for lodgement till (reviewed by Eyles et al. 1982) are lacking in the basal diamictite, including fissility, shear lamination ("smudges" of Kruger 1979) and a systematic jointing pattern. However, it seems unlikely that these features would be preserved in the highly indurated, metamorphosed, post-lithification-jointed, basal diamictite. Most other criteria for the recognition of lodgement till also apply to basal melt-out till (clast orientation and shape for example). Although the presence of stratified intrabeds and thin discontinuous sandstone lenses in the basal diamictite supports a melt out genesis, the basal diamictite lacks sufficient features to conclusively select the appropriate subdivision.

The unusual clast-supported diamictite which overlies the unconformity surface regolith in two paleodepressions also appears to be

a subglacial deposit. The massive, non-sorted nature and occurrence directly below the basal tillite suggests a tillite interpretation. However, preservation of the regolith in paleodepressions and restricted occurrence of the Dcm in paleodepressions suggests a unique mode of subglacial deposition in which subglacial cavities formed at a south-facing scarp. The unusual diamictite overlying these breccias is interpreted as a subglacial, lee-side deposit in these cavities. Boulton (1971), Eyles and Menzies (1983) and Hillefors (1973) discussed possible mechanisms of deposition in lee-side cavities. Boulton (1978) termed these deposits lee-side tills. A possible model for the Cobalt occurrences is shown in Figure 9. Basal debris, much of it locally derived, is expelled from the overriding ice due to pressure-release and collects in the cavity. The random orientation of clast long-axes in this diamictite (Figure 4A) may reflect such subglacial expulsion of clasts into a cavity. Lack of stratification and sorting in the clast-supported diamictites or reworking of the north breccia implies that little meltwater was present. This suggests flow of the south breccia downslope may have been a slow, slope-creep event rather than a rapid water-saturated mass flow. The faintly-stratified, matrix-supported diamictite lens below the south breccia suggests some early subglacial meltwater activity.

Figure 9. Model for subglacial deposition in a lee-side cavity based on Hillefors 1971; Boulton 1971; Eyles and Menzies 1983).

4.2 Subaqueous Outwash Fans

The coarsening-upward fan associations are interpreted as deposits of subaqueous outwash fans as defined by Rust and Romanelli (1975), termed subaqueous esker-deltas by Thomas (1984). Many features suggest that deposition occurred in a subaqueous environment: sandstones within the fan associations contain dropstones; the fan lithofacies are at the same stratigraphic level as, and overlain by, diamictite-rhythmite-sandstone lithologies that also contain dropstones; sedimentary structures indicative of subaerial exposures are completely lacking from all lithofacies within the study area; regionally, the Coleman Member is conformably overlain by nonglacial, marine, prodeltaic mudstones deposited below wavebase (Rainbird 1985).

Rhythmites and the nonrhythmic, fine-grained lithofacies are interpreted as lower-fan and fan-distal deposits. Paleocurrent indicators and the lithologic distributions suggest that the southerly-directed meltwater discharges were the only significant current-source in this part of the basin. Laterally equivalent poorly-laminated mudstones may represent distal areas where the direct effects of this meltwater input were rarely felt. Similar types of deposits are described from glaciolacustrine lakes by Smith (1978) and Gustavson (1975). Alternatively, if the basin was marine, the poorly-laminated mudstones could reflect normal marine sedimentation in relatively distal areas where the high sediment concentrations and lowered salinity due to high meltwater discharge do not strongly affect the sedimentation patterns (Mackiewicz and Powell 1982; Domack, 1984).

The thin, basal silt-clay rhythmites are interpreted as distal-fan deposits. Whereas a marine environment is possible (discussed in Chapter 5), the characteristics of these sediments are very similar to distal

rhythmites/varves described from glaciolacustrine lakes (Ashley 1975; Gustavson et al. 1975; Gustavson 1975; Ashley et al. 1985). The sharp, non-erosive couplet contacts, lack of current-structures, thicker clay than silt layers, and generally sharp silt-clay contacts are similar to features described from rhythmites formed by sediment-rich interflow/overflows (Ashley et al. 1985; Ashley 1975). These correspond to the distal varves of Bannerjee (1973), lake varves of Gustavson et al. (1975), and Group I varves of Ashley (1975). Ashley et al. (1985) provided a review of known processes of interflow/overflow formation and resultant deposits. They concluded that the differentiation of interflow from overflow deposition is impossible on the basis of sedimentary characteristics alone.

Some couplets in the lower rhythmites are continuous, normally-graded sequences without distinct silt-clay contacts. This is more typical of density-driven, turbid underflow deposits (Kuenen 1951; Bannerjee 1973; Ashley 1975), which can be a result of quasi-continuous distal meltwater underflows or short-lived, slum-generated surge-currents (Ashley 1975; Shaw and Archer 1977). The scarcity of microlaminae in the couplet layers and the transitional silt-clay contact is more consistent with single sudden-event deposition rather than irregular, long-term deposition from meltwater underflow (see discussion in Ashley et al. 1985; p. 197).

The intermediate rhythmites show an increase in multiple silt lamina, complex grading patterns and more evidence for basal currents (deformed flames, rare cross-lamination) in comparison to their distal equivalents. These features suggest deposition predominantly by density underflows as proposed for the Group II varves of Ashley (1975) or

intermediate varves of Bannerjee (1973). Sharp silt-clay contacts are still relatively common, and the silt layer microtextures (laminae, multiple grading) indicate underflow rather than overflow/interflow conditions in many cases. Multiple graded silt laminae within similar Pleistocene and recent rhythmites are commonly attributed to the unsteady nature of the quasi-continuous meltwater underflow or fluctuations in sediment content of the meltwater stream (Ashley 1975; Shaw 1975; Gustavson et al 1975; Smith 1978). Flow types were probably combined with underflows becoming increasingly important closer to the meltwater influx point, changing to overflows/interflows in more distal areas. Slump-generated surge currents also occurred. They best explain rare starved-ripple sequences and single, anomalously-coarse laminae or thin beds of sandstone or coarse siltstone, rarely cross-laminated.

Thicker rhythmites of the upper rhythmite sequences are interpreted as proximal basin deposits or fan bottomsets (delta varves of Gustavson et al 1975; Group III varves of Ashley 1975). Underflows appear to have been the dominant sediment transporting agent, as suggested by the presence of ripple cross-bedding, multiple normally-graded fine sand and silt lamina and local erosion of underlying rhythmites (producing scours and rip-ups). As with the intermediate rhythmites, the multiple coarse-grained laminae probably indicate velocity pulses in the quasi-continuous underflow. Fluctuating discharge velocities and sediment concentrations are well-documented in modern glacial meltwater currents (Smith 1978; Gustavson 1975). Rare, thin clay laminae within multiple sand-silt lamina may indicate pauses in the overall discharge pattern (Ashley et al. 1985). Thicker (up to 5 mm), normally-graded, silt-rich clay laminae are thought to represent periods of low sediment input, an interpretation proposed for similar Pleistocene sequences (Gustavson et

al 1975; Ashley 1975; Ashley et al 1985), These major discharge fluctuations could be seasonal, but the presence of other controls on discharge rates in modern environments makes such a conclusion tentative (see Smith 1978 for discussion). The grading and silt content of these clay laminae may indicate a lack of flocculation as has been proposed by Ashley (1975) for similar clays in her Group III varves.

The massive to faintly laminated sandstone beds which occur within upper rhythmite sections are interpreted as sediment gravity flows off prograding mid- to upper fan regions. The ~~generally~~ massive beds, occasional dish and pillar structures and lack of basal erosion are indicative of transitional grain flow/fluidized flow (Middleton and Hampton 1976), termed liquefied/fluidized flow by Lowe (1976b, 1979). The main grain support method for these flows was probably a combination of dispersive pressure and escaping pore fluid. Loading of these beds into the underlying rhythmites suggests that the entire bed flowed en masse onto the water-saturated muds. These sand accumulations are associated with some of the deformation features in the rhythmites. For example, thrusting of rhythmite layers into the sands (Plate 3H). Where thrusting has not occurred, the basal sandstone contact is deeply loaded with large asymmetric flames of rhythmite showing southward transport. This load and flame deformation of the water-saturated rhythmites was followed in some areas by the decoupling of flame structures on the south edge and downslope thrusting of rhythmite sections. Shear stress caused by the rapid deposition of the sand flow is thought to account for this deformation. Similar but less extensive downcurrent deformation occurs in other subaqueous fans, and was also related to loading by sediment flows (Rust and Romanelli 1975).

Minor, short-displacement, downslope thrusts of rhythmite laminae (Plate 4C) appear to be a result of downslope shear stress. Rare, convolutedly deformed packages of laminae seem to fit the generally postulated origin of liquefaction deformation as discussed by Lowe (1975), and Mills (1983). Convolute bedding and thrust faulting in rhythmites have been interpreted to be indicators of overriding by advancing/readvancing glaciers (Hansen et al. 1961; Moran 1971). However, relative rarity and localized occurrence of these features at Cobalt suggests that they instead reflect minor deformation, probably from downslope drag forces generated by slumps, sediment flows, sudden sediment loading, or normal compaction effects on a slope (as suggested for similar types of deformation by Mills 1983; Visser et al. 1984). Rare clastic dykes of massive sandstone that cut the rhythmites are considered to be dewatering structures where fluidized sands were injected upwards from underlying, overpressured sand units, a process discussed by Lowe (1975). The above methods also can trigger clastic intrusions (Lowe 1975).

A few isolated high-angle normal and reverse faults are probably due to compaction, as suggested for similar structures in the Dwyka Formation in South Africa (Visser et al. 1984). These do not resemble the paired high-angle fault systems seen in Pleistocene sequences and interpreted to be the result of the melting of buried ice blocks (McDonald and Shilts 1975; Boulton 1972; Shaw 1977). No features suggestive of buried ice masses were observed in the study area.

The transitional contact of rhythmite-sandstone units reflects the continuous distal to proximal variations in grain-size and sedimentary structures due to increased velocity and coarser-sediment load closer to the site of meltwater influx. A proximal-distal pattern of sedimentary

structures and grain-size variations is a common characteristic of delta or fan deposition, both in glacial and nonglacial environments (Gustavson et al. 1975; Church and Gilbert 1975; Walker 1984).

The thinly-bedded, graded, fine-grained sandstones of the sandstone-rhythmite transition and the lower portions of the continuous sandstone bodies are interpreted to be more proximal equivalents of the finer-grained rhythmites. Deposition is again thought to have resulted from quasi-continuous underflows. The fluctuating nature of these flows is reflected in the grading, occasional ripple forms and small-scale planar cross-laminations that are preserved within these beds. Climbing-ripple sequences are not abundant in the rhythmite-sandstone transition, in contrast to many Pleistocene and Recent deposits (Gustavson et al. 1975; Jopling and Walker 1968; Ashley et al. 1985). Where poorly-developed climbing-ripple sequences are developed, the sinusoidal lamination form of Jopling and Walker (1968), termed draped lamination by Gustavson et al. (1975), are most abundant. Flume studies suggest that this structure results from suspension settling during the waning stages of short-period, lower-flow-regime pulses (Ashley et al. 1982). The relative scarcity of climbing-ripple structures at Cobalt must reflect flow strength and/or sediment concentration levels that preclude the formation of this structure.

Planar cross-bedded and occasional trough-crossbedded sandstone and pebbly sandstones of the upper sandstone bodies reflect higher current velocities in increasingly proximal areas. Graded cycles of pebble-granule-coarse sand beds reflect temporal flow fluctuations. Bannerjee and McDonald (1975) interpreted similar gravel-sand cycles in a Pleistocene esker-delta as representing annual flow variations. An

annual periodicity is possible for the Cobalt examples, but existence of non-seasonal controls on meltwater discharge rates makes such a specific interpretation impossible. Rare, isolated beds of massive to faintly stratified, non-graded, clast-supported pebble diamictite within the pebbly sandstones are interpreted to be debris flows from fan apical diamictites. These coarse flows may initiate, or be proximal equivalents of, surge-current deposits and other sediment flows seen in the more distal facies.

Variations in the overall coarsening-upward sandstone-pebbly sandstone trend occur. An example is the sudden upward transition in MS-7 (Appendix 1) from coarse-grained sandstone to graded, gravel-pebbly sandstone, then to cross-bedded sandstones. This and similar sequences may reflect migration of discharge currents across mid- to upper-fan areas.

