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STRATIGRAPHY AND GENESIS OF
EARLY PROTEROZOIC DIAMICTITES:
NORTH AMERICA

by

DENNIS D. KURTZ

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

DOCTOR OF PHILOSOPHY

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ABSTRACT

STRATIGRAPHY AND GENESIS OF
EARLY PROTEROZOIC DIAMICTITES
NORTH AMERICA

DENNIS D. KURTZ

Glaciogenic rocks are present throughout the world, in strata of all ages. Where thought to represent glacial marine or glacial aquatic deposition their interpretation has been hampered by the lack of a sedimentary model based upon modern glacial marine processes. A model constructed from the study of Antarctic marine sediments and Pleistocene marine sequences exposed in the Puget Lowlands is used in this thesis to interpret Early Proterozoic (middle Precambrian) glaciogenic rocks. Possible tillites were studied in the Gowganda Formation, Ontario, the Headquarters Formation, Wyoming, and in the Black Hills.

Antarctic glacial marine sediments reflect the interaction and relative importance of glacial, marine, and gravity-driven sedimentary agents. Subglacial deposits on the continental shelf exhibit no indication of marine current action. Glacial marine tills on the continental shelf and slope display both glacial and marine characteristics. Marine current deposits are also present on the continental slope. Sediment gravity flow deposition of several kinds occurs, principally on the continental slope, and these sediments are interbedded with glacial and marine sediments. Sediment texture, the kinds of sedimentary structures, pebble characteristics, and sedimentary associations are the major criteria used for
distinguishing these sediments types.

The Gowganda Formation in northern Ontario is a thick, widespread unit that has long been thought to represent glacial deposition. A sequence of rocks representing pre-glacial and periglacial sedimentation, subglacial and glacial aquatic conditions, and post-glacial deposition is typically present. The glacial unit contains both basal and floating ice deposits. This formation is interpreted as representing one major advance and retreat of a large grounded and floating ice sheet. Local fluctuations of the grounding line, and of the retreating ice margin probably occurred but there is no need to invoke more than one glaciation to explain these deposits.

The Headquarters Formation in southeastern Wyoming contains tillites that are interbedded with a variety of non-glacial sediments (fluvial-deltaic deposits, turbidites, etc.). This unit probably represents deposition in a near-shore setting under frigid climatic conditions. There is no evidence for the presence of a nearby large ice mass.

Metaconglomerates in the Black Hills are of unknown origin. The presence of lonestones in argillites and gradational contacts between units suggests glacial aquatic deposition.

There is no evidence in the deposits studied which indicates that a continental ice sheet covered North America at that time; though a large ice sheet was present in northern Ontario.
ACKNOWLEDGEMENTS

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INTRODUCTION

Ancient glacial strata are known throughout the world, from many periods of geologic time. Many of these sequences have been interpreted as being wholly or partly glacial marine (Carey and Ahmad, 1961; Reading and Walker, 1966; Frakes and Crowell, 1967; Aalto, 1961; Lindsey, 1971; Sylvester, 1973; Karlstrom and Houston, 1979; and others). Indeed, Frakes and Crowell (1975) argue that ancient glacial sequences may be dominantly glacial marine because such deposits would more likely be preserved than terrestrial tills. Until recently, however, students of ancient deposits had no modern glacial marine analogs upon which to base their interpretations. Models developed from the study of Permo-Carboniferous sequences in Tasmania (Carey and Ahmad, 1961) and Pleistocene units in the Puget Lowlands and British Columbia (Armstrong and Brown, 1954; Easterbrook, 1963) were most frequently used; or, researchers developed depositional models based on the rocks at hand. These models were based on a combination of inferences drawn from modern non-glaciogenic marine sediments and assumptions based upon glaciologic theory. Their validity in a true glacio-marine setting is only now being tested.

We are presently formulating a glacial marine sedimentary model which can be used to interpret ancient sequences. This model is based upon the study of modern Antarctic sediments and late Pleistocene sediments in the
Puget Lowlands and British Columbia. The Antarctic continental margin is an ideal place to develop a modern sedimentary model because many of the factors affecting the characteristics of glacial marine sediment facies can be observed and studied there. Much of the continent is covered by a permanent ice cap, with the ice sheet having both wet- and dry-base portions (Hughes, 1973). It is grounded above and below sea level — very near to the continental shelf break in some areas, while more than 500 km from the shelf break in others. Much of the east Antarctic coastline is covered by grounded ice which extends into the sea as a narrow floating ice shelf (Bentley, 1964). In west Antarctica, vast floating ice shelves extend hundreds of km out to sea. Outlet glaciers or ice tongues may be the only portion of the ice mass to reach the sea along mountainous lengths of the coast. The temporal and spatial variations in these glaciologic conditions are reflected in the complex suite of glacial marine sedimentologic facies which is deposited.

Other facets of glacial marine sedimentation, particularly nearshore and interglacial deposition, can be studied in the late Pleistocene deposits. Though the glaciologic conditions affecting their deposition cannot be observed, many of these deposits appear similar in texture and origin to Antarctic sediments (Cole, 1979). Furthermore, they contain a diverse microfossil assemblage from which paleoclimatic and paleo-oceanographic
inferences can be made.

A number of ancient glacial sequences were chosen to evaluate, and to refine, our glacial marine sedimentologic model. The most intensively studied stratigraphic units in the present study are the Huronian Gowganda Formation, Ontario, and the middle Precambrian Headquarters Formation, Medicine Bow Mountains, Wyoming. The 'Bluebird Formation', in the Black Hills of South Dakota, and the Reany Creek Formation, Upper Peninsula, Michigan were studied in lesser detail. These strata are all of Early Proterozoic age (1.7-2.5 Ga). Some of them are thought to represent deposition during a middle Precambrian continental glaciation (Young, 1970).

The Gowganda Formation was selected for study because it is the best-studied Precambrian glacial sequence in North America (Pettijohn, 1962; Ovenshine, 1965; Schenk, 1965 a,b; Lindsey, 1966, 1969, 1971; Casshyap, 1969; Young, 1966, 1970, 1973; and others). Good outcrops, wide regional extent, low metamorphic grade, and easy accessibility make it an ideal succession in which to evaluate the modern model. The Gowganda Formation was probably deposited beneath and adjacent to a large ice mass (Pettijohn, 1962; Casshyap, 1969; Young, 1970; Lindsey, 1971), thus, an Antarctic sedimentation model should be applicable.

The Headquarters Formation represents the westernmost exposure of mid-Precambrian glaciogenic rocks in North
America. It has been only slightly metamorphosed and is preserved as part of a thick miogeosynclinal sequence (Houston and others, 1968). The Headquarters Formation may be laterally equivalent to Huronian strata. Sylvester (1973) concluded that this formation represented glacial marine sedimentation in proximity to a large ice sheet, and that several glacial episodes were recorded.

The present study seeks to test, using an understanding of modern glacial marine sedimentary processes, Young's (1970) model of a mid-Precambrian continental glaciation, and Sylvester's (1973) sedimentologic and paleoclimatic interpretations. Also of interest are the lateral and vertical facies relationships in the ancient sediments -- associations which have not, as yet, been adequately studied in modern environments.

Young's hypothesis is examined on the basis of Schermerhorn's (1974) criteria for demonstrating continental glaciation. These are: 1) a glacial origin for the rocks in question must be proven, 2) stratigraphic successions must be present which are consistent with glacial advance and erosion, glacial retreat, and associated glacial-eustatic and glacio-isostatic processes, 3) the glaciogenic deposits must be present over a region of continental dimensions, and 4) widely separated units must be shown to be time correlative. Using Antarctic models, criteria 1 and 2 can be directly tested. Furthermore, the glacial regime and the position on the
continental margin where deposition took place can be identified. Thus, even though criteria 3 and 4 cannot be precisely demonstrated, sedimentologic limits can be set as to the glacial and marginal setting that was present. For instance, evidence for a major ice sheet in one region, coupled with information suggesting valley glaciers in another, would not support a hypothesis of continental glaciation including both of those units.