The clast-supported pebble-cobble-boulder diamictites which commonly cap the sandstone units are thought to be deposits at the fan apex, which roughly corresponds to the subglacial meltwater influx site. The proximal gravel facies of other subaqueous outwash fans have similar characteristics (Rust and Romanelli 1975; Rust 1977; Cheel and Rust 1982; Thomas 1984). The poor sorting, crude stratification and poorly-developed grading patterns suggest rapid deposition from meltwater streams suddenly exiting from confined subglacial/englacial tunnels. This interpretation is supported by the parallel-to-flow clast long-axis orientations characteristic of some of these diamictites (Figure 7G-J). These orientations can be due to saltation transport of high gravel concentrations near the bed (Rust 1977; Walker 1984). The high energy conditions required for saltation transport of cobbles and boulders is dissipated after exit of the meltwater from the tunnel into an unrestricted basin. Some bedload rolling of clasts is indicated by

the slight transverse-to-flow orientations. A lack of observed channels is common to the Cobalt deposits and to those of Rust and Romanelli (1975), a feature Rust (1977) felt ~~could be~~ due to the difficulty in distinguishing such forms in the very coarse-grained material.

In some sequences, cyclic, normally-graded pebble-granule-coarse-grained sand beds occur above the thick, crudely stratified, clast-supported diamictite. Textures and sedimentary structures are similar to those in the graded cycles occurring below the diamictites. They could be due to lateral migration or waning flood-stage currents of the main meltwater flow in proximal areas of the fan, or might reflect a rapid retreat of the ice-front, causing overlap of more distal upper fan facies onto the fan apex gravels. Possible ice-front controls on sedimentation are discussed in more detail in Chapter 5.

The thinner, less extensive, fining-upward fan associations usually contain lithologies and sedimentary structures similar to those of the coarsening-upward fans. Similar overall proximal-distal trends are observed, but with a reverse order of vertical sequences. In the best exposed example (base of MS-1, Appendix 1), the crudely-stratified proximal gravels of the larger fans are not present. The lowest unit consists of cyclic, normally-graded, clast-supported diamictite, pebbly-sandstone beds which grade vertically into thinly-bedded, dropstone-rich, proximal rhythmites. Fluctuation in flow strength of meltwater underflows again appears to be responsible for these cyclic deposits. The relative thinness of these associations and their fining-upward trends, suggest deposition during short periods of high meltwater activity, combined with rapid retreat of the ice front (discussed in

Chapter 5). The random orientation of clast apparent long-axes in these

beds is unexpected. Possibly it reflects saltation and bedload rolling transport in a small channel combined with fluctuating (waning overall) currents. This could cause preferred orientations both parallel and perpendicular to the flow direction, in this case giving a seemingly random overall pattern. The possible bimodal trend of Figure 7L supports this hypothesis.

4.3 Lower Assemblage - Heterolithic Diamictite Complex

The diamictites, sandstones and minor fine-grained lithofacies of this assemblage occur in interfan areas where meltwater currents were not dominant depositional agents. Most of these lithologies are interpreted to be the deposits of sediment gravity flows, originating from prograding fans, ice-marginal banks or perhaps from flows off the ice sheet itself.

Sediment gravity flow (also called sediment flow or mass flow) is sediment transport in which movement parallel to the bed is due to gravity (Middleton and Hampton 1976). It encompasses a wide range of flow types and resultant depositional sequences. The classification scheme and nomenclature of Lowe (1979, 1982), used here, is based on the nature of the dominant sediment-support mechanism and the flow behaviour (plastic or fluid), and differs slightly from the Middleton and Hampton (1976) classification as shown in Table 2.

Rhythmite units are common at the base of, and intercalated within this heterolithic complex. These were interpreted earlier as distal fan interflow/overflow deposits. Poorly-laminated mudstones were interpreted as deposits in the most distal areas from the meltwater

influx sites, but not necessarily distal with respect to the ice front.

Whereas most diamictites of the interfan complex overlie sandstones

or rhythmites of fan associations, some occur directly on basal diamictite or the unconformity surface. These matrix-supported units resemble the basal diamictite, but are irregularly-stratified with a faint, sometimes distorted lamination or bedding. Long-axis orientations of gravel-sized clasts within these stratified diamictites show a slight reorientation with respect to the basal diamictite (Figure 7E,F). The adjacent stratigraphic association and similarities in texture and composition to the basal diamictite suggests a similar till origin. However, the presence of distorted stratification and the pebble-fabric trends indicate that resedimentation has occurred. The poor sorting, lack of grading, non-erosive contacts and homogeneous appearance of these diamictites suggests debris flow transport. Their stratigraphic position and facies association supports an origin as ice-marginal debris, most likely as small morainal banks similar to those described by Powell (1981, 1984) that form at the margin of subaqueously-grounded ice sheets. These banks form from englacial and subglacial melt-out of debris, with debris possibly added from meltwater currents or flows off nearby fans. A slowly retreating or quasi-stable grounding line is implied, possibly coupled with minor (perhaps winter) advances of the ice sheet causing the push moraines described by Powell (1981, 1984) and May (1977). Clast shapes are similar to those of the basal diamictite, suggesting subglacial-englacial transport with little included supraglacial debris, based on studies of boulder-shape and ice-transport paths (Boulton 1978; Dowdeswell et al. 1985). This supports an origin as banks formed at the ice-sheet grounding line since

englacial layers are not thought to be significantly deformed or sheared upward in the front of large, subaqueously grounded ice sheets (Powell

FLOW TYPE		SEDIMENT SUPPORT MECHANISM
	Turbidity Current	Fluid Turbulence
	Fluidized Flow	Escaping Pore Fluid
	Grain Flow	Dispersive Pressure
	Debris Flow	Matrix Strength
FLOW BEHAVIOUR	FLOW TYPE	SEDIMENT SUPPORT MECHANISM
FLUID	- High Density Turbidity Current - Low Density Fluidized Flow	Fluid Turbulence Escaping Pore Fluid (Full Support)
	D e n s i t y G r a i n L i q u e f i e d F l o w Liquefied Flow	Escaping Pore Fluid (Partial Support)
PLASTIC (Bingham)	D e b r i s F l o w Debris Flow	Dispersive Pressure Matrix Strength and Matrix Density
	M u d f l o w C o h e s i v e D e b r i s F l o w Mudflow or Cohesive Debris Flow	

TABLE 2. Sediment gravity flow classification schemes of Middleton and Hampton 1976 (Top); and Lowe 1979 (Bottom).

1984; Anderson et al. 1984). These banks are highly unstable, with flows off the bank-slopes common and complete collapse possible when a previously stationary grounding-line retreats (Powell, 1984). Shock waves from ice-calving may also initiate flows off the unstable slopes of these banks and from the outwash fans (Rust 1977; Powell 1984). At Cobalt, these banks are interpreted to have collapsed by a series of debris flows. This term is used in the general sense of Lowe (1979) for plastically behaving flows with the sediment supported by a combination of dispersive pressures, matrix strength and minor escaping pore fluids.

The clast orientations at both sites show a weak secondary trend parallel to the underlying basal diamictite. This weak trend may reflect the original till orientation, with the main trend due to reorientation of clasts during mass flow off the banks. Lawson (1979, 1981) documented preferred orientations both parallel and perpendicular to flow in sediment flows of water-saturated tills in Alaska. Similar orientations were predicted by May (1977) and reported by Evenson et al. (1977) for subaqueously resedimented diamictons.

Similar remobilized subaqueous tills have been documented in Pleistocene or pre-Pleistocene deposits and termed flow tills (Evenson et al. 1977; Dreimanis 1982), lacustrotill (May 1977) or ice-marginal debris flows (De Jong and Rappol 1983; Vissor 1983). Facies associations and stratigraphic positions are major elements supporting a till origin. In isolation, features of these units reflect debris flow transport, but not necessarily a till origin. For this reason the terms "flow till" or "lacustrotill" are rejected in favour of subaqueous debris flow deposits (a convention supported by Gravenor et al. 1984; and Powell 1984).

Matrix-supported diamictites interbedded in higher levels of the

interfan complex are also interpreted as debris flows. These massive, poorly-sorted diamictites show a lack of lateral continuity, non-erosive basal contacts, and interbedding with other sediment gravity flows, indicating that these units are not tills deposited by readvances of the ice sheet. Instead, these features are typical of cohesive debris flows which travel downslope with grain support from matrix strength and density. They are deposited by mass emplacement when the gravity-caused shear stress drops below the yield strength of the moving material (Lowe 1982).

Rose diagrams for two of these units (Figure 7A,D) show strongly preferred orientations (NNE-SSW). Evidence for flow directions were not observed in these specific diamictites. Studies by Enos (1979), Lindsey (1968), Middleton and Hampton (1976) suggest that parallel to flow orientations of clasts might occur within debris flows. However, Lawson (1979, 1982) and Evenson et al. (1977) showed that both parallel- and transverse-to-flow orientations can be developed in water-saturated debris flows originating from glacier debris. Thus the use of fabric as the only means of flow direction indicator is not warranted. The strong central tendency of clast apparent long-axes in these diamictites argues against a dropstone diamictite interpretation with ice-rafting as the major source of the clasts. Domack (1983) and Domack and Lawson (1985) showed that ice-rafted diamictites have a very weak or random horizontal orientation of clasts. Anderson (1983) suggested that bottom currents might slightly realign ice-rafted clasts after deposition. The strength of the fabric patterns for these diamictites seems greater than could be attributed to bottom currents alone.

Crudely-stratified, rarely poorly-imbricated diamictites within the

interfan complex contain features similar to those of the massive diamictite, again suggesting debris flow transportation. However, the poor imbrication, slightly erosive lower contacts, and evidence of dewatering at upper contacts in some units suggests that grain-support mechanisms also included fluid effects and slight turbulence (Lowe 1976b, 1979; Middleton and Hampton 1976). Similar features have been interpreted as the result of density-modified grain flows of gravels (Lowe 1982; Lash 1984), a transitional debris flow - high-density turbidity flow process (Lowe 1979). Enos (1977) showed that erosive turbulence can occur in initial stages of debris flow. This may account for the slightly erosive contacts in places observed at Cobalt. As initial flow velocities decrease, the turbulence changes quickly to more typical laminar conditions at the boundaries of the debris flow (Enos 1977; Middleton and Hampton 1976; Lowe 1979, 1982). Laminar conditions could cause the preferred clast-orientations noted on horizontal surfaces of some of these diamictites, as well as the observed subhorizontal orientation of many clasts in vertical sections. Similar orientations were predicted by Lindsey (1968) for debris flows and documented by Lash (1984) in gravelly, density-modified grain flows.

Dropstones within these flows indicate that ice-calving was occurring penecontemporaneously. Rare clusters of intact-framework gravel-sized clasts may also be related to ice-calving. Melt-out debris commonly accumulates on recent iceberg surfaces and, with overturning, a gravel mixture is deposited on the basin floor in localized concentrations (Powell 1981; Owenshine 1970). Pleistocene occurrences of these dump structures were reported by Thomas and Connell (1985). The clast concentrations at Cobalt are exposed on smoothed horizontal surfaces, and thus the conical mound shape expected for these

structures could not be documented. The downslope oriented grooves uniquely preserved between two flows probably are due to clasts sliding at the base of the upper debris flow. This is a feature that Lowe (1979) suggested could be common at the base of debris flows. Middleton and Hampton (1976) interpreted similar bedding-plane grooves as slide marks formed when blocks of debris produced by tensile separation slid rigidly ahead of the main debris flow.

Clast-supported diamictites within the interfan areas are interpreted as high-density sediment gravity flows, probably originating from upper-fan meltwater deposits. Channelized, stratified diamictites could have originated as erosive high-density turbidity currents. Similar, discontinuous units were described by Walker (1984) and Hein (1982) as pebbly-sandstones and were related to suspension-sedimentation of gravels as turbulent flow begins to wane. Sandy upper layers form during continued deceleration of the flow. This is similar to the process proposed for the graded-stratified conglomerate model of Walker (1975). In cases where the channelized sequence contains multiple beds of graded clast-supported diamictite and pebbly sandstone, surging flows are suggested. Surging flows show an oscillating decline of velocity, competence and capacity. Each surge exhibits an abrupt velocity increase followed by a gradual deceleration, resulting in repetitive grading and structure divisions (cf. Lowe 1982).