Sequences in the Black Hills and the Upper Peninsula of Michigan were also examined with regard to Young's theory. Metasediments in the Black Hills are Early Proterozoic in age (Goldich and others, 1966; Zartman and Stern, 1967) and were deposited in a eugeosyncline (King, 1976). Because these metasediments might be equivalent to Huronian rocks, and because of their basinal depositional setting, one would expect that some evidence of a widespread Early Proterozoic glaciation would be preserved in these strata, if such a glaciation did indeed occur. Localized exposures of Early Proterozoic (Animikie) rocks in the Upper Peninsula are also thought to be equivalent to Huronian strata (Young, 1970). Again, interpretations as to their origin should prove useful in testing the continental glaciation hypothesis.

Sylvester's (1973) multiple glaciation hypothesis for the Headquarters Formation can also be tested using Antarctic analogs. Such a sequence of events should deposit a definite suite of sediments whose origin is
related to glacial and periglacial processes.

Lateral and vertical facies associations on a regional scale cannot be observed in Antarctica even though a wide range of sediments types have been recovered there (Anderson, 1972; Chriss and Frakes, 1972; Anderson and others, 1979). Knowledge concerning the genesis of these modern sediments, coupled with the facies distributions of their lithologic analogs, may well enable sedimentologists to test climatologic, and related glaciologic and oceanographic theories.

This dissertation has been organized such that each chapter is more or less a separate paper. A glacial marine model based on modern sediments is presented and the origin of strata in each of the ancient sequences is discussed with respect to the model. The final chapter summarizes the conclusions presented regarding each area and discusses Young's (1970) and other regional models.
METHODS

Sediment units in Antarctic piston cores were initially defined using x-radiographs and visual core descriptions. Samples were taken from those units distinguished on this basis. These samples (~1.5 cc) were texturally analyzed using the Rice University Automated Sediment Analyzer (Anderson and Kurtz, 1979).

Percentages of minerals or material in rock specimens were estimated by point counts on thin sections.
TERMINOLOGY

The terms 'paraconglomerate' and 'orthoconglomerate' are used as outlined in Pettijohn (1957a). 'Paraconglomerate' refers to conglomerates with clasts dispersed in a finer-grained matrix. 'Orthoconglomerate' refers to conglomerates which are clast supported or which contain high percentages of clasts. 'Conglomerate' is used to refer to both kinds, or in place of 'orthoconglomerate' where usage is unambiguous. The adjective 'polymictic' refers to a clast assortment consisting of many lithologies (Pettijohn, 1957a).

'Diamictite' is a non-genetic term that refers to a poorly sorted rock containing material of all sizes. Such rocks are actually quite rare and more descriptive terms such as 'pebbly argillite' or 'pebbly sandy argillite' are used instead. Rocks referred to as 'pebbly graywackes' are perhaps the closest in texture to diamictites.

The terms 'wet-base' and 'dry-base' refer to thermal conditions at the base of an ice sheet. 'Wet-base' conditions are those where no net freezing occurs. Net melting can occur. 'Dry-base' conditions are those where net freezing occurs. Boulton (1971) offers a detailed discussion of these situations and their effects on glacial sedimentation.

A most important sedimentary boundary in the glacial aquatic environment is the ice grounding line. Landward
of this line deposition is affected solely by glacial processes. Seaward, marine processes also influence sedimentation and become increasingly important farther from the ice. The terms 'proximal' and 'distal', where used in reference to glacial aquatic sediments refer to the distance seaward from the grounding line.
MODERN GLACIAL MARINE SEDIMENTATION

An understanding of the factors governing modern terrestrial glacial and glacial marine sedimentation is necessary to interpret ancient glaciogenic sequences. Terrestrial glacial deposits have been extensively studied since Bernhardi and Agassiz first recognized them (Flint, 1971). However, as Carey and Ahmad (1961) point out, most ancient glacial deposits probably represent nearshore and deep water glacial marine conditions because these sediments, in their basinal setting, will more likely be preserved. Observing and inferring sedimentary processes in modern environments has enabled us to appreciate the complexity of glacial marine processes and to reconstruct, in greater detail, ancient depositional settings.

There are three distinct marine depositional settings associated with a major ice sheet. These are 1) subglacial, 2) proglacial shelf, and 3) periglacial slope and rise (Kurtz and Anderson, 1979b). Descriptions of glacial marine sediments and processes characterizing these areas appear in a number of papers (Anderson and others, 1977a,b, 1979, in press; Kurtz and Anderson, 1979a). They will be summarized in this chapter. Factors affecting biogenic sedimentation are not considered because such sediments are not known from the Precambrian.
The Subglacial Setting

Both erosion and deposition take place beneath grounded ice. Perhaps the most important factor determining which of these processes prevails is the basal thermal regime of the ice mass (Boulton, 1971). In general, glacial abrasion and depositon of lodgement till are more active beneath wet-base glaciers than dry-base glaciers. Erosion and transport are more effective in dry-base situations. The particular glacial thermal conditions at any given site depend upon prevailing climate, ice thickness, substrate character, basal shear stress, and geothermal heat flux. Ice grounded below sea level is inherently unstable (Hughes, 1973) and tends to achieve stability by becoming afloat. Thus, subglacial grounded ice deposits may be intercalated with floating ice sediments.

Sediments deposited by grounded ice are termed 'orthotills' (Harland and others, 1966). They are restricted to the continental shelf and are indistinguishable from terrestrial tills. Orthotills from both Antarctica and the Puget Lowlands are massive, poorly sorted, pebbly sandy muds (Fig. 1). They exhibit no grading and are texturally homogeneous downcore (Kurtz and Anderson, 1979a). Pebbles are dispersed throughout a finer matrix, and are rounded to subrounded (E. Domack, pers. comm.). These units can be much thicker than terrestrial lodgement tills. Seismic reflection (Houtz and Davey, 1973) and subsequent deep sea drilling (Hayes and others, 1975) in the Ross
FIGURE 1. Composite cumulative frequency curve and one standard deviation envelope for Weddell Sea orthotills.
Sea revealed over 1500 m of marine till, consisting in part of orthotills (Barrett, 1975; K. Balshaw, pers. comm.).

The non-sorted texture of modern orthotills reflects the absence of marine current activity in this setting. Because this texture is solely the result of glacial processes, any deviations from it reflect marine influences.

The Proglacial Shelf

Deposition on the proglacial shelf is largely by floating ice and through reworking by marine currents. Bathymetry plays a role in that it affects marine circulation patterns and hence influences sediment transport. Erosion by ice is of minor influence.

Floating ice deposits are 'paratills' (Harland and others, 1966). They can be deposited anywhere on the continental margin. Paratills range in texture from pebbly sands to sandy muds (Anderson and others, 1979, in press). They are crudely- to well-stratified and may be texturally variable within a given unit. Anderson and others (1977a) recognized two kinds of paratills. RESIDUAL PARATILLS are stratified pebbly muddy sands that have had their finer fraction removed through marine current action (Fig. 2). COMPOUND PARATILLS are stratified or laminated pebbly sandy muds which have been enriched in fine-grained sediments relative to orthotills (Fig. 3). These two type of paratills form a textural spectrum, and can be interbedded with one another.
FIGURE 2. Composite cumulative frequency curve and one standard deviation envelope for Weddell Sea residual paratills.
FIGURE 3. Composite cumulative frequency curve and one standard deviation envelope for Antarctic compound paratills.
Residual paratills are most common on the continental shelf. Seaward, away from the ice front and in deeper water, compound paratills dominate. Pelagic clays deposited on the abyssal plain which contain small quantities of ice-rafted debris can be considered an extreme type of compound paratill.

Superimposed on this seaward-fining trend are local effects due to bathymetry. Bathymetric highs can be sites of intense current winnowing and residual paratill deposition if they are shoal enough to be influenced by surface currents. In deeper water, thermohaline circulation is controlled by irregularities on the sea floor, and fine-grained sediments tend to accumulate in depressions. Rerouting of marine currents by bathymetry can result in portions of the continental margin being sediment-starved. Thus, very slow rates of sedimentation may characterize these areas. If ice-rafted debris is being distributed evenly over the shelf, pebbly or sandy sediments will be deposited where deposition of finer-grained material is limited.

Deposition from floating ice is influenced by a number of variables. Where debris-laden ice enters the sea, melting probably begins almost immediately. Even where repeated melting and refreezing of ice occurs deposition continues. Thus, most sediment is probably released from the ice very near the grounding or calving line. Coarse material may remain there but, where marine currents are
present, silts and clays are swept further out to sea.
The importance of this process depends upon current strength,
water depth, and local bathymetry. Substantial ice-rafting
occurs far out to sea only when the grounding line advances;
when debris-laden ice is moving rapidly as in surging
glaciers; or when detritus is carried englacially or in
shear zones (Anderson and others, in press, J. Glac.).

The proglacial shelf is a transition zone. Near the
ice front, sedimentation is controlled principally
by glacial processes. Marine agents become more effective
seaward until, at the shelf break, marine processes may
play a dominant role in sedimentation. This is reflected
in sediment textures and the degree of stratification.

The Periglacial Slope and Rise

On the continental slope and rise, or on any submarine
slope, marine and gravity-driven sedimentary processes
prevail over glacial ones. But, the presence of an ice
sheet still influences sedimentation because all material
delivered to the marine environment is brought there by
ice; either directly, or indirectly by melt-water streams.
The latter process apparently plays a minor role in
introducing sediment to the Antarctic seafloor. No fluvial,
aeolian, or coastal processes are acting to sorting
sediments. Sediment sorting and reworking prior to its
delivery to the shelf break are via marine processes.
Hence, large quantities of well-sorted sediment reach
the continental slope only where marine currents are sufficiently strong to transport and deposit sediment there.

The most common forms of sediment gravity flows on the Antarctic continental margin are debris flows and turbidity flows (Anderson and others, 1979; Kurtz and Anderson, 1979a). Debris flow deposits are massive, poorly sorted pebbly sandy muds that are texturally homogeneous within a given unit. Their texture reflects their derivation from orthotills and paratills. Debris flow deposits appear to be most common on smooth continental slopes where non-channelized flow has occurred. They reflect the delivery of large unstable amounts of unsorted debris to the outer shelf -- probably by ice (Kurtz and Anderson, 1979a). Subsequent failure may occur during isostatic adjustment upon glacier retreat.

Turbidites are well-sorted, graded, pebbly sands and sands. They commonly grade upwards into silt- or clay-sized material. Unlike debris flow deposits, turbidites are rare on smooth slopes but are characteristic of slopes dissecting by submarine canyons. Turbidites reflect marine winnowing of tills, probably on the upper slope by strong contour currents (Anderson and others, 1979). In some cases turbidites may be transported toward the continent as in the vicinity of the George V Coast (E. Domack, pers. comm.).

Laminated marine current deposits, so-called
'contourites', are common on smooth continental slopes (Piper and Brisco, 1975; Hollister and Craddock, 1976; Tucholke and others, 1976; Anderson and others, 1977b) and are interbedded with debris flow deposits. These sediments are most common on the lower slope and rise. They are non-pebbly or sparsely pebbly. Several kinds of laminae are present (Anderson and others, 1979), including rhythmic bimodal couplets, graded muds, and interbedded sands, silts, and clays. DSDP drilling indicates that laminites may be of tremendous thickness, up to 300 m (Piper and Brisco, 1975). Laminated muds are of several origins. Some quite probably represent distal turbidites (Bridge, 1978), others may be current laminites (Bouma and Hollister, 1973), but still others represent sporadic sediment influxes into stagnant basins.

Non-pebbly, non-laminated muds are also present on the Antarctic continental slope and rise. These sediments are structureless but contain mycelia in x-radiographs. Their genesis and origin is poorly understood; all known deposits are from the vicinity of the Amery Ice Shelf.

Figure 4 depicts the spectrum of glacial marine sediment types found on the Antarctic continental margin. The apex of the triangle represents glacial sediments deposited on the continental shelf with no marine influences. The base of the triangle represents more distal continental shelf, slope, and rise deposits which are greatly influenced by marine agents. Marine current energy
FIGURE 4. Diagramatic representation of the relationships between major glacial marine sediments types and glacial and marine processes, current strength, and continental margin position.
decreases from left to right across this triangle.

The orthotill field is necessarily at the apex. These sediments interfinger with paratills which occupy the bulk of the figure. Residual paratills fall to the left because they are winnowed by relatively strong currents. Compound paratills, influenced by weaker currents, are on the right. The most distal deposits display more marine than glacial characteristics. Sediment transported by high-velocity traction currents leads to turbidite deposition on the outer margin. Lower velocity currents deposit laminated muds. Non-laminated muds indicate weak or no currents, possibly stagnant conditions. Debris flow deposits are unique in that they can occur anywhere and be interbedded with any type of sediment. They, and turbidites, reflect gravity-driven sedimentary processes.

During preglacial, interglacial, and post-glacial times, a complex suite of sediments may be deposited in the nearshore glacial marine environment. Nearshore facies associations may contain fluvial and valley glacial deposits, widespread orthotills and paratills, and marine sediments (Fig. 5) (Cole, 1979). There is no single lithology which characterizes these deposits. But, the facies variability, reflecting shifting depositional conditions and repeated erosion, is unique.

Secondary glacial sedimentologic influences are important because they complicate glacial marine sedimentary sequences tremendously. Large scale erosion by ice sheets
FIGURE 5. Several closely-spaced measured sections and tentative correlations in Pleistocene nearshore glacial marine sediments in the Puget Lowlands. Note the lithologic complexity.
or interglacial fluvial action removes considerable portions of the sedimentary record and juxtaposes unrelated sediments. Sculpting of the continental shelf by ice can also form bathymetric features which control subsequent marine current action and sediment transport paths.

The great mass of a continental ice sheet isostatically deforms the crust beneath it, forming a proglacial depression on the continental shelf (Broecker, 1966; Walcott, 1970). Compound paratills and non-laminated muds may then accumulate in this depressions which other portions of the margin are sediment-starved. Furthermore, depending upon the time frame of glacial fluctuations, this proglacial depression may migrate with the shifting ice front.

Ice drainage patterns can result in the channelling of large quantities of sediments to certain portions of the continental margin. For instance, the Ronne-Filchner, Ross, and Amery Ice Shelves drain 53% of Antarctica but deposit sediment over only 10% of the continental margin. Sediments deposited near a large ice shelf are predominantly of the proglacial shelf facies; subglacial sediments are laminated or absent.

Other Forms of Glacial Aquatic Deposition

Two other forms of glacial aquatic sedimentation which are not associated with a major ice sheet are important. These are 1) valley glacial aquatic sedimentation, and 2) fast ice or shore ice-rafting. Neither process indicates
a glacial age but both demonstrate cold climatic conditions.

Valley glacial aquatic deposits have not been extensively studied. Cole (1979), describing sediments from the Puget Lowlands, noted that valley glacial deposits ranged in texture from pebbly sands to pebbly sandy muds. Stratification is well-developed in some units and varying amounts of fine material reflect current intensity. Clasts observed on valley glaciers and in valley glacial aquatic deposits are commonly angular (Ovenshine, 1970) because they are formed through frost riving and transported supraglacially and englacially. These sediments are limited in extent and may be intercalated with other types of deposits. Gravity flow deposits, turbidites, basinal non-pebbly muds, or fluvial-deltaic sediments may all also be present.

Fast ice rafting occurs in lakes, rivers, and along coasts in middle-high latitudes (Fuchs and Whittard, 1930; Dionne, 1969; Vanney and Dangeard, 1976). Pebbles or sand grains are derived from coastal or fluvial deposits and are thus well-rounded. These sediments typically constitute only a small percentage of the sediments in any given sequence; other processes only secondarily related to cold climate dominate sedimentation.