These channelized sequences can resemble the cyclic, graded, gravel-to-pebbly sandstone beds in the upper fan areas. They may represent channels in lower fan areas which were formed by unusually strong meltwater underflow currents flowing down the fan slope. Such an underflow is technically not a sediment gravity flow, because the

sediment is being transported by the moving fluid. The scarcity of these sequences, and their association with other deposits of sediment gravity flow origin, supports the first interpretation presented.

More extensive clast-supported diamictites of interfan areas contain features typical of resedimented conglomerates as outlined by Walker (1975, 1984). The massive, non-graded, non-erosive, poorly-sorted lithotypes correspond to the disorganized-bed unit of Walker, and an origin as cohesive debris flows is suggested. Rodine and Johnson (1976) and Hampton (1979) demonstrated experimentally that, when clast densities are high (up to 95%), the matrix strength of the flow is unchanged, but the greatly increased buoyancy allows support of isolated large boulders for great distances on very low slopes. This may explain the irregular upper surface of some of these units, in which large clasts commonly project in to, and are draped by, the overlying unit. Projecting clasts have been cited as evidence for cohesive debris flows (Middleton and Hampton 1976; Lowe 1979, 1982; Nemec and Steel 1984).

Some massive diamictites have a vaguely-defined, coarser-grained central portion. This corresponds to the rigid plug zone thought to be a common feature of cohesive debris flows (Middleton and Hampton 1976). Enos (1977), Hampton (1975) and Middleton and Hampton (1976), demonstrated that in subaqueous debris flows, zones of shearing occur at the bottom and top of the flow, but the inner zone acts as a rigid plug. Hampton (1975) showed that competence is significantly greater in the rigid inner plug, and thus grain sizes should be coarser in this zone. Because the rigid plug migrates during flow, sharp intraflow boundaries are unlikely to form (Middleton and Hampton 1976).

Figure 7B shows the apparent long axis orientations of clasts in a clast-rich (partially clast-supported), diamictite which was deposited

over a slightly eroded sandstone (shown in Plate 6G). A poorly defined, nonsorted, internal plug of larger clasts, clasts projecting at the top, and its general lack of sorting all suggest a debris flow origin (cf. Middleton and Hampton 1976; Lowe 1982). The erosive lower contact is not typical of debris flows, and suggests some turbidity flow in initial stages at the base of the otherwise non-turbulent flow. The nature of the lower erosive contact, geometry of the diamictite body, and estimates of the local paleoslope all suggest that flow was roughly to the northwest. The strong preferred orientation thus is transverse to flow, probably reflecting clast-clast interactions or rolling of lower clasts as bedload. A slight parallel-to-flow orientation is also apparent, perhaps the result of laminar flow at flow edges during late stages of flow (Lindsey 1968).

The massive, clast-supported diamictite that contains fractured boulders (described in detail on pages 41-42) also appears to have formed as a cohesive debris flow. The massive nature, lack of sorting or grading, and presence of clasts projecting from an irregular upper surface, are, as discussed above, typical of cohesive debris flows. Although fractured boulders within cohesive debris flows are rare, Johnson (1970) documents recent cases of boulders fractured prior to flow, transported passively within subaerial debris flows and emplaced with the pieces only slightly separated. A similar (but subaqueous) origin is suggested for the fractured boulders at Cobalt. The original fracturing may have been a freeze-thaw or pressure effect related to subglacial or englacial transport. Alternatively, clast interactions within the flow could have caused the final separation of partially fractured boulders. The matrix density and strength of a cohesive debris flow could keep the pieces from separating widely, especially if

they were transported in a rigid plug zone. Infilling of the slight separations could occur either during flow or in the last stages of mass emplacement, perhaps due to a slight kinetic sieving mechanism similar to that proposed by Naylor (1980).

Inverse- to normally-graded and normally graded units, both with slightly erosive and/or loaded bases, are interpreted as high-density flows of the type described by Walker (1975) and Lowe (1982). The grading types suggest sediment-support mechanisms in addition to matrix strength and density. Bouyancy forces and dispersive pressure probably are major additional support mechanisms in these types of flows (Lowe 1976a, 1982; Lash 1984), termed density-modified grain flows. This is a type of flow transitional between cohesive debris flows and high-density turbidity flows as defined by Lowe (1976a, 1982; see Table 2). Inverse grading at the base of some units may reflect a sieving mechanism in which smaller grains displace larger grains upwards (Naylor 1980). Alternatively, a traction carpet layer can deposit a basal inversely-graded zone when intergranular dispersive pressure at the base of a slightly turbulent flow rapidly "freezes" as the velocity drops below the minimum necessary to maintain dispersive pressure (Lowe 1976a, 1982).

Occasionally observed inverse- to normally-graded sequences at Cobalt are interpreted according to the models of Walker (1975) and Lowe (1982). Inverse grading is formed from a highly-concentrated traction carpet layer, and normal grading represents direct suspension-sedimentation of coarser suspended gravel. In other units, extreme flow unsteadiness resulted in direct suspension-sedimentation without the development of a traction carpet, depositing a normally graded clast-supported diamictite. The last two diamictite types discussed correspond to the inverse- to normally-graded, and normally-graded

conglomerates of Walker (1975, 1984) and the R_2 and R_3 of Lowe's (1982) ideal gravelly flow sequence.

Both Walker and Lowe suggested that proximal to distal changes are apparent in flow deposits (disorganized to inverse- to normally-graded, to graded bed types in Walker's 1975 model). However, extreme flow separation is probably common, resulting in separated deposition sites without preserved lateral transitions (Lowe 1982). At Cobalt, these lateral transitions could not be documented within single units, suggesting that such flow separations occurred.

Some interfan clast-supported diamictites are directly overlain by thin sandstone or mudstone beds or laminae which are usually parallel or cross-laminated. These probably reflect winnowing of finer material from the gravelly, high-density flows. Hampton (1972) and Krause and Oldershaw (1979) discuss such a process where low-density turbulent clouds develop on the top of the main flow due to backward streaming of displaced water and sediment at the head of the flow. Deposition of the gravelly sedimentation wave is followed by deposition from a separate low-density turbidity current (shown in Figure 11). At Cobalt, these planar-laminated or thin-bedded sandstones and mudstones with ripple bedforms are interpreted as the B and C divisions of a Bouma sequence.

Coarse- to medium-grained interfan sandstone beds are interpreted as high-density sandy flows. These may be the residual portions of gravelly flows which continued downslope after deposition of the coarser gravel (Lowe 1982). This is a flow separation effect similar to that described previously. Grading sequences are similar to those seen in the clast-supported diamictites, and the processes probably were essentially the same, with density-modified grain flows and sandy, high-

density turbidity flows accounting for most of these isolated units.

Some are overlain by thin, planar-laminated or rippled fine-grained sandstone or mudstone units. These are interpreted as B and C divisions of the Bouma turbidite model, reflecting waning turbulent flows velocities.

4.4 Upper Assemblage - Heterolithic Diamictite Complex

The restricted and in most places poorly-exposed occurrence of this assemblage hinders an extensive discussion of its origin. There is no direct evidence for a sudden change in depositional environment, or of an unconformity between the lower stratigraphic assemblage previously discussed and this complex. However, whereas the lower diamictite assemblage appears to occur in areas laterally equivalent to those of the subaqueous outwash fan associations, the upper package does not include well-developed rhythmite/sandstone/clast-supported diamictite associations. This suggests a significant change in the depositional environment of the upper assemblage.

Fine-grained lithofacies of this upper assemblage commonly consist of discontinuous silt and clay laminae of variable thickness with diffuse gradational contacts. These are in sharp contrast to the lower rhythmite units, interpreted to have been deposited by meltwater underflows and proximal interflows/overflows. The non-rhythmic laminae could reflect deposition in areas distal from the meltwater input sites. The diffuse contacts and discontinuous laminations are similar to features described by Mackiewicz *et al.* (1984) for distal laminated muds deposited by tidewater glacier meltwater in the Glacier Bay fjords of Alaska. Deposition is by suspension-settling of material transported by turbid overflows and/or interflows. Clay flocculation causes deposition of clay and silt at similar rates, resulting in a poorly-laminated

mudstone. The site of deposition is distal with respect to underflow deposits, but can still be within hundreds of metres to a few kilometres of the ice-front (Mackiewicz et al. 1984). This process has also been observed in Canadian Arctic fjords (Gilbert, 1983). Domack (1983) described similar mudstones (his pebbly-mud lithofacies) from a ice-proximal, Pleistocene glaciomarine environment. The similar features in the fine-grained lithofacies of the upper assemblage at Cobalt suggest comparable deposition in a glaciomarine environment, although not a fjord. This might reflect a significant change in the basin from lacustrine to marine conditions, or increased salinity effects in an ice-distal marine environment with deposition of the lower strata mimicking lacustrine conditions due to extreme meltwater input and sediment concentrations. These possibilities are discussed in detail in the next chapter. Single beds of diamictite or rarely sandstone that occur within these mudstones are interpreted as sediment gravity flow deposits in areas of otherwise quiescent bottom conditions.

Dropstones are common within the upper assemblage mudstones, in contrast to underlying fan association rhythmite, where dropstones are relatively rare in the distal deposits. Some poorly-laminated mudstones contain abundant gravel-sized clasts, distributed randomly throughout the finer-grained matrix. Many of these clasts pierce mudstone laminae, implying a dropstone origin. These gravel-rich mudstones are a type of matrix-supported diamictite, apparently formed by introduction of the larger clasts into the mudstones. The term dropstone diamictite (Powell 1984) seems applicable to these units. Pebble mudstones of similar origin were termed compound para-tills by Anderson et al. (1980), but use of the term "till" for these deposits is inappropriate in view of the definition of till used in this study.

Some matrix-supported diamictites are massive and unsorted. These appear to be more extensive than the similar diamictites of the lower assemblage. An origin as subglacial tills deposited during a readvance of the ice sheet is considered unlikely, because major glaciotectonic deformation features are absent in the underlying strata. Also, there is no evidence of erosion, shaping, or incorporation of the substratum. Clast apparent long-axis orientation data for these diamictites supports a non-till interpretation. The random patterns (Figure 8A-D) are in sharp contrast to the strong trends typical of subglacially deposited tills (Holmes 1941; Boulton 1971).

Possible alternative origins for these diamictites are as dropstone diamictites or cohesive debris flows. Direct evidence to discriminate between these two is lacking in the study area. The presence of the probable dropstone diamictite discussed previously supports a similar interpretation for the massive units. However, clast-supported diamictites within the upper assemblage contain evidence of sediment gravity flow origins (discussed below). Thus, a facies association approach is inconclusive. The random orientations of large clasts are characteristic of dropstone diamictites (Domack 1983; Lawson and Domack 1985; Anderson 1983), but can also occur in debris flows (Lindsay 1968).

Clast-supported diamictites of this upper assemblage are similar to those of the interfan areas. The inversely-graded zone at the base of otherwise massive units suggest traction-carpet deposition at the base of high-density flows, either as debris flows or as density-modified grain flows of the type discussed by Lowe (1982) and Lash (1984). The presence of a preferred long-axis orientation of gravel-sized clasts within these units supports this interpretation. Walker (1975) and Hein

(1982) suggested that unimodal orientations in similar resedimented conglomerates are parallel to the dominant flow direction. This could not be confirmed at Cobalt due to a lack of independent paleocurrent or paleoslope evidence for these or adjacent lithotypes. Fine-grained interbeds that occur between poorly-defined subunits of this clast-supported diamictite type probably reflect sedimentation between multiple flow events.

Clast-supported diamictite with crude-stratification and poorly-developed, normally-graded sequences are interpreted as deposits from high-density, surging flows of the type described by Hein (1982) and Lowe (1982). Extreme flow unsteadiness can cause crude, normally-graded sequences as flow velocities fluctuate due to flow separation effects (Hein 1982; Lowe 1982). Pebbly sandstone interbeds at the top of these units reflect deposition during the waning stages of transportation, as Walker (1975, 1984) suggested in his general model for graded-stratified, resedimented conglomerates. The strong unimodal trend of clast apparent long-axis orientations (Figure 8E-F) is typical of these types of gravity flows, and should parallel the main flow direction (Walker 1975; Hein 1982; Massari 1984). Independent paleocurrent evidence to confirm this interpretation is lacking in units of the upper assemblage.