Facies variability is characteristic of valley glacial and fast ice rafting settings but, unlike nearshore glacial
marine sequences, sedimentary units are generally conformable. Widespread unconformities due to ice deformation or fluvial and ice erosion are rare.
GOWGANDA FORMATION

Introduction

The Gowganda Formation is one of the best studied sequences of ancient glacial strata in the world. Coleman (1907) first proposed a glaciogenic origin for this formation. This genesis has since been documented by numerous workers (Pettijohn, 1962; Ovenshine, 1965; Schenk, 1965a,b; Casshyap, 1969; Young, 1966, 1970; Lindsey, 1971). Portions of the Gowganda Formation have been interpreted as having a glacial marine origin (Lindsey, 1971; Young, 1973) but these researchers' interpretations were very generalized because of the lack of a well-studied modern analogy. Lindsey (1971, p. 22) summarized this situation when he wrote "...the true distribution of facies, especially with regard to sedimentary structures, is largely unknown in modern glacial marine environments; hence correlation between ancient glacial marine deposits and modern environments is nearly impossible. At the present state of knowledge cautious interpretation of the facies relationships in individual sequences of glacial marine rocks seems most desirable."

Our recent extensive sampling efforts on the Antarctic continental margin, and work in the Puget Lowlands, have enabled us to define facies relationships in a modern glacial marine environment. These facies associations reflect changing subglacial and proglacial sedimentary
conditions through one or more glacial episodes, and can be used to interpret ancient sequences.

This thesis deals only with that portion of the Gowganda Formation outcropping in Ontario north of Lake Huron, from just west of Bruce Mines to Espanola (Fig. 6). Exposures in the region north of Sudbury, or in Quebec, were not studied. The following sediment and sediment facies descriptions emphasize not only lithology, but also sediment texture and sedimentary structures, and the lateral variability of these features. These characteristics are compared with those from modern sediments to formulate a sedimentary model for the origin of the Gowganda Formation.

Previous Work

The Gowganda Formation was first described by Collins (1917) from exposures west of Cobalt. The unit has since been identified and mapped throughout much of Ontario in the vicinity of Lake Huron. The Gowganda Formation is part of the Huronian Series. Its age, dated by Rb-Sr dates on the intrusive Nippissing Diabase and the underlying basement, is between 2.1 and 2.5 Ga (van Schmus, 1965; Fairbairn and others, 1960). Fairbairn and others (1969) attempted to date the metasediments themselves and achieved an age of 2.3 Ga. In the northern part of its outcrop belt the Gowganda Formation overlies Archean basement, filling a surface of considerable topographic relief (Wood, 1975), whereas farther south it overlies Huronian
FIGURE 6. Location map showing Gowganda Formation outcrop and positions of measured sections, Ontario.
metasediments of the Cobalt and Bruce Groups. The Gowganda Formation is overlain, in many places conformably, by the Lorrain Quartzite of the Cobalt Group.

Two units within the Gowganda Formation are regionally recognizable -- a lower conglomeratic or paraconglomeratic unit, and an upper argillitic and arenitic unit. Thomson (1957), in the area near Cobalt, has named these the Coleman Formation and Firstbrook Formation respectively. This terminology has not been applied in other areas, however, because correlation is not possible. The lower conglomeratic unit is widely regarded as representing glacial climatic conditions, with deposition occurring in both terrestrial and marine settings (Lindsey, 1971; Schenk, 1965a). The upper unit is thought to exhibit minor or no glacial influences and to have been deposited on a subaqueous slope (Lindsey, 1967; Young and others, 1977).

The Gowganda Formation regionally thickens toward the south (Lindsey, 1971), however, in many areas, particularly in the north, substantial local thickness variations are present. These thickness variations reflect topographic relief, in some places as much as several hundred m, present at the time of deposition. At some northern locales the basement reportedly overlies a striated pavement (Schenk, 1965b).

Paleotransport determinations from sedimentary structures in arenites (Pettijohn, 1957b; Pienaar, 1963) and regional changes in unit thicknesses (Lindsey, 1971)
indicate that the paleoslope dipped towards the south. Orientations of the long axes of elongate pebbles suggest that ice movement was, in general, southerly (Pettijohn, 1962; Lindsey, 1966, 1969). However, many units exhibit a poorly developed pebble fabric, or none at all (Lindsey, 1969).

Pebble lithologies are variable and also indicate a northerly source (Casshyap, 1969). They consist primarily of granitic clasts (65-75%), with other igneous rocks (~15%) accounting for the remainder (Young, in press). Pebble shape ranges from angular to well-rounded (Lindsey, 1969) with some faceted stones being observed. Lindsey (1969) suggests that well-rounded pebbles indicate fluvial transport prior to glacial deposition.

To date facies analyses in this formation have largely been aimed at delineating terrestrial vs. marine glacial environments (Lindsey, 1966, 1971) and at documenting the glacial history (Young, 1970). Lindsey (1966) used the distribution of varved argillite and silty limestone to delineate terrestrial and marine facies respectively. He found that marine facies were present only in the southeastern portion of the outcrop belt (Lindsey, 1966, Fig. 2). Young and others (1977) have also interpreted rocks in this region as being glacial marine. This inference is based on the presence of crudely stratified paraconglomerates and pebbly and non-pebbly laminated argillites. They also suggest that each of several
separate paraconglomeratic units represent different glacial events. To date no one has examined the regional facies distribution from the standpoint of current glaciological and climatological theory, particularly as these relate to sedimentation patterns associated with an advancing or retreating ice mass.

Description and Distribution of Sediment Units

The Gowanda Formation can be divided into three major sedimentary units or lithologic groupings. In ascending order these are: UNIT I - a relatively coarse grained conglomeratic and arenitic sequence; UNIT II - a unit composed primarily of massive and stratified polymictic paraconglomerates; and UNIT III - a sequence of interbedded laminated argillites and graded arenites. The units in many places are gradational with one another, and the dominant lithologies in one are commonly present in subordinate amounts in others. Regional stratigraphic distributions of these three units and important lithologies are shown in figure 7.

UNIT I

This unit consists primarily of interbedded polymictic pebble to boulder orthoconglomerates and coarse - to fine-grained feldspathic arenites. The relative amounts of these two lithologies vary from section to section. Varying subordinate amounts of pebbly and non-pebbly
FIGURE 7. Fence diagram illustrating correlations between measured sections and lithologic units in the Gowganda Formation.
argillite and siltstone are also present. UNIT I occurs only in the basal portions of the Gowganda Formation, in the northwestern part of its outcrop belt in this area (Fig. 7). Though dramatic local thickness variations are present, the greatest thicknesses (~150 m) of UNIT I are in the north, whereas this unit is thin or absent in the most southerly or southeasterly sections measured. Also, the unit becomes finer-grained towards the south. Orthoconglomerates constitute greater than 75% of this unit in the vicinity of section ML (McElrea Lake) (Fig. 7) but are subordinate to arenites in other, more southerly, locales. Fine-grained accessory lithologies, such as argillite and paraconglomerates, are also more prevalent in the south. The unit may become finer upwards but because the upper contact is commonly not seen, this is difficult to document.

The basal contact of UNIT I is sharp and irregular, both on regional and local scales. At section ML the unit directly overlies Archean basement; and a zone of altered granite, possibly a paleoregolith, is present. Wood's map (1975, Map 2305) vividly illustrates that the Gowganda Formation, here comprised almost totally of UNIT I sedimentary rocks, has filled in valleys in this older terrain. Similar local thickness variations are present farther south in the vicinity of section WR (Little White River) (Fig. 7). Figure 8 depicts a group of measured sections near section WR and the maximum inferred thicknesses for UNIT I sediments.
FIGURE 8. Detailed lithologic logs of several measured sections near section WR in southeast Albanel Township, Ontario.
Though the unit is more laterally continuous here than farther north, it still appears to be filling ancient topographic depressions on a surface having at least 100 m relief. Here, UNIT I rests unconformably on the Serpent Quartzite. However, 25 km to the southwest near section CL (Constance Lake) (Fig. 7), it overlies the much older Mississagi Quartzite (Robertson, 1963, Map 2032), a stratigraphic difference of from 500-600 m, which may also reflect past topography.

Basal lithologies in UNIT I are variable. In some sections (ML, El - Elliot Lake, Fig. 7) coarse-grained deposits directly overlie older formations, but in others (CL, WR) argillites are present at the base.

Orthoconglomerates in UNIT I are poorly sorted, ranging in size from medium sand-sized material to boulders. Clasts are well-rounded to subangular. The coarsest units observed are in section ML (Fig. 9a) where the orthoconglomerates directly overlie granitic basement. There a wide variety of immature, granitoid clasts (coarse-grained augen gneiss, granites, and pegmatite) is present. The matrix is an arkosic subgraywacke. Whereas the exposures near McElrea Lake are massive, orthoconglomerates near sections EL and WR are distinctly stratified (Fig. 9b). In these areas conglomerates are interbedded with, and grade into, feldspathic arenites. The beds are lensoid and contacts with other beds are sharp and appear erosional. Near the base of the Gowganda Formation some orthoconglomerate beds consist primarily of
FIGURE 9. a) Basal orthoconglomerates - UNIT I - section ML.

b) Crudely stratified conglomerates - UNIT I - near section EL.

c) Rip-up clasts of underlying Serpent Quartzite - basal UNIT I - near section EL.
angular clasts of the underlying metasediments (commonly the Serpent Quartzite) (Fig. 9c).

A range of textures are present from cobble conglomerates through pebbly arkosic arenites to non-pebbly arenites. The great majority of pebbles in these deposits are well- to sub-rounded. Sand-sized material is more angular. Grain size of the matrix ranges from coarse sand to very fine sand size. Sorting in these arenites is variable, with examples of extremes shown in figures 10a-b. Pebbly arenites possess dispersed clasts or basal pebbly zones. All arenite units are arkosic with approximately 25% of the sand-sized grains being feldspathic. Beds are lenticular to tabular. They are both normally graded and non-graded. Many possess large scale (>15 cm) foreset bedding, cut and fill structures, or horizontal laminations. Contacts between beds are sharp and commonly erosional. These sandstones occur as amalgamated arenite sequences, up to 30 m thick, containing few or no conglomeratic or argillitic beds.

Feldspathic beds also occur in interbedded arenite-argillite sequences. There, the arenites grade upwards into laminated finer-grained rocks and exhibit incomplete Bouma sequences. Particle size ranges from medium sand to clay size. These arenite-argillite intervals are rarely more than 5 m thick but do represent a lithofacies that is distinct from the amalgamated arenites described above.

Important associated lithologies include pebbly and
FIGURE 10.  a & b) Photomicrographs of different arenite textures - UNIT I.

Frame width ~1.5 mm.
non-pebbly laminated argillites, and siltstones. Pebby argillites typically contain less than 5% pebbles. Though not everywhere evident in the field, all of these sediments are laminated to some degree. Where laminations are visible, these argillites display well-preserved dropstone structures (Fig. 11a). Texture varies in that some intervals appear to contain coarse debris of all sizes, whereas in others the coarse fraction is somewhat sorted, consisting primarily of pebbles. Clasts in these pebbly argillites are well-rounded to sub-angular. Laminations in laminated argillites consist of thin graded couplets (Fig. 11b), coarse, non-graded layers or lenses in sharp contact with surrounding finer-grained material (Fig. 11c), or interbedded layers of different texture (Fig. 11d). In the third case the layers consist primarily of silt-sized material and are relatively coarse compared with the finer portions of other kinds of argillites. All of these layered textures can occur within cm of each other; in a given section, however, one kind typically dominates.

Siltstones are non-pebbly. They most commonly appear massive but small scale (<5 cm) ripple cross-laminations are present in some beds. These beds range from 1 to 2 m thick and form the top of graded sequences, being transitional with underlying arenites. They are lenticular and are present in what would otherwise be an amalgamated arenite sequence. Arenite-siltstone sequences differ from inter-bedded arenite-argillite units in that they are much
FIGURE 11.  a) Dropstone - UNIT I.

    b-d) Laminations in silty argillites - UNIT I.

    Frame width ~1.5mm.
thicker (2-4 m/couple vs. .5-1 m/couple); that they contain lensoid beds and cut and fill structures; that the siltstones are not laminated but are crossbedded or massive; and that the arenites are coarser-grained.

The most important characteristics of UNIT I are: the abundance and coarseness of orthoconglomerates, the highly feldspathic nature of arenites, immature clast lithologies with well-rounded to sub-angular clasts, the presence of lenticular beds and large scale sedimentary structures, dropstone structures in laminated argillites, graded arenite-argillite sequences, and considerable local thickness variations with the unit as a whole becoming thinner and finer-grained to the southeast.

UNIT II

UNIT II consists principally of stratified and non-stratified polymictic chloritic paraconglomerates (Fig. 12a,b). The unit also contains localized thin arenitic and orthoconglomeratic sequences interbedded with paraconglomerates. The unit occurs throughout the Gowganda outcrop belt. UNIT II ranges in thickness from 75m at section ML to 450 m at section WF (Whitefish Falls), thickening in general towards the southeast (Fig. 7). Locally some sections are thinner than might be expected, probably due to substrate relief. In section WF (Fig. 7) UNITS II and III interfinger.

Matrix texture varies widely in these paraconglomerates. In some units the matrix is poorly sorted, the rocks being pebbly graywackes (Fig. 12c). Other units have matrix
FIGURE 12.  a) Massive polymictic paraconglomerate -
UNIT II - section WF.
b-d) Matrix textures - UNIT II paraconglomerates.
Frame width ~1.5mm.
material that is more well-sorted with the mean grain size of the matrix varying from coarse sand- to silt-sized (Fig. 12d). Some pebbly argillites do occur, particularly in the southernmost sections. In general, the highest percentages of pebbles are associated with the coarsest matrices. Typically these paraconglomerates contain 5-20% pebbles (Fig. 12a) but coarser layers may contain as much as 40% (Fig. 12e). A spectrum of textures exists between these coarse paraconglomerates and interbedded orthoconglomerates with a coarse sand or grit matrix (Fig. 12f).

Unlike similar deposits in UNIT I, the coarser material in these paraconglomerates is not well-sorted. All sizes from grit to boulders >2 m in diameter are present. Large sedimentary clasts are present in some locales that are as much as 4 m in diameter (Fig. 12g). Clasts are well-rounded to angular but overall are less rounded than those of UNIT I. Pebbles in UNIT II orthoconglomerates are typically more well-rounded than those in paraconglomerates. In general, pebbles become more angular up-section in UNIT II.

Paraconglomerates in UNIT II typically appear massive. Closer inspection in the field and in thin section reveals that 'massive' deposits are actually crudely stratified. Rarely, well-developed laminations are present. Stratification is due to differences in matrix texture between layers. Individual layers range in thickness from <1 to ~10 m, and typically appear tabular. Contacts between beds are both sharp and gradational. In many exposures textural
FIGURE 12. e-f) Pebble-rich conglomerates - UNIT II - section EL.

g) Large Clast - UNIT II.
differences are subtle, slight differences in sorting or mean grain size, but are nevertheless traceable over tens of m (Fig. 12h-j). In addition, thin sections indicate that, in many beds, elongate quartz grains are oriented parallel to bedding (Fig. 12k).

Localized arenites and orthoconglomerates in UNIT II are typically graded, with sharp upper and lower contacts (Fig. 12f). They are tabular and are present both in sets and as isolated beds. A smaller percentage of conglomerate beds are transitional with surrounding lithologies and are not ordinarily normally graded. They appear to represent an increase in the percentage of pebble-size material, or a decrease in the amount of finer material (Fig. 12l). These units are isolated in the section and are thinner and less laterally continuous than are graded units.