CHAPTER V

CHARACTERISTICS AND SUMMARY OF THE GLACIOGENIC PALEOENVIRONMENT AT COBALT

5.1 Regional Glacial Setting

The extensive glacial deposits of the lower Gowganda Formation reflect continental-scale glaciation (Lindsey 1969, 1971). Lindsey proposed an ice sheet model for this deposition, based mainly on pebble-fabric and paleocurrent studies. At Cobalt, the stratigraphic relationships and gentle paleotopography also suggest deposition beneath an ice sheet, as opposed to ice tongues or valley glaciers.

The lateral equivalence and intercalation of diamictites and sandstones with the dropstone-bearing fine-grained lithofacies indicates a subaqueous environment of deposition. Dropstones in the sandstones and the lack of sedimentary structures indicative of subaerial exposure also support this interpretation. Studies from regions to the north (Miall 1983; Long 1985) and south (Young 1981a, 1985; Miall 1985; Lindsey 1971), also suggest that lower Gowganda Formation deposition was subaqueous. Thus, all preserved parts of the formation appear to have been deposited in a subaqueous environment. The regional extent defines a basin of considerable size, and if correlations of this formation with other early Proterozoic glacial strata of interpreted subaqueous deposition are correct (Young 1973; Marmo and Ojakangas 1984), an even larger basin is implied. This large size does not require a marine basin, as glaciolacustrine environments of this scale existed during the Pleistocene Epoch. Consequently, in the continental margin tectonic setting proposed for upper Huronian Supergroup deposition, the Cobalt area would have occupied an inner shelf zone in the sense of Gravenor et al. (1984), where marine or lacustrine conditions are not specified.

5.2 Glaciomarine vs. Glaciolacustrine Deposition

The regolith on the unconformity surface indicates subaerial exposure before glaciation, and this could be used to support a glaciolacustrine interpretation for subsequent Coleman Member deposition. However, coupled with an already subsiding continental margin tectonic setting, isostatic loading due to initial ice sheet advance could have resulted in subsidence of the unconformity surface below sea level. Thus the unconformity surface regolith does not preclude a glaciomarine interpretation.

The observed lithofacies could form in either a freshwater or saline basin, with the possible exception of the fine-grained rhythmites. Lindsey (1966, 1969, 1971) considered this lithotype, which he interpreted as varves, to indicate a freshwater environment for the northern occurrences of the lower Gowganda Formation, including the Cobalt area. Legun (1981) also suggested a freshwater origin for the Cobalt strata based on this single criterion, although he later (1984) speculated that the basin may have been marine.

The rhythmites in the Cobalt area are very similar to some glaciolacustrine rhythmites in grading patterns, contact relationships and proximal-distal variations. The formation of the proximal rhythmites by meltwater underflow deposition also appears to support a glaciolacustrine interpretation. Modern observations document that where meltwater enters a marine environment, overflows or possibly interflows, form due to freshwater-saltwater density contrasts (Gilbert 1983 presented a recent discussion of these processes). Suspended sediment increases the density of the meltwater, but probably not enough to overcome buoyancy effects except in unusual cases (Kuenen, 1951;

Mackiewicz et al. 1984). However, Mackiewicz et al. (1984) documented underflow deposits of fine-grained sand/silt-clay couplets in ice-proximal (<0.5 km) areas of Glacier Bay, Alaska. They attributed formation of these underflows to the added density effects of a high bedload concentration of sediments in subglacial streams, and to the unique hydraulic conditions of subglacial streams (pipe-flow rather than open channel flow). These hydraulic differences suggest that suspension sedimentation may be more uniform and in higher concentrations in subglacial streams than in open channels. Sediment loads can also be increased after discharge by entraining morainal bank debris, or by turbulent mixing at the site of discharge due to the hydraulic jump effect (Mackiewicz et al. 1984). Domack (1984) cited similar processes to explain rhythmic interbedding of sands and muds and varve-like, laminated silts and muds in a Pleistocene glaciomarine sequence in the Puget Sound of Washington. He (and Gilbert 1983) also suggested that where large volumes of meltwater enter a marine environment, a dilution effect can occur, decreasing the salinity and, as a result, reducing the density contrast between inflowing meltwater and the sea water in proximal areas.

Both Mackiewicz et al. (1984) and Domack (1984) documented proximal to distal changes in predominant flow types with respect to deposition of fine-grained laminae (fine sand, silt and clay). They observed that underflows in proximal areas change distally to interflows/overflows as sedimentation concentration and perhaps salinity-dilution decreases. In the most distal areas, flocculation produces poorly laminated mudstones rather than interlaminated silt-clay couplets. This general sequence corresponds well with the interpretation at Cobalt of underflow transport for proximal couplets and interflow-overflow transport for the

more distal couplets. The non-rhythmic, poorly-laminated mudstones at Cobalt correspond to areas of normal salinity and low sediment concentrations. Similar underflow to overflow/interflow changes can occur in glaciolacustrine sequences, but generally this applies only if the glacier is not present within the lake basin (Ashley 1975; Ashley et al. 1985). In ice-contact lakes, underflow deposition appears to dominate even in areas distal to the meltwater influx (Ashley et al. 1985; Gustavson 1975). The evidence for ice-contact, subaqueous deposition is abundant at Cobalt, therefore the previous discussion suggests a glaciomarine interpretation is warranted.

5.3 Ice Sheet Characteristics - Lower Stratigraphic Units

The upper assemblage of the heterolithic diamictite complex contains lithotypes and associations which are in some respects unlike those of the underlying strata. The lower strata (basal diamictite, subaqueous outwash fan and interfan [lower heterolithic diamictite complex] associations) form the bulk of the well-exposed areas in Cobalt, and this has resulted in a more thorough understanding of the depositional processes for the lower stratigraphic units at Cobalt. For this reason, the conclusions regarding ice sheet characteristics and its controls on sedimentation presented below apply only to the lower stratigraphic units. A brief discussion of possible ice sheet controls on the upper stratigraphic units is presented separately.

Grounded vs. Floating Ice Sheet Models

Presence of an extensive, subglacially deposited tillite, rare lee-side tillite, and a shaped and quarried unconformity surface indicate that the ice sheet was grounded during at least the initial advance. The presence of basal tillites at Cobalt is consistent with glaciomarine

deposition from a grounded ice sheet. Subglacial deposition beneath a grounded ice sheet should produce the same deposits whether the ice sheet is grounded subaqueously or subaerially (Powell 1984). Cenozoic age basal tills are recognized throughout the Antarctic continental shelf and probably reflect subglacial deposition hundreds of metres below sea level (Anderson et al. 1980a).

At Cobalt, the recognition of morainal banks and subaqueous fans also indicates deposition at the grounding line of a subaqueously-grounded ice sheet (Powell 1984, Rust and Romanelli 1975, Gravenor et al. 1984, Edwards 1984). This type of ice-proximal deposition can occur at the front of an ice-sheet that terminates at an ice cliff, termed a tidewater glacier by Powell (1981, 1984). Similar deposition can occur at the grounding line of an ice sheet where it has decoupled from the basin floor to form an ice shelf (Gravenor et al.; Powell 1984). At Cobalt, the distribution of dropstones provides strong evidence to support a tidewater glacier model. A rapid decrease in the abundance of dropstones is apparent in increasingly distal rhythmites of the subaqueous outwash fan associations. Proximal rhythmites in the western portion of the study area consist of >10% dropstones in some sequences. In contrast, dropstones make up <1% of the distal rhythmites. Drewry and Cooper (1981), Powell (1984); and Eyles and Miall (1984) cited evidence to show that ice shelves deposit basal and low englacial debris by undermelting and ice rain-out within a short distance of the grounding line (a few km according to Drewry and Cooper). This suggests that in an ice shelf environment, dropstones should occur in the distal rhythmites (still within 100's or a few thousand metres of the meltwater influx) in approximately similar quantities as in the proximal

rhythmites. In contrast, Ovenshine (1970) observed that directly following ice-calving, icebergs in Glacier Bay undergo an initial period of fragmentation and rapid overturning before stabilization. Many icebergs calve from the base of subaqueously grounded ice fronts (Gustavson 1975, Anderson et al. 1980b; Powell 1983) and contain significant debris. This initial fragmentation thus should yield abundant ice-rafted debris in ice-proximal positions. Boulton and Deynoux (1981) suggested that in open marine conditions, icebergs are rapidly swept out of the ice-proximal zone. A combination of initial instability and rapid transport of icebergs could account for the variations in dropstone abundances at Cobalt. The interpretation of rare clast-clusters in the Cobalt strata as having resulted from iceberg overturns also supports a tidewater glacier model. This type of feature could not occur beneath an ice shelf (Powell 1984).

Tidewater glaciers can be grounded in considerable depths of water. Powell (1984) cites a theoretical limiting depth of approximately 250 m, although ice sheets ground below 310 m in Antarctica (Robin 1979). Whereas the abundance of dropstones at Cobalt indicates that ice-calving was common, no iceberg-contact features are preserved within the strata. These could include grounding structures such as those documented by Thomas and Connell (1985), impact marks (Powell, 1983) and ice-scour gouges (as in Dredge, 1982). Anderson et al. (1984) observed tabular icebergs with drafts exceeding 200 m, but these were calved from ice shelves and probably exceed the size of icebergs originating from tidewater glaciers. Observations at tidewater ice fronts suggests that ice calving impact rarely occurs below 100 m (Powell 1983). Based on the preceding discussion, a conservative estimate of water depth at Cobalt during deposition is 50-300 m.

Retreat Rate of Ice Sheet

The lack of deformation or erosion features normally associated with overriding of proglacial sediments by an advancing glacier suggests that deposition occurred during overall retreat of the ice sheet. However, the coarsening-upward nature of the fan associations suggest that retreat rates were sufficiently slow to allow progradation to occur. A rapid retreat should cause deposition of fining-upward subaqueous fan associations (Ryst and Romanelli 1975); minor advance and quasi-stationary periods in ice-front position could have occurred without significantly changing the patterns of deposition. A slow retreat rate is also compatible with the formation of morainal banks at the grounding line (Powell 1981, 1984).

Basal Thermal Regime

The basal thermal regimes of glaciers have been generalised into wet-based (temperate, free water at base) and dry-based (cold, frozen to bed) types (Edwards 1978). However, the actual regimes are complex, with wet- and dry-based sections present within the same glacier and conditions at a single position varying over daily, seasonal, or longer time periods (Powell 1984; Eyles et al. 1983). At Cobalt, the abundance of meltwater deposits suggests that wet-based conditions predominated near the grounding-line during deposition of these sediments. The data provided by this study do not allow a more detailed interpretation of the basal thermal regime at Cobalt.

5.4 Ice Sheet Characteristics - Upper Assemblage of the Heterolithic

Diamictite Complex

A tidewater ice sheet model is proposed for deposition of the subglacial sediments, subaqueous fans, and the interfan deposits (most of the strata exposed at Cobalt). In the overlying assemblage of the heterolithic diamictite complex, lateral variation in frequencies of dropstones, and the presence of clast concentrations suggestive of iceberg overturn deposits, were not observed. This can be attributed to less extensive exposure, but the presence of dropstone diamictite, and of massive diamictite with random clast orientations, suggests a change in ice-sheet characteristics.

The absence of glaciotectonic deformation, structures, or evidence of erosion and incorporation of underlying material in this sequence, indicates that readvance did not involve a grounded ice sheet. The lack of such features has been cited in studies of Pleistocene deposits to support ice shelf depositional models (Eyles and Eyles 1983, McCabe et al. 1984). Ice shelf deposition at Cobalt would account for the random long-axis orientations observed in the massive diamictite, and also for the presence of dropstone diamictite. The non-rhythmic nature of the poorly laminated mudstones and the lack of fan associations suggests little direct deposition by meltwater currents. However, there is no evidence of a major retreat of the grounded ice sheet prior to deposition of this upper assemblage. Thick associations of dropstone-poor, non-rhythmically laminated mudstones would be expected if normal marine conditions developed due to a significant retreat of the ice sheet prior to the readvance. Such a lithotype is not present at Cobalt. A more likely possibility is that partial decoupling of the ice sheet occurred to the north of the study area so that the readvance was

of a partially floating ice sheet. This type of ice-sheet decoupling has been proposed elsewhere to explain similar rapid changes in Pleistocene age lithotypes suggesting both grounded ice and ice shelf deposition (McCabe et al. 1984; Dreimanis 1982). These authors suggested that ice sheet thinning or sea-level rises could have caused the partial decoupling. At Cobalt, no evidence was observed to indicate a cause for this possible decoupling of the ice sheet.