The contact of the lowest paraconglomerate of UNIT II with underlying UNIT I rocks is sharp. However, more arenitic or conglomeratic beds are found near this contact than elsewhere in UNIT II. Hence, UNITS I and II are probably transitional into one another.

The upper contact, with UNIT III, is transitional but is marked everywhere by lenticular arenite and conglomerate beds. Near Whitefish Falls a sedimentary breccia is present (Fig. 12m) which interfingers with stratified arenites. The metasedimentary clasts in this breccia are biotite schists and do not represent lithologies found in the Gowganda Formation. Here, and elsewhere, these coarse
FIGURE 12. h-j) Stratified paraconglomerates - UNIT II.
FIGURE 12. k) Elongate sand grains parallel to bedding.
 UNIT II. Frame width ~1.5.

l) Probable zones of coarse sediment
 enrichment due to bottom currents;
 note lee-side lag adjacent to large
 boulder.

m) Sedimentary breccia - UNIT II - section WF.
arenites and conglomerates are interbedded with polymictic paraconglomerates and are overlain by pebbly laminated argillites with dropstone structures. These pebbly argillites are polymictic, and the clasts are subrounded to angular. They pass transitionally into the overlying non-pebbly laminated argillites of UNIT III.

The upper portion of section WR differs significantly from the others in that it contains a very thick (~100 m) interbedded arenite-paraconglomerate sequence near its transition with UNIT III. In most other localities this uppermost transition is less than 100 m thick. Further north, at section ML, essentially all of UNIT II is characterized by interbedded arenites, orthoconglomerates, and paraconglomerates. No distinct upper transition is present.

The lithologic units in the UNIT II-UNIT III transition are everywhere lenticular and discontinuous. Figure 13 illustrates this lateral variability in the area just south of Whitefish Falls. The stratified arenites thicken and thin dramatically, as does the overlying polymictic paraconglomerate. Higher in this same section, at another UNIT II-UNIT III contact, similar lithologies are present. This is well illustrated in the measured section in Young (in press; Fig. 2).

The most important characteristics of UNIT II are: the presence of crudely- to well-stratified polymictic paraconglomerates, interbedded arenites and orthoconglomerates, arenitic and conglomeratic beds gradational
FIGURE 13. Detail of lateral lithologic variability - upper UNIT II - section WF.
with paraconglomerates and depleted in fine grained material, the ubiquitous presence of discontinuous arenites and ortho-conglomerates near the upper transition, and dropstone structures in the highest laminated argillites.

UNIT III

UNIT III consists of non-pebbly laminated argillites and stratified arenites. It is present throughout the study area and, where best developed, consists of two upward coarsening sequences or cycles (Fig. 14). The unit becomes thicker and the cycles more well-developed towards the southeast.

Laminations in the argillites are well-developed (Fig. 15a), commonly being traceable for tens of meters. Localized disturbed zones of contorted and discontinuous bedding disrupt this continuity in places. Laminae consist of numerous, non-rhythmic, very thin (.1-1 mm) sand, silt, and clay layers. Laminae have sharp upper and lower contacts and some are graded. No consistent thickness trends are apparent. They exhibit wavy bedding and large scale (>15 cm), very low angle crossbedding. Few pebbles are present in these argillites above their base.

The argillite-arenite contact is transitional (Fig. 15b). In the lower portions of this transition, thin (~5 cm) tabular siltstones beds are intercalated with laminated argillites. Up-section these siltstone beds become thicker and coarser-grained, passing into a zone of interbedded argillites, siltstones, and arenites. Higher in the section,
FIGURE 14. Detail of section AL showing well-developed UNITS II and III.
FIGURE 15.  

a) Laminated argillites - UNIT III - section AL.

b) Transition between argillites and arenites - UNIT III - section AL.
argillites disappear and finally, even siltstone beds are no longer present; the unit consists of amalgamated tabular or broadly lenticular arenites. These arenites are graded and have sharp contacts with each other. Few or no pebbles are present in these deposits and the arenites are less feldspathic than those lower in the section (<20% feldspar). The arenite beds become thicker and slightly coarser upwards. If a second argillite-arenite cycle is developed, it sharply overlies arenites of the first cycle. Magnificent exposures of this unit are present near sections AL (Algoma Mills) (Fig. 7) and WF.

The most important features of UNIT III are: its coarsening upward nature, its transitional lower contact, and the scarcity of pebble-sized material.

Environmental Interpretation of Sedimentary Units

UNITS I, II, and III represent, in general, preglacial, glacial, and post-glacial sedimentation. The preglacial and post-glacial sediment facies consist of deposits formed in several terrestrial and marine environments. These sediments, by their nature, are not found in Antarctica, though they are known from many other modern settings. UNIT II, on the other hand, is interpretable using Antarctic glacial marine sedimentary examples. This unit is thick and widespread, suggesting that its deposition was influenced by one or more large ice masses. With the exception of the coarsest conglomerates, all of the lithologies, and lithologic associations,
present in UNIT II are known from Antarctic cores. Many of
the sedimentary structures and textures found in modern sedi-
ments, features which reflect prevailing physical oceanog-
graphic and glaciologic conditions are also present in
this unit.

UNIT I -- Preglacial and Periglacial Deposits

UNIT I consists of terrestrial preglacial and periglac-
ial fluvial and lacustrine (?) deposits. These
sediments were laid down on a surface of considerable
relief. Consequently, dramatic local variability in
thickness and lithologies are present.

In the northernmost section (ML) UNIT I shows no
evidence of nearby glaciation. The boulder conglomerates
there probably represent fanglomerates, and are locally
derived. They fill valleys in the Archean terrain and
are probably correlative with finer-grained feldspathic
arenites and orthoconglomerates to the south. The arkosic
nature of these deposits indicates that they were deposited
rapidly, or were transported in a cold or arid climate.
Whether the seemingly sudden onset of fluvial runoff is
due to tectonic uplift, glaciation, or both is unknown.

Cut and fill structures, large scale cross-bedding,
lenticular arenite and conglomerate beds, pebbly lag
layers, well-rounded clasts, and interbedded ripple
laminated siltstones all suggest a fluvial setting. These
structures probably represent migrating channels and
transverse braid bars. The large amount of debris
available for fluvial transport during either a tectonic event or the early stages of glaciation would result in braided stream sedimentation. Siltstone units resemble modern fluvial deposits where cross-laminated silts are deposited during the waning stages of flooding.

Figure 8 illustrates the lateral variability between several measured sections in southeast Albanel Township. The correlations shown are tentative due to poor exposures and extensive faulting. Furthermore, the basal surface of the upper polymictic paraconglomerate was probably not actually horizontal. The changes in thickness and lithologic variability are present, however, and maximum thicknesses are shown in all cases.

Sediment transport was towards the southeast (Pettijohn, 1957b; Pienaar, 1963; Lindsey, 1971). Thus, the line from section G I to SL I probably runs perpendicular to a paleovalley while the remainder of the sections are aligned roughly parallel to the paleoslope. Units thicken within this valley and thin or pinch out to either side of it. This entire sequence is missing at section CL, only 25 km away. Such rapid thickness and lithologic changes are to be expected in a high energy fluvial setting, particularly one with substantial topographic relief. Similar lateral lithologic and thickness changes have been observed in interglacial fluvial deposits in the Puget Lowlands (Cole, 1979) (Fig. 5).

Graded arenite-argillite sequences may represent
turbidites, in either a lacustrine or marine setting. Such deposits would be expected where large amounts of debris are being transported into a quiescent body of water. The dips of imbricated clasts in these units suggest southerly or southeasterly transport.

The pebbly argillites interbedded with these arenites and conglomerates represent deposition in quiescent waters and concomittant ice rafting. The environment may have been lacustrine, open marine, or in an interdistributary bay in a deltaic environment. The pebbly argillites appear to have been deposited only on surfaces of low relief - in the southern portion of the outcrop belt or relatively high in the section (Fig. 7). These quiescent water bodies may have been relatively short-lived phenomena because pebbly argillites are interbedded with fluvial and other deposits which suggest a continually changing depositional setting.

Ice-rafting of pebbles in the pebbly argillites was probably not by icebergs. Pebbles are rare, occupying less than 5% of the rock by volume. The deposits are typically texturally bimodal, with very little material in the size range between pebbles and mud. Furthermore, the clasts are well-rounded. If ice-rafting were by icebergs, during the onset of glaciation, poorly-sorted, polymodal sediments would have been deposited. This is because running water was probably present at some time during the year, and repeated freezing and thawing thus
occurred. Debris accumulating on glaciers under those circumstances is of all sizes and the clasts are very angular. Sediment-laden icebergs observed by Ovenshine (1970) from such an environment contained enormous quantities of angular, poorly-sorted debris. Pleistocene valley glacial deposits described by Cole (1979) were poorly sorted, not bimodal (Cole, 1979; Fig. 30). Thus, a better explanation (suggested by J.B. Anderson) for these sparsely pebbly argillites is that they were formed by fast ice-rafting. The well-rounded, relatively well-sorted pebbles were probably present on beaches where fast ice formed each winter. Fast ice-rafting is a commonly observed phenomenon in modern temperate lakes and rivers. Because this process is a rather inefficient way of transporting large quantities of debris, the pebbles form only a small percentage of the rock by volume.

Pebbles could also have been blown out onto winter ice during storms, to be deposited during melting in the spring. Pebbles up to 5 cm in diameter have been sighted skidding across smooth ice as far as 4 km from shore (Kindle, 1924).

Lithofacies present in UNIT I do not preferentially indicate either a tectonic event or a climatic one. The mineralogic immaturity of these sediments and the presence of ice-rafted clasts do, however, suggest a
frigid climatic regime. As Flint (1971) has pointed out tectonism with resulting changes in elevation, and the onset of glaciation go hand in hand. Because the characteristics of UNIT II so strongly indicate widespread glaciation, UNIT I is interpreted as pre-glacial. The presence of some tectonic activity is strongly suggested, but its magnitude and importance with regard to sedimentation are unknown.

UNIT II - Aquatic and Terrestrial Glacial Deposits

The polymictic paraconglomerates in UNIT II closely resemble orthotills and paratills cored on the Antarctic continental margin. Paraconglomerates which have so poorly sorted a matrix as to be pebbly graywackes could represent either orthotillites or some type of paratillite. Many of these deposits appear to possess an azimuthal pebble fabric (Pettijohn, 1962), suggesting deposition by grounded ice. One cannot actually determine if these tillites were deposited above or below base level, but a terrestrial or transitional environment is inferred for those beds lowest in the section which are closely associated with fluvial deposits. Where possible orthotillites are interbedded with paratillites, they are interpreted as being subaquatic, possibly submarine, grounded ice deposits. From a glaciologic standpoint, a shifting grounding line is more likely to produce
an interbedded sequence of orthotills and paratills than are repeated advances and retreats of the ice mass. Glaciologic changes of that magnitude should produce a variety of sediment facies and numerous erosional surfaces.

Those paraconglomerates whose matrix is relatively coarse grained and depleted in fine material are probably residual paratills. They reflect current winnowing. Paraconglomerates with a very fine-grained matrix are most likely compound paratills. They are enriched in fine-grained material relative to orthotillites. The texture of paratills reflects the action of currents and the sediments are thus aquatic. Interbedded compound and residual paratills indicate that currents were continually fluctuating.

The basal contact of UNIT II is sharp, particularly in the northwest. This sharp contact may reflect glacial erosion, and the presence of orthotillites above this contact supports the idea of grounded ice. However, nowhere in the sections studied is there evidence that grounded ice remained for a long period of time. Orthotillites are only 10 m thick at the most, whereas associated paratillite sequences are many times thicker, constituting most of the section. In the southeast, in the most distal sections, there is no evidence for the presence of a major grounded ice sheet. There, the tillites are crudely- to well-stratified, even in
the oldest units. The relatively thin pebbly graywackes which are present probably represent debris flow deposition, or floating ice sedimentation in the absence of strong current. Thus, the majority of glacial aquatic sediments in UNIT II were probably deposited by floating ice, most likely a floating ice shelf. There is no indication that multiple major advances or retreats of the ice grounding line occurred because the tillites have the character of floating ice deposits throughout UNIT II above its base. This is the case even in the most proximal sections.

Arenites and conglomerates in UNIT II represent either extreme instances of winnowing or sediment gravity flows. Excellent examples of both these kinds of units crop out along Highway 108 just north of Elliot Lake. A thick (15 m) sequence of tabular graded orthoconglomerates, representing an episode of repeated slumping, is present near the CKSO television tower on Highway 108. Both above and below this sequence individual graded beds are intercalated with paratillites. The whole interval is less than 30 m thick.

The above sequence appears to represent continuous deposition, probably beneath a floating ice shelf. A retreat of the grounding line further upslope could have given rise to these conglomerates, either through mass wasting at the grounding line, or by the action of subglacial meltwater streams. Isostatic imbalances
resulting from a sudden absence of loading could have created unstable slopes which subsequently failed. Another possible interpretation for this sequence also involves glacial retreat and mass wasting. The difference is that, instead of continuous deposition beneath a floating ice shelf, post-retreat deposition could have occurred via ice berg rafting instead. Strata above this conglomeratic zone are more well-stratified than lower in the section, and laminations are more common (Kurtz, 1979). Improved stratification could indicate a more vigorous current regime. Such a situation might occur where open water was present, subject to wind stress. However, thermohaline circulation beneath a thick floating ice shelf could also give rise to the same structures.

The uppermost horizon of interbedded arenite, sedimentary breccia, orthoconglomerate, paraconglomerate, and pebbly laminated argillite that outcrops in UNIT II (Figs. 7, 13) also represents a mass wasting event. Because only thin pebbly laminated argillites occur above this zone, the best explanation is that mass wasting is in conjunction with rapid or catastrophic glacial retreat. The pebbly laminated argillites represent ice-rafting by icebergs in the waning stages of glaciation. Clasts are somewhat more angular than in underlying till units. Angular clasts might form during climatic deterioration when frost riving is again an important process.
This sequence is present at the top of UNIT II in sections AL, Sl (Sugar Lake) (Fig. 7), and WF but in section EL it may be in the middle (i.e. the boulder orthoconglomerates described above). This may reflect the more proximal position of section EL, and longer lasting glaciation there. Other proximal sections (ML, WR) have thick sequences of interbedded arenites and paraconglomerates suggesting that glacial retreat in those areas was not a simple event. In section WR, it is quite thick, occupying at least the upper 100 m of UNIT II. The ice sheet margin may have stabilized in this area, giving rise to a greater thickness of clastics. Where UNIT II and III interfinger, the mass wasting horizon is near the basalmost boundary of UNIT III (Fig. 7). Above this, UNIT II is represented by ice-rafting deposits and sediment gravity flow units.

The mass wasting horizon consists of numerous interbedded sediment gravity flow deposits. Crosscutting and erosional relationships are quite evident by the unit geometries shown in figure 13. They are almost certainly time transgressive because glacial retreat undoubtedly occurred earlier in some places than others. Furthermore, in some regions, ice shelf retreat may have been followed by a time of extensive perennial ice cover. There, no ice-rafting occurred, though icebergs might have been common sedimentologic agents elsewhere. This mechanism offers an explanation for the non-pebbly laminated
argillites of UNIT III which are interbedded with UNIT II sediments at Whitefish Falls. Upon further climatic deterioration the perennial ice cover broke apart and ice-rafting resumed.