A partially floating ice shelf model would be expected to deposit large morainal banks at the grounding line zone due to rapid undermelting of basal and low englacial debris, accompanied by ice-push effects (Powell 1984; Gravenor et al. 1984). These large accumulations of diamicton (a subtype of undermelt diamicton in the classification of Gravenor et al. 1984) should have been a major source of sediment gravity flows into distal areas. These flows are initiated on bank slopes due to initial slope instability and oversteepening from advance of the grounding line (Powell 1984). This process could account for the thick resedimented diamictites which form a major component of the upper assemblage at Cobalt. Sandstones intercalated with these diamictites may reflect secondary flow initiation at the head of the high-density flows, a process discussed previously.

Whether this readvance of the ice sheet was part of a major readvance, or merely a large-scale fluctuation in the overall retreat, has not been established. The Coleman Member at Cobalt is incompletely preserved, with perhaps >100m of the uppermost strata missing (based on regional correlations). For this reason, the importance of the evolution of the glacial depositional environment for the upper assemblage at Cobalt cannot be ascertained.

5.5. Summary of Depositional Sequence at Cobalt

The simplified summary diagrams of Figures 11 and 12 illustrate the glaciogenic depositional environments envisioned for the Cobalt area:

1. The local setting was an area of low to moderate relief on the inner shelf of a slowly subsiding continental margin. A regolith was developed on part of the subaerially exposed (at least initially) Archean unconformity surface.

2. Continental-scale glaciation involved southerly advance of an ice sheet, perhaps inducing isostatic loading to below sea level.

3. Subglacial processes caused plucking, brecciation and shaping of the unconformity surface. The regolith was incorporated by the advancing ice sheet, except where cavitation occurred over paleotopographic lows. Lee-side till was deposited into these subglacial cavities, covering the remaining regolith. A primary basal till was deposited over much of the unconformity surface.

4. Deposition during retreat was from a wet-based tidewater glacier grounded approximately 50-300 m below sea level.

5. Slow retreat rates resulted in deposition of prograding subaqueous outwash fans where subglacial/englacial meltwater channels entered the basin. Deposition from underflows induced by proximal meltwater changed distally to deposition from interflows and/or overflows.

6. Morainal banks formed at the grounding line in interfan areas due to englacial/subglacial melt-out and fluctuations in ice-sheet retreat rates.

7. Oversteepening of fan and morainal bank slopes, bank collapse during retreat, and perhaps the shock effects of ice-calving, initiated sediment gravity flows into interfan areas. Numerous sediment-support

mechanisms resulted in a variety of intercalated flow types.

8. Ice-calving caused deposition of IRD in areas near the ice front. Rapid iceberg transport caused less dropstone deposition in relatively distal areas.

9. The upper strata of the Coleman Member probably were deposited by readvance of a floating or partially-floating ice sheet. Undermelt diamictons were initially deposited near the grounding line (north of the study area) and were redeposited as sediment gravity flows within the study area. Ice-rafted debris from melt-out beneath the shelf was in part deposited as dropstone diamicton.

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Figure 10. Depositional model for the lower part of the Coleman Member at Cobalt.

Figure 11. Depositional model for the upper part of the Coleman Member at Cobalt.

PHOTOGRAPHIC PLATES

(Location of photographs is shown on Figure 23, back-pocket)

Plate 1. Unconformity surface and basal breccia.

- A. Oblique view of joint-bounded depression in unconformity surface infilled with Coleman Member diamictite.
 - B. Vertical face (south to the right) showing south-facing step on unconformity surface, and locally derived breccia.
 - C. Horizontal exposure of extensively jointed unconformity surface. Dark infillings of angular depressions are Coleman Member diamictite.
 - D. Vertical exposure of sharp unconformity contact between Archean felsic volcanic and overlying Coleman Member diamictite.
 - E. Thin section of breccia derived from lee-side erosion of unconformity. Breccia fragments "float" in a sandstone matrix similar to that of the Coleman Member basal diamictite.
 - F. Basal breccia preserved in a paleodepression. Extensively fractured Archean mafic volcanic rock at base of photo is in place, and grades upward to increasingly displaced breccia fragments. White rounded clasts at upper right are in the basal part of a Coleman Member clast-supported diamictite which overlies the breccia and infills the remaining portion of the paleodepression (also shown in Plate 2G,H).
 - G. Felsic volcanic clasts of the southern breccia lens.
-

Plate 2. Basal diamictite association.

- A. Typical basal diamictite with gravel-sized clasts floating in a sandstone matrix.
- B. Horizontal surface showing possible faceted clasts in the basal diamictite. Some clasts margins are outlined by concentrations of chlorite, a metamorphic alteration product.
- C. Thin section of basal diamictite matrix showing poor sorting and angularity of many grains. Note high percentage of angular silt-sized grains.
- D. Thin section of basal diamictite matrix showing lack of alteration of most grains. Quartz grains generally are pristine, with only slight edge alteration. Many feldspar grains are essentially unaltered, especially in cores. Large grain at bottom centre is untwinned K-feldspar.
- E. A vertical exposure of basal diamictite containing irregular, thin, slightly distorted sandstone lenses.
- F. Irregular laminations at a gradational contact between basal diamictite and an overlying rhythmite unit.
- G. Clast-supported diamictite (upper third of photo) overlying basal breccia in a paleodepression on the unconformity (same outcrop as in Plate 1F).
- H. Vertical exposure of the clast-supported diamictite of Plate 2G.
Note poor sorting and lack of obvious fabric.

Plate 3. Fan association: rhythmite and sandstone units

- A. Well-developed rhythmic alternation of siltstone (dark-coloured) and claystone laminae. A thin bed of siltstone near top of photo has loaded into the underlying claystone; associated flames have been thrust to the right (southeast, approximately equal to the local paleoslope).
- B. Distal rhythmites showing multiple graded silt-clay couplets and two coarse silt laminae, one of which is normally graded. Ovoid mass of silt and clay near right centre is interpreted as a till pellet. Scale = .5mm.
- C. Rhythmites with silt laminae generally thicker than clay, a variety of grading patterns, and common microlaminations of silt in the clay laminae. Central ovoid mass is interpreted as a till pellet.
- D. Lenticular to wavy fine-grained sandstone interbeds in rhythmites. Some ripple bedforms are apparent. Some lenses are slightly deformed (especially lenses below scale card).
- E. Proximal rhythmites (top to left in photo) with graded or massive sandstone to siltstone thin beds relatively common and multiple silt-clay laminations separating coarser-grained layers.
- F. Sinusoidal climbing ripples, some transitional to "type B" of Jopling and Walker (1968). Correspond to "draped lamination" of Gustavson et al. (1975).
- G. Thick beds of massive sandstone within upper portion of rhythmite sequence. Bases of some sandstone beds are loaded into rhythmites.
- H. Rhythmite laminae below a massive sandstone interbed with well-developed loading and flame structures plus decoupling and thrusting of a portion of the rhythmites. Thrusting and deformation of flames is to the south (right of photo).
- I. Sandstone interbed in rhythmites showing breached convolute lamination. Massive vertical zones separating the concave-up laminated zones probably were the result of early dewatering.

Plate 4. Fan association: rhythmite and sandstone units.

- A. Proximal rhythmites with graded sandstone bases, some containing fragments of finer-grained rhythmite. Loading of sandstone bases into the underlying laminae is common.
- B. Dropstone in rhythmites - see Figure 5A for discussion of the contact relationships of this dropstone.
- C. Deformation structures in rhythmites (top to left of photo). Light-coloured clay-rich laminae in layer 1 cm left of scale have been thrust to the right (southeast), approximately down the paleoslope. Laminae in centre of rock slab are deformed and broken, perhaps due to a combination of thrusting and dewatering.
- D. Massive clastic dyke of fine-grained sandstone that has intruded and deformed rhythmites. Top of tape measure is at top contact of sandstone.
- E. Thin section of poorly laminated mudstone. Laminae are wavy, discontinuous and of variable thickness.
- F. Fine-grained sandstone pseudonodules in a poorly laminated mudstone. Pseudonodules display distorted internal lamination, and appear to be the result of the complete foundering of a laminated sandstone bed in a water-saturated mudstone.
- G. Thin section of a fan-association medium-grained sandstone (modal grain size in photo = .4-.5mm) Condensed packing (sutured grain boundaries) is typical of these sandstones. Feldspar grains are only slightly altered, supporting a cold climate hypothesis for weathering and transport.
- H. Low-angle planar crossbedding in the mid portion of a sandstone unit. Current transport to the right (approximately south).

Plate 5. Fan association: sandstones and clast-supported diamictites

- A. Upper portion of a sandstone unit. Pebbly coarse-grained sandstone with poorly defined trough crossbedding (curved erosion surface parallels a trough outline).
- B. Upper portion of a sandstone unit (top to left). Repetitive cycles of pebbly sandstone (to granule conglomerate) and planar laminated coarse-grained sandstone. Some cycles show normal grading between the coarser base and finer top.
- C. Pebbly sandstone/granule conglomerate cycles at the top of a sandstone unit. Transitional to a clast-supported diamictite above.
- D. Dropstone near the base of a sandstone unit.
- E. Typical clast-supported diamictite showing poor sorting and apparent lack of stratification.
- F. Crude stratification in a clast-supported diamictite. Stratification defined by horizontal alignment of clasts and poorly defined graded cycles.
- G. Stratified, clast-supported diamictite with moderate sorting and relatively well-developed graded cycles.
- H. Upper subunit of a clast-supported diamictite with moderately sorted beds of pebbles (some graded) and sharply defined normally graded beds of small pebble to very coarse-grained sandstone. Planar crossbedding dips southward (left in photo).

Plate 6 Heterolithic diamictite association: lower stratigraphic
assemblage (interfan association)

- A. Cyclically repeated clast-supported diamictite and pebbly sandstone beds of a fining upward fan association.
- B. Matrix-supported stratified diamictites in an interfan area. Irregular beds and lenses of mudstone and sandstone occur within and between individual diamictites.
- C. Pentagonal outline of a clast in an interfan diamictite. Similar clast outlines are moderately common and suggest a faceted shape.
- D. Two units of matrix-supported diamictite and interbedded rhythmites. The lower contact of the upper diamictite is sharp and erosive into the underlying rhythmite.
- E. Grooved surface on the top of a matrix-supported diamictite. A thin veneer of siltstone partially fills some grooves (linear light grey zones above, and to the left of hammer). Pleistocene striations are faintly visible, oriented approximately 90° to the grooves.
- F. Boulder of clast-supported diamictite in a matrix-supported diamictite. Clasts at edge of boulder are not truncated and some protrude. Largest cobbles are at base of boulder. Faint laminae in host diamictite are depressed beneath and at lower edges of boulder, and some are pierced by boulder.
- G. Erosive contact between a generally clast-supported, very poorly sorted diamictite and a bedded sandstone unit. Both units occur as discontinuous sheet-like bodies in an interfan area.
- H. Normally graded clast-supported sheet-like diamictite with clasts projecting into overlying sandstone (top right corner shows best example). Overlying sandstone unit is shown in Plate 7a.

Plate 7. Heterolithic diamictite complex: lower and upper
stratigraphic assemblage

- A. Detail of sandstone overlying the diamictite shown in Plate 6H. Unit fines upward overall from a normally graded coarse-grained sandstone to a rippled (some climbing) fine- to medium-grained sandstone. Planar, laminated siltstone caps the sequence, and coarse-grained sandstone sharply overlies the siltstone.
- B. Boulder-rich massive diamictite with in situ fractured and separated boulder fragments.
- C. Close-up of separated fragments of a boulder shown in Plate 7B. Spaces between fragments have been infilled by the enclosing diamictite.
- D. Bedding-parallel view of laminated mudstone draped around a clast of the underlying diamictite shown in Plate 7B.C.
- E. Sandstone which occurs as a discontinuous sheet-like body in an interfan area. Inverse-to-normal grading is apparent in the bed shown (base of bed 1 cm below scale, top not shown; dark areas in top left and above scale are weathered surfaces).
- F. Upper stratigraphic assemblage showing nonrhythmically laminated fine-grained sandstone and mudstone that contains abundant clasts. Many (perhaps all) of the large clasts are dropstones.
- G. Clast-supported diamictite of the upper assemblage, showing a well-defined inversely graded zone above its lower contact. The contact appears to be slightly erosive with respect to the underlying mudstone.
- H. Thin section of poorly laminated mudstone of the upper assemblage. Laminae are nonrhythmic, discontinuous and contacts are diffuse.
- I. Erosive contact between a matrix-supported diamictite and a laminated mudstone. A fragment of the underlying mudstone (right of scale) has been incorporated into the diamictite.

APPENDICES

APPENDIX I

Measured Sections

These nine measured sections are abbreviated versions of the original section descriptions, plus interpretations of the units based on knowledge gained through this study. Localities of the measured sections are shown in Figure 12. Table 1 (page 5) shows the lithofacies code used during this study; Table 3 is a legend of symbols used in the graphic logs. Tables 1 and 3 have been combined in a single removable back-pocket addition (Figure 23) to facilitate examination of these sections. Vertical distances shown on the left of the sections are in metres.

Figure 12 Localities of Measured Sections. Lines indicate sections partially measured along the topographic surface. Diamonds indicate sections measured vertically on an exposed face of an abandoned pit or vein cut.

LEGEND - MEASURED SECTIONS

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LITHOLOGIES

Nipissing Diabase, N

DIAMICTITES, D

Clast-Supported

Matrix-supported, stratified

Matrix-supported, massive

SANDSTONES, S

Pebbly

Fine to Coarse-Grained

FINE-GRAINED LITHOLOGIES, F

Silt > Clay

Clay > Silt

BRECCIA, Bx

ARCHEAN ROCKS, A

COVERED INTERVAL

CONTACTS

Sharp

Erosional

Deformed

Gradational

Lateral Gradational

STRUCTURES

Ripple Marks

Climbing Ripples

Planar Crossbedding

Trough Crossbedding

Discontinuous Interbed

Dropstone

Deformed Laminations

Rip-up Clasts

VERTICAL SCALE

SECTION WIDTH VS. GRAIN SIZE

MS-1 CONIAGAS-TRETHIEWAY PIT

OBSERVATIONS

INTERPRETATIONS

Dmm 10-15% clasts in fg sand matrix; largest clast 40cm, mode 2-4cm; most granitic; non-sorted, no app. orient. laterally extensive, 100's - 1000's of metres; rare discont. fg Sh or Fl lenses, 10's cm thick, <10m length

Upper Complex Probably series of debris flows with lenses of Sh and Fl as interflow deposits; dropstone diamictite origin possible, but evidence lacking due to massive nature of rocks

Dcs-pShd-pSpd 30-50% clasts in poorly bedded sand-sized matrix; poorly sorted, some beds/lenses w. crude subhor. align. of peb. long axes; largest clast 1m, mode 2-6 cm; most granitic but 10% blk. chert peb.; some dropstones in pSh-pSp; Dcs-pSh unit to north appears equivalent

Interfan Complex Pro-fan flows from fan assoc. to north; combined turb. and lam. flow-types plus high component

Prd-Sbd couplets of fg sandst., siltst., mudst.; most <1cm thick, some to 2cm; thicker and coarser to top of unit; sharp contacts between couplets, occ. microloads into mudst.; occ. thin beds (2-4cm) of fine-cse grained massive sandst., loads into Prd, rare beds (to 30cm) of pebble-sized Dcs; dropstones common (to 10%) esp. in top 5m, some occur in poorly defined lenses

Fan Association Relatively prox. mudst. underflow rhythmites of fan prograding from the north. Sm and Dcs beds rep. grain flows and debris flows from more proximal areas; high dropstone content reflects proximal position to ice-front; dropstone lenses may be iceberg overturn deposits. Lack of overlying sandst.-Dcs units of fan suggests shifting of outlet location or cutoff of subglacial meltwater channel prior to complete progradation of fan at this point.

Sh med.-grained; thins from 35cm to <5cm N.; slightly erodes into underlying Dmm base

Interfan Complex sediment gravity flow, thickness and erosive contact suggest density-modified grain flow

Dmm 10-20% clasts in fine to med.-grained sandst. matrix, 20-25% clasts in top 2m; largest clast 120cm; random sizes and orient. non-sorted; clasts 85% granitic, 15% volc.

Interfan Complex Debris flow or flows, perhaps from moraine banks formed at ice front in interfan area to north.

Dcs-pShgn peb./cse-grained sandst. w. eros. base into Prd; peb. base, crude norm. graded med/cse grained sandst. tp; unit thins over 20m from >2m to <50cm (then covered), not present on pit wall 20 m. to Nth.

Interfan/Fan Association Channelized turbulent flows from proximal fan area; perhaps result of short-lived extreme meltwater influx event?

Prd-Sbd couplets fg sandst., siltst., mudst.; most <1cm thick. sandst. based couplets to 3cm couplets coarser/thicker to top; sharp couplet contacts, occ. microloaded bases, rare rip-ups Pr in basal Sh; rare ripples in Sh; <5% dropst.

Fan Association proximal-underflow-deposited rhythmites, perhaps part of meltwater system which deposited underlying units, but increase up of lam. thickness and grain-size suggests renewed meltwater input.

Dcs-pShgn interbedded 10-35cm mod-sorted pebble bases grade to <20cm of pebbly, cse-grained, thin-bedded (2-4cm) sandst., Dcs lower contact sharp, occ. erosive w. pShgn below; poorly defined ripples in pShgn

Fan Association Proximal deposition to meltwater outlet in ice sheet. Initial fining-up trend suggests waning current strength due to ice retreat, lower ice-melt rates, or fan migration

bDmm <10% pebble-cobble clasts, random in a fg sandst. matrix; exposed in S.W. corner of till; unconformity very poorly exposed

Basal Tillite subglacial, primary till

A mass. volcanic: exposed in S.W. corner pit

MS-2 VEIN 64' PIT

OBSERVATIONS

INTERPRETATIONS

Des-pShgn 20-50cm beds w. peb.-cob., base (10-35cm) and med-cse grained norm. graded sandst. top; largest clast 25cm, mode 2-4cm. mod. sort.; <5% random peb. in sandst.

Sh? inaccessible on cliff face, appears med-cse grained, med. bedded

Dcm-Dcm 75-85% pebbles-cobbles in a cse-grained sandst. matrix; largest clast 40cm, mode 2-4cm; poor sort.; rare crude stratif. w. slight conc. of similar sizes in poorly defined beds; clasts >50% granitic, <50% felsic volc.; mafic volc.; med.

Dmm 10-15% pebbles-cobbles in a vfg sandst. matrix; faintly laminated, non-rhythmic, no obv. grading or grain-size variations in matrix, rest of unit as for Dmm below

Dmm 10-15% pebbles-cobbles in vfg sandst. matrix; nonsorted, no obv. clast orient.; granitic, <20% volc.

Fan Association Upper fan high energy deposition, related to underlying deposits, reflecting rapid changes in meltwater influx and lateral fan migration

Fan Association upper to mid fan, distal vs. overlying Des-pShgn

Fan/Interfan Association one or several debris flows into interfan area from prox. upper fan Des source, perhaps reflects initial fan migration into interfan area

Interfan Association debris flow or flows? perhaps from morainal banks at ice sheet edge, laminae might reflect distal meltwater or other currents

Interfan Association Similar origin to above unit, ind. flows not appar. of basal tillite, but Archean not found in pit.

Archean volcs. exposed to west of pit and overlain by thin (<2m) bDmm. Projection and information from mine reports suggest base of section is within 5m of Archean contact.

MS-3 LITTLE SILVER VEIN CLIFF

OBSERVATIONS

INTERPRETATIONS

Dcs-Dcm >80% pebbles-boulders in a cse-grained sandst. matrix; largest clast 90 cm, mode 4-6cm; poor sorting, crude strat. with subhor. clast align., poorly-defined thick beds of similar clast sizes; rare discont. contorted cse-grained sandst. lenses >30cm. thick and <5m exposed length

pStgn-Dcsgn trough crossbedded units; up to 1.5m long overlapping troughs w. erosion of trough below., approx. basal 25cm of each trough preserved; small peb./granule basal lenses grade up to granule, cse-grained sandst. w. rare pebbles; paleocurrents towards SW

Sp med/cse-grained feldspathic arenite planar crossbedded beds up to 1m thick, most <50cm; crossbeds dip approx. 20° towards Sth/SW

Sh-Sr, med-grained feld. arenite; faintly bedded (3-20cm); rare ripple w. internal x-strat.; rare dropstones up to 15cm dia.

Fr-Sm intercalated med-grained Sm beds (15-40cm) in Fr; Sm bases loaded w. flames of Fr distorted to Sth.; poss. dewatering pillars in some Sm beds; Fr lams 1cm thick w. fg sandst. bases and rare 1-2cm Sr beds w. ripples asym. to ath.

Fr complets of siltst., mudst. vfg sandst. coarser-grained and thicker (to 1cm) upward; bases sharp w. occ. microloads; occ. single beds (1-3cm) fg x-lam. sandst.; occ. ripples w. internal x-lam. most show sth. transport, occ. nth. directed; occ. poorly dev. climbing-ripples near top (sth. climbing).

Covered interval. Inaccessible vein cuts, drillhole data, and scattered outcrops indicate all of interval consists of Fr.

Frd complets of siltst., mudst.; lams 1-3mm thick; sharp bases, occ. definite dropstones

bDm 20-30% pebbles-cobbles in a vfg sandst./mudst. matrix; largest clast 30cm, mode 2-4cm; rare fg discont. contorted sandst. lenses <5cm thick, 1m length; non-sorted, no obv. clast orient.; top 20cm lam., grad. change to Fr.

Dcs-pShgn 20-30cm peb.-cob. base w. 10-20cm poorly graded med/cse-grained sandst. top; mod. sort; discont., not present 20m nth.

A pillow volc. uncon. poorly exposed in vein-cut W. of cliff, well-exposed SW of vein-cut.

Fan Association Proximal upper fan deposition at influx site of subglacial/englacial meltwater channel into basin. Sandst. lenses may reflect fluctuations in input & current strength.

Fan Association Upper/mid fan. Continual change upward in grain size and sed. structures reflects increasing current strength towards influx site, progradation of fan into basin and temporal fluctuations in current strength (graded upper beds)

Fan Association transition from lower fan Fr to mid-fan S. Sm as density modified grain flows from southward prograding mid-fan

Fan Association lower fan, deposition by density underflows (proximal) and interflow/overflows (distal); Thicker and coarser-grained lams. reflect southward fan progradation.

Basal Tillite Association primary subglacial till; sand lenses may indicate melt-out origin; faint lams. in upper part due to reworking by currents depositing overlying Frd

Basal Tillite Association small subglacial meltwater channel

MS-4 RIDGE EAST OF VALLEY FAULT, COBALT TOWNSITE

OBSERVATIONS

INTERPRETATIONS

pShgn patchy o/c of med-cse sandst.; mod-poor sort.; occ. peb. bases; poorly exposed

Upper Complex gravelly turb. sed. grav. flow? related to Dcm below?

Dcm-Dcs 80-85% peb.-cob. clasts in cse-grained sandst. matrix; largest clast 30cm, mode 3-4cm; poor sorting, crude strat. as occ. poorly defined thick beds; discont. lenses med/cse-grained massive sandst., <5cm thick, <10m length

Upper Complex Gravelly debris flows with rare lam. flow giving crude bed. Sm may define flow boundaries and be density-modified grain flows from backstreaming in gravel flows.

Dmm 30-50% peb.-cob. clasts in med-cse grained sandst. matrix; non-sorted, no obv. clast orient.; clasts >60% gran., <40% volc.; rare discont. lenses vfg sandst./mudst., <10cm thick, <5m length

Upper Complex debris flows or dropstone diamictite; Sm-lm lenses may be interflow beds or low-current deposition when little IRD input

Fld midst./ vfg sandst.; non-rhythmic laminations, many wavy and discont.; lam 5mm-1cm thick; rare 2-3cm fg massive sandst. beds; basal lam drape projecting clasts of Dmm-Dcm below

Upper Complex ice-distal deposition in quiet environ., sed. from distal meltwater input or IRD; currents distal meltwater or normal basinal currents

Dmm-Dcm 35-65% peb.-cob. clasts in fine to cse-grain sandst. matrix; non-sorted, no obv. clast orient., clasts 60-70% gran., 30-40% volc., <5% sed; projecting clasts at top into Fld

Upper Complex debris flow or flows, poss. dropstone diamictite but proj. clasts supports debris flow interp.

Dcm-Dcs 70-85% peb.-cob. clasts in med/cse-grain sandst. matrix; largest clast 25cm, mode 4cm, poorly sort., crude 1-2m thick beds sep. by discont. Fl-Sh lenses <10cm thick, <5m length; most beds mass., poor subhor. clast align. in spots, occ. poor inv. grading at base, norm. grading at top; clasts 50-60% gran., 40-50% volc. Dcmgr part of above unit but massive except basal 30 cm inv. graded; basal cont. sharp, undulatory (loaded?) and erodes Sm

Upper Complex gravelly sed. grav. flows; high density debris flows and fluidized flows; traction carpet deposition at bases gives inv. grading, slight lam. flow gives crude beds and norm. grading; Fl-sh lenses mark flow contacts, form as den. mod. grain flows, perhaps sed. from backstreaming effects in gravel flows.

Shd-Smd poorly exposed vfg to fg sandst. perhaps faint bedding? no obv. structures, rare limestones (pebble size)

Upper Complex density-modified grain flow or flows? limestones as dropstones? poor exp. hinders int.

Covered bushy zone at base of cliff, possible location of Valley Fault (but may be just west of unit blow)

Dmm-Fld o/c approx. 15m. of cliff; 25-30% peb.-cob. clasts in vfg sandst./siltst. matrix; largest clast 60cm, mode 2-3cm; non-sorted, no obv. clast orient.; matrix gen. faintly lam., esp at top, occ. mass., lam gen. <5mm thick, non-rhythmic, some clasts definite dropstones

Upper Complex combined debris flows and dropstone diamictite, lamina suggest ice-distal currents, clasts as IRD plus reworked debris flows?

SECTION APPROX. 120M ABOVE UNCONFORMITY (based on assessment reports, mine plans and cross-sections drawn for this thesis)

MS-5 WEST SIDE PETERSON LAKE

OBSERVATIONS

INTERPRETATIONS

Fan Association upper fan portion smaller and better sorting vs. other fans in area; boulder9 as dropstones? (doesn't explain linear trend)

Fan Association as above; seq. of structures and coarsening-up ind. increased energy due to sth. fan progradation; dropstones support subaqueous fan interpretation.

Fan/Interfan Association fan-distal meltwater dep.; sug. fan above from rapid migration into interfan area

Interfan Complex Combined debris flows and high IRD input into area of fan-distal meltwater input. Sth. transition to Frd and grad. contact w. bDmm suggests ice-prox. deposits, perhaps collapsed moraine banks.

Basal Tillite Association primary subglacial till; unusually high % volc. clasts and position on SE side major Archean paleohigh (Nipissing Hill) suggests local source for many of these clasts

HS-6 McDONALD VEIN PIT

OBSERVATIONS

INTERPRETATION

Fan Association Upper fan, prox. meltwater underflows, fluctuating (seasonal?) input causes grading and changes in sed. structures, less prox. than Dcm-Dcs below due to lat. fan migration, ice sheet retreat and/or changing subglacial meltwater paths

Fan Association Proximal fan deposition at influx site of subglacial/meltwater channel into basin. Some remobilization as high-density sed. grav. flows poss. w. traction carpet dep. at base giving inv. grading.

Fan Association lower fan, deposition by meltwater underflows and perhaps interflows/overflows (lower section); Sm as density modified grain flows from sth. prograding mid-fan; increased grain size and lam. thickness upward reflect prograd. of fan;

Interfan Association debris flow or flows; very similar to basal tillite, may be flows from interfan moraine banks at edge of ice sheet

Fan Association small (short-lived?) fan deposit; fineing-up sequence and lack of major gravel units suggests relatively lower energy (vs. other fans in study) and waning meltwater input

Archean not seen at base, present approximately 200m to S.E. where massive volcanics are sharply overlain by bDmm. Map and cross-section information suggest unconformity is within 5m of base of section.

MS-7 RAINBIRD TUKSIS AREA

OBSERVATIONS

INTERPRETATION

Fan Association Upper and mid fan
Continual change upward in grain size and sed. structures reflects increasing current strength towards influx site (where Dcm deposited), progradation of fan into basin and temporal fluctuations in input current strength (causing grading). Dcm from debris flow off of upper fan.

Basal Tillite Association
subglacial, primary till; sand lenses may indicate melt-out origin; faint lams in upper part due to reworking by meltwater currents (Frd overlies unit to south)

Basal Tillite Association
subglacial, primary till; location in paleodep. covering regolith suggests origin as lee-side infill of a subglacial cavity; high % volc. clasts may reflect basal transport and local source

Regolith pre-Coleman Member deposition, perhaps periglacial cold climate weathering; only preserved in small paleodepressions w. sth.-facing scarps causing initial subglacial cavities

Glacially Shaped Uncon. Surface
fracturing periglacial or subglacial freeze/thaw effect, angular depressions are subglacial plucked blocks, infilled by subglacial till

MS-8 SCAMPELL THESIS AREA (WEST)

OBSERVATIONS

INTERPRETATION

Interfan Association series of debris flows, density-modified grain flows, high-density turb. flows into interfan area from sth. prograding fan and morainal banks; prob. IRD component but difficult to recognize due to massive or poorly laminated nature

Fan Association Relatively complete but condensed (vs MS-1) fan succession. Sth extension of MS-7 units. Coarsening-up and fan progradation. Sm beds in Frd thick density-modified grain flows off of mid fan. Sudden loading by Sm caused thrust flame structures and convolute laminations. High sedimentation rates may account for unusual thickness and number of grain flows into lower Frd.

Basal Tillite Association subglac. primary till; lamina in upper part may reflect reworking by meltwater currents during dep. of Frd

Glacially Shaped Uncon. Surface ang. depressions from subglacial plucking of trac. uncon. surface; sth-facing scarps show lee plucking effects (similar to roche moutonnée), indicates sth-west ice sheet movement

MS-9 SCAMMELL THESIS AREA (CENTRAL)

OBSERVATIONS

INTERPRETATION

Dms-Dms 30-60% clasts in fg sandst. matrix; poor sorted, no obv. clast orient. largest clast 80cm, mode 4-5cm; clasts 50-60% gran., 35-45% volc., <5% sed.; occ. faint lam.; occ. discont. lenses Fld, Shgr/gn, Sr, <30cm thick, most <10m length, some cont. over 30m; well-developed grooves on top of Dms in one area, grooves infilled by <2cm thick vfg Sh; base of unit erosional into pShgn below

Interfan Association series of debris flows from upper fan and morainal banks; sep. flows recog. where interflow deposits pres.; grooves from drag and flow separation at debris flow base; Sh dep. as dens. mid. grain flows and sandy turbidity flows; Fl as distal meltwater deposits between flow events

pShgn-Dca 10-60cm beds w. 2-50cm thick peb. bases grading to 5-30cm thick med/cse-grain. sandst, mod. sort.; largest clast 2cm, mode 1cm.; base of Dca sharp; base of unit sharp, possibly erosive into Dms below

Fan/Interfan Association Typical of upper fan deposits from strong, fluctuating meltwater underflows, but adj. units sug. interfan area? Perhaps from short-lived period of extreme meltwater input?

Dms 10-35% peb-cob clasts in fg sandst./siltst. matrix; non-sorted, no obv. clast orientation; largest clast 15cm, mode 3cm; clasts 60-70% gran., 25-35% volc., <5% sed.;

Interfan/Basal Tillite Association poss. debris flow or flows from interfan morainal banks, may be subglacial primary till; evidence inconclusive for either interp.

Archean not seen at base, cross-sections from this study suggest unconformity in within ten metres of base of section.

APPENDIX 2

Apparent Long-Axis Orientations of Diamictite Clasts

Surfaces approximately parallel to bedding (defined by adjacent or nearby stratification) were selected for measurement of apparent long-axis orientations of clasts with apparent a:b ratios of 2:1 or greater. Large clasts (pebbles and cobbles) were measured for ease of sampling and because they should show the least variable fabrics (Boulton and Deynoux 1981). As recommended by Rust (1975), who observed that in glaciofluvial gravels small pebbles showed more scattered orientations, clasts with apparent long axes greater than 3 cm were measured. Azimuths of apparent long-axes were measured using a Brunton compass. A minimum of 40 clasts were measured per site. To obtain this minimum number of measurements no size restrictions were placed on the area of the sample site.

As recommended by Andrews (1971) for the statistical analysis of till fabrics where three-dimensional orientations cannot be measured, the two-dimensional vector method of Curray (1956) was applied. This method is summarized in Table 3. The BASIC programs in Table 4 were used to compute all statistics. The significance of the resultant vectors was measured by the Rayleigh significance test which Curray (1956) showed gave values similar (or slightly higher) than chi-square tests. Orientation rose diagrams were plotted in the form suggested by Andrews (1971), with 20° class intervals.

For each 20° class interval:

$$\text{Resultant Vector } \phi = \frac{1}{2} \arctan \frac{A}{B}$$

$$\text{where } A = \sum_{i=1}^n \sin 2\theta \quad n = \text{number of observations in interval}$$

$$B = \sum_{i=1}^n \cos 2\theta \quad \theta = \text{azimuth of each observation}$$

$$\text{Vector Strength } R = (A^2 + B^2)^{0.5}$$

$$\text{Vector Magnitude } L\% = \frac{R}{n} 100$$

For total sample site:

Total Resultant Vector

$$\phi = \frac{1}{2} \arctan \frac{A_T}{B_T}$$

$$\text{where } A_T = \sum_{i=1}^K A$$

K = number of intervals
= 9 for this study

$$B_T = \sum_{i=1}^K B$$

Total Vector Strength

$$R_T = (A_T^2 + B_T^2)^{0.5}$$

Total Vector Magnitude

$$L\% = \frac{R_T}{N} 100$$

N = total number of observations

Significance (Rayleigh test of probability)

$$S = \text{from graph in Curray 1956 (Figure 4)}$$

Table 3. Formulae used in the statistical analysis of two-dimensional orientation data (based on Curray 1956; Andrews 1971).

Calculation of Vector Mean and Magnatude for Each Interval

```

5  CLS
10  PRINT "INPUT NUMBER IN SET"
15  INPUT "NUMBER IN SET"; N%
20  PRINT "INPUT DATA FOR INTERVAL"
23  INPUT "NUMBER IN INTERVAL"; T%
25  DIM THETA!(T%), T2!(T%), ST2!(T%), CT2!(T%), RTH!(T%)
30  ASUM! = 0.00
35  BSUM! = 0.00
40  FOR J% = 1 TO T%
50      INPUT "ANGLE"; THETA!(J%)
60      T2!(J%) = THETA!(J%) * 2
70      RTH!(J%) = T2!(J%) * 0.01745 'VERT TO RAD
80      ST2!(J%) = SIN(RTH!(J%))
90      ASUM! = ASUM! + ST2!(J%)
100     CT2!(J%) = COS(RTH!(J%))
110     BSUM! = BSUM! + CT2!(J%)
120     NEXT
130     ACT! = ATN(ASUM!/BSUM!) * 0.5
140     ACT! = ACT! * 57.29578
145     VM! = (SQR(ASUM!^2 + BSUM!^2)/N%) * 100
150     PRINT "SUMA, SUMB, ARCTAN, VMAG"
155     PRINT ASUM!; BSUM!; ACT!; VM!
160     END

```

Calculation of Total Vector Mean, Strength, Magnatude

```

5  CLS
10  PRINT "VECTOR MEAN - STRENGTH - MAGNATUDE"
15  INPUT "NUMBER IN SET"; N%
20  PRINT "INPUT DATA FOR INTERVAL, A FIRST THEN B"
25  DIM A!(9), B!(9)
30  ASUM! = 0.00 : BSUM! = 0.00
40  FOR J% = 1 TO 9
50      INPUT "A"; A!(J%)
60      ASUM! = ASUM! + A!(J%)
65      NEXT
70  FOR J% = 1 TO 9
75      INPUT "B"; B!(J%)
80      BSUM! = BSUM! + B!(J%)
90      NEXT
100  VM! = ATN(ASUM!/BSUM!) * 0.5 * 57.2958
110  VS! = SQR(ASUM!^2 + BSUM!^2)
115  VW! = (SQR(ASUM!^2 + BSUM!^2)/N%) * 100
120  PRINT "SUMA, SUMB, VMEAN, VSTREN, VMAG"
130  PRINT ASUM!; BSUM!; VM!; VS!; VW!
140  END

```

Table 4. BASIC programs for statistical analysis of two-dimensional, orientation data using formulae in Table 3. (BASIC for Radio Shack TRS Model 100. Programs written by J. Richardson, Ottawa-Carleton Centre for Geoscience Studies.)

APPENDIX 3

PALEOPLACER GOLD POTENTIAL AT COBALT

Previous studies of the lower Gowganda Formation Coleman Member indicated that there is little potential for paleoplacer gold concentration (Long 1981, 1982; Mossman and Harron 1983, 1984). However, none of these studies specifically examined the immediate Cobalt area.

A major component of Coleman Member deposition at Cobalt is interpreted to comprise prograding subaqueous outwash fans (of the type documented by Rust and Romanelli, 1975) resulting from subglacial and/or englacial meltwater streams entering a proglacial body of water. Preserved parts of these small fans (areas of less than 2-3 km² in the Cobalt region) consist of a coarsening upward sequence of siltstone-mudstone rhythmites overlain by horizontal- and planar-crossbedded fine- to medium-grained sands, less-common trough-crossbedded sands, and pebbly sands with sparse pebble lags; all capped by moderately to poorly sorted orthoconglomerates.

On the basis of pebble-cobble long-axis orientations, Lindsey (1967) suggested SSW-directed movement of the Gowganda ice sheet. This was confirmed by the discovery during this study of lee-side glacial quarrying features on the unconformity surface at Cobalt and the strong northeast/southwest trend of clast long-axes in the basal diamictite (interpreted as a primary subglacial tillite). The combination of an excellent gold source area to the north (the Abitibi Greenstone Belt) and the abundance of current-worked sands and gravels at Cobalt, suggested that sampling and analysis was justified.

The results of this sampling program are shown in Table 4.

The general locations of sample sites are shown in Figure 17. Some high values were obtained in the initial analyses. However, analysis of the retained portions of these samples resulted in trace values at best, suggesting lab error or perhaps the presence of isolated gold-rich volcanic or sulphide clasts (D. Long, pers. com. 1984). One repeat of sample A8 was slightly anomolous (0.012 oz./ton), but a second analysis of the retained portion of the same sample preparation yielded only 0.003 oz./ton, again suggesting that no real anomaly exists. Additional sampling resulted in more low values. Thus, in spite of the sedimentologically promising setting, results from the Cobalt area complement those obtained from other areas, and suggest that the Coleman Member contains little paleoplacer gold potential.

Sample	Gold Value oz/ton		Lithology	Interpretation
	Initial	Repeat		
Fan A				
A1	nil(2)	nil(2)	top of granule-pebble orthocgl.	Upper (Proximal) Fan
A2	trace(2)	nil(2)	upper zone, A1 unit	
A3	0.019 0.001(2)	nil	mid A1 unit	
A4	trace	-	med-cse pebbly sandstone	Mid to
A5	nil(3)	-	med-cse sandstone	
A6	nil	nil	base of graded trough peb. SS	
A7	nil 0.012	-	med sandstone	
A8	0.112	0.003 nil	peb. lag of trough, x-bedded SS	
A9	nil(2)	-	graded granule cgl-cse SS	Fan
A10	nil(2)	nil	cse, pebbly, hor. bedded SS	
A11	0.006	nil	graded cse-med sandstone	
A12	nil	-	cse sandstone	
Fan B				
B1	0.004	0.002	pebble-cobble orthocgl.	Upper
B2	0.002	-	base: same as B1	Fan
B3	0.006	nil	top: med-cse peb.	Mid to
B4	0.004	nil	base: troughed SS	Upper Fan
Fan C				
C1	nil	-	med-large peb. orthocgl.	Upper Fan
C2	trace	-	small peb. orthocgl.	Mid to
C3	nil	-	peb. lag, graded trough SS.	Upper Fan
Fan D				
D1	trace	-	med-cse, graded peb. SS.	Mid
D2	trace	-	med-grained pebbly SS.	Fan
Misc.				
M1	trace	-	small peb orthocgl. on Archean uncon. surface	Subglacial Meltwater Channel
M2	nil	-	similar to M1	Mass Flow
M3	nil	-	graded hor. bed peb cse SS.	Mass Flow
M4	nil	-	small peb. orthocgl lense in diamictite (matrix sup)	Mass Flow in interfan zone

Table 4 Assay results from Coleman Member of the lower Gowganda

Formation in the Cobalt study area. Assays are grouped within fan complexes and in correct relative stratigraphic position where possible. Bracketted numbers after assay values indicate multiple samples from the same unit. The general location of sample sites are shown in Figure 17.

APPENDIX 4

Locality Maps Showing Data Collection Sites

Figure 13 Sample sites - Orientations of apparent long axes of clasts in diamictites of the Basal Diamictite Association (see Figure 4)

Figure 14 Sample sites - Paleocurrent measurements (see Figure 6A-D)

Figure 15 Sample sites - Orientations of apparent long axes of clasts in diamictites of the Fan and Interfan Associations (see Figure 7).

Figure 16 Sample Sites - Orientation of apparent long axes of clasts in diamictites of the Upper Diamictite Complex (see Fig. 8).

Figure 17 Sample Sites - Gold Assays of Table 6

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59°00'00" E

79°42'00"

81

82

79°41'50"

83

52°10'00" N

09

47°24'20"

08

07

06

05

GOWGANDA FORMATION

COLEMAN MEMBER

COBALT ONTARIO

Northern Sheet

Contour Interval: 1 Metre

Scale: 1:2000

LEGEND*

PROTEROZOIC

Basic Intrusive Silt: Missing Diabase

Intrusive Contact

HURONIAN SUPERGROUP

COBALT GROUP

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES**

Upper Heterolithic Diamictite Complex***

- UD upper Diamictite
- UDm matrix-supported
- UDc clast-supported (rare)
- UD-m massive (<10% irregular stratification)
- UD-s stratified
- UD--(r) resedimented

Diamictite, clast-supported

GOWGANDA FORMATION

COLEMAN MEMBER

COBALT ONTARIO

Northern Sheet

Contour Interval: 1 Metre

Scale: 1:2000

LEGEND*

PROTEROZOIC

Basic Intrusive Silt: Nipissing Diabase

Intrusive Contact

HURONIAN SUPERGROUP

COBALT GROUP

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES**

Upper Heterolithic Diamictite Complex***

- UD upper Diamictite
- UDm matrix-supported
- UDc clast-supported (rare)
- UD-m massive (<10% irregular stratification)
- UD-s stratified
- UD--(r) resedimented

Diamictite, clast-supported

Magnetic declination
approximately 11° west

SYMBOLS

Geologic contact: defined, approximate, assumed

Boundary of rock outcrop

Small outcrop

Strike and dip of bedding: inclined, horizontal, vertical

Strike, tops of pillowed volcanic rock: dip known, unknown

1 OF/DE

79°40'40" 98 79°40'30" 01 79°40'20" 02 79°40'10" 03 79°40'00" 04 05 79°40'00" 06

u0-m massive (<10% irregular stratification)
 u0-s stratified
 u0--(r) resedimented

Diamictite, (clast supported)

Dcm massive
 Dcs stratified

Sandstone

ps pebbly sandstone (>5% gravel-sized grains)
 Sm massive
 Sh horizontal lamination
 Sr rippled
 St trough cross bedded
 Sp planar cross bedded
 S-gn graded, normal
 S-gr graded, reverse

Fine-grained facies (mudstone, minor very fine-grained sandstone)

Fr rhythmically laminated (sand-silt and/or silt-clay alterations)

Fl laminated (non-rhythmic)
 Fm massive (<10% laminations)
 F-d dropstones

Basal Diamictite (Tillite)

bDm matrix-supported, massive

-other symbols as for Upper Diamictite Complex

Breccia

Bx(r) resedimented

▲ small occurrences

Angular Unconformity

ARCHEAN

Basic/Ultrabasic Intrusions

Intrusive Contact

A undifferentiated Archean
 Ap basic volcanic rock - pillowed
 Am basic volcanic rock - massive
 Af felsic volcanic rock
 Ai interflow sedimentary rock

SOURCES OF INFORMATION

* Outcrops are shown in dark colour. Inferred extension of units are shown in light tone of same colour.

** Lithofacies code used for mapping adapted from Eyles et al. (1983) and Powell, (1984). In some areas, units are missing or not in sequence shown in legend.

*** Contains sandstone and rare mudstone interbeds, mapped where thick and traceable.

Geology, 1984: P. Mustard, R. Scannell, B. Wilson, R. Rainbird

1985: P. Mustard, E. Dodd

Geology compiled by P. Mustard to accompany Mustard, P.S. 1985. Sedimentology of the Coleman Member, Gowganda Formation, at Cobalt, Ontario. Unpublished M.Sc. thesis, Carleton University, Ottawa, Ontario.

Major Fault Locations: Thomson R. 1964a. Cobalt silver area, northern sheet, Timiskaming district. Ontario Department of Mines, Map 2050.

Topographic Base Map: Ontario Ministry of Natural Resources, Urban Topographic Series, 1:2000 scale

50F/DE

ical

vertical

unknown

unknown

m wide

2 m wide

ny

any

the

at

F

6
OF/DE

Strike, tops of pillowed volcanic rock: dip known, unknown

8 OF DE

/DE

Ap basic volcanic rock - pillowed
 An basic volcanic rock - massive
 Af felsic volcanic rock
 Ai interflow sedimentary rock

50F/DE

12 OF/DE 12

OF/DE

10F/DE

DE

Peterson Lake
30F/DE

78°42'00"

78°42'00"

78°42'00"

78°42'00"

6010000E

Peterson Lake

4 OF/DE

6
OF/DE

GOWGANDA FORMATION

COLEMAN MEMBER

COBALT ONTARIO

Southern Sheet

Contour Interval: 1 Metre

Scale: 1:2000

LEGEND

PROTEROZOIC

Basic Intrusive Sill: Nipissing Diabase

Intrusive Contact

HURONIAN SUPERGROUP

COBALT GROUP

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES

Upper Heterolithic Diamictite Complex***

uD upper Diamictite
 uDm matrix-supported
 uDc clast-supported (rare)
 uD-m massive (<10% irregular stratification)
 uD-s stratified
 uD--(r) resedimented

Diamictite, clast supported

Dcm massive
 Dcs stratified

7
OF/DE

Peterson Lake

GOWGANDA FORMATION

COLEMAN MEMBER

COBALT ONTARIO

Southern Sheet

Contour Interval: 1 Metre

Scale: 1:2000

LEGEND

PROTEROZOIC

Basic Intrusive Sill: Nipissing Diabase

Intrusive Contact

HURONIAN SUPERGROUP

COBALT GROUP

GOWGANDA FORMATION - COLEMAN MEMBER LITHOFACIES

Upper Heterolithic Diamictite Complex***

- u0 upper Diamictite
- u0m matrix-supported
- u0c clast-supported (rare)
- u0-m massive (<10% irregular stratification)
- u0-s stratified
- u0--(r) resedimented

Diamictite, clast supported

- Dcm massive
- Dcs stratified

Magnetic declination
approximately 10° west

SYMBOLS

Geologic contact: defined, approximate, assumed

Boundary of rock outcrop

Small outcrop

Strike and dip of bedding: inclined, horizontal, vertical

Strike, tops of pillowed volcanic rock: dip known, unknown

Paleocurrent indicator: direction known, unknown

Dike attitude: inclined, vertical

80F/DE