UNIT III -- Post-glacial and Glacial Recession Deposits

UNIT III consists of two, in some placed only one, shallowing upward or progradational sequences. Laminated argillites possess all the characteristics of contour current deposits as described by Bouma and Hollister (1973), being non-rhythmic, and exhibiting wavy bedding and large gently dipping foresets. These laminites are transitional with underlying pebbly laminated argillites and the contact between the two units essentially marks the cessation of ice-rafting. Upwards these current laminites pass transitionally into probable turbidites. The arenites are interbedded with argillites only at the transition. But, in spite of the absence of a thick monotonous sequence of interbedded arenites and argillites, a turbidite origin for these sandstones seems most likely. There are no lateral or vertical facies variations, which are consistent with a nearshore deltaic environment. It is difficult to conceive of a post-glacial delta that does not shift laterally with time and changing sea level. In addition, no other facies suggestive of a coastal environment are present in the Gowanda Formation.

With regard to glacial marine sedimentary processes, two observations concerning UNIT III are important.
First is the presence of probable current laminites. Previously, these rocks may have been mistaken for varves and interpreted as glacial lacustrine deposits. They are quite different from varves, however, in that they are cross-laminated and non-rhythmic; sediment textures range from sand to clay size. Varves generally occur as rhythmic couplets of horizontally laminated silt and clay. Their transitional lower contact with possible glacial marine deposits suggests that marine deposition may have occurred over a much greater area than was previously thought (Lindsey, 1971). Secondly, the basal coarsening upward sequence may be related to isostatic adjustment following glacial retreat. This adjustment would take place over several thousand years and a great thickness of sediments could accumulate.

Synthesis of the Depositional History of the Gowganda Formation

The glacial event represented by metasediments in the Gowganda Formation was a widespread one, perhaps of continental scale. The lateral extent of the Gowganda rocks indicates that the influence of the ice mass was felt over an area of at least 20,000 square km, with a proximal to distal distance of at least 150 km.

At the onset of climatic cooling, whether due to a tectonically increased slope, increased precipitation, or both, weathering of the Archean basement, fluvial
runoff, and erosion increased dramatically. At first, fluvial deposition was restricted to topographic lows but, eventually, the tremendous volume of sediment deposited appears to have blanketed the landscape. Climate was temperate then, probably with cold winters, but glaciers had not yet formed, or were not locally present.

As the climate cooled further, valley glaciers and then a large ice sheet formed. As the ice sheet advanced it deposited orthotills over the older periglacial deposits. Also, it isostatically depressed the land surface, lowering terrestrial settings below baselevel. In places the ice was probably grounded below baselevel but in other areas floating ice shelves formed. Stratified paratillites above the terrestrial sediments of UNIT I record this. In distal areas (section WF) deposition was perhaps subaqueous throughout this glaciation, because only floating ice deposits are present there.

After the initial advance the ice mass appears to have become buoyant over much of this region because orthotillites are most common at the base of UNIT II. The remainder of UNIT II probably represents deposition beneath a floating ice shelf where circulation was restricted. Small scale fluctuations in the grounding line resulted in interbedded paratillites and orthotillites in some northern sections but there is no evidence for more than one large ice advance.
The situation was stable until the ice mass began to recede. This event is marked in many places by the mass wasting horizon at the top of UNIT II.

Glacial retreat did not occur throughout the area simultaneously, nor were post-glacial conditions everywhere the same. A case in point is the section at Whitefish Falls. This is the most distal region and the ice shelf apparently left this area before it diminished elsewhere. The complete absence of ice-rafting after this local retreat, while ice-rafting was occurring elsewhere, is probably due to the formation of an extensive perennial ice cover. Such areas of perennial ice cover are common along the Antarctic coast. Yet, they may be within a few tens of km of areas which are ice-free each austral summer. This scenario explains the thick sequence of non-pebbly laminated argillites present in section WF that is overlain by pebbly arenites and argillites. The latter deposits formed upon further climatic warming when ice-rafting, probably by valley glaciers, and fluvial runoff were again important. The thick sequence of interbedded arenites and pebbly argillites at the top of UNIT II in sections WR and ML were probably deposited at this time; when the ice sheet had stabilized over the northern areas, and ice covered the proglacial ocean or lake.

As the ice finally retreated from these areas, base level rose and transgressed over the isostatically
depressed land mass. Post-glacial rebound led to the deposition of a coarsening upward sequence.

Figure 16 utilizes actual stratigraphic sections and hypothetical distal extensions of them to illustrate the regional facies relationships that would form as a result of a single glacial advance. The oldest deposits are the pre-glacial fluvial sediments and basal tills deposited upon glacial advance. Peripheral to the grounded ice a floating ice shelf and, perhaps, an extensive perennial ice field was present. When the ice mass becomes floating over much of its aquatic extent, floating ice sediments are deposited above these orthotills. During glacial retreat, the floating ice shelf-perennial ice boundary also retreats and, in the final stages, only valley glacial iceberg rafting occurs. The post-glacial transgression causes deposition of fine-grained sediments above the glacial sequence, but, due to isostatic compensation, a shoaling upward succession is deposited. Only at the onset of glaciation will extensive erosion occur and so, if only one major glaciation was present the entire sequence could be preserved.

Conclusions

1. The Gowganda Formation can be divided into three general units:

   UNIT I -- interbedded feldspathic arenites and polymictic orthoconglomerates with subordinate siltstones,
FIGURE 16. Postulated facies relationships that would be developed through a complete cycle of glacial advance and retreat. Constructed from actual and hypothetical (H) sections. See text for detailed explanation.
and pebbly and non-pebbly laminated argillites.

UNIT II -- massive to well-stratified polymictic paraconglomerates with subordinate tabular arenites and orthoconglomerates.

UNIT III -- one or more upward coarsening sequences of non-pebbly laminated argillites and tabular arenites.

2. UNIT I represents preglacial and periglacial deposition. It was deposited on a surface of high relief and exhibits dramatic lateral facies variability. UNIT I was deposited in response to tectonic uplift, the onset of glaciation, or both. Pebby argillites in UNIT I reflect deposition under frigid climatic conditions.

3. UNIT II consists of terrestrial and aquatic glacial deposits. Most of this unit was deposited subaqueously. Orthotillites, and residual and compound paratillites are present in UNIT II and closely resemble analogous modern Antarctic sediments. UNIT II contains deposits in its upper portion which document rapid retreat of the ice.

4. UNIT III was deposited post-glacially. The unit probably does not represent deltaic sedimentation but is a prograding sequence. Current laminites in UNIT II superficially resemble varves and have been misinterpreted in the past. The basal coarsening upward sequence may have been deposited in response to post-glacial isostatic adjustment.
5. There is no evidence of a long-lived grounded ice sheet occupying the study area. There is no evidence of more than one glacial advance or retreat. The widespread continuity of facies indicates that a continental scale ice sheet was present. But local variations suggest that glaciologic conditions varied from place to place in the ice mass.

6. A well-preserved suite of sedimentary facies is preserved. It is indicative of a single glacial advance, formation of a large floating ice shelf, subsequent retreat, and post-glacial isostatic adjustment.
HEADQUARTERS FORMATION

Introduction

Supposed Early Proterozoic tillites have been known from the Medicine Bow Mountains since they were first described by Blackwelder (1926). These rocks are the best preserved examples of middle Precambrian diamictites this far west in North America.

Diamictites are present in several formations in the Medicine Bow Mountains, but the present study is concerned only with those in the Headquarters Formation. This unit, originally termed the "Headquarters Schist", was named and described by Blackwelder (1926). Runner (1928) included the Headquarters Schist in his "Snowy Range Series" but Houston and others (1968) later renamed these the Headquarters Formation and the Libby Creek Group. Sylvester (1973) divided the Headquarters Formation into many lesser units but, because of poor outcrop and extensive faulting, many of these assignments are erroneous. Recently, others (Karlstrom, 1977; Lanthier, 1978; and Karlstrom and Houston, 1979) remapped this unit and described several new formations consisting, in part, of rocks previously believed to be part of the Headquarters Formation. This most recent stratigraphic work was the basis for the field work done during this study. The generalized map of the Headquarters Formation (Fig. 17) is adapted from Karlstrom and Houston (1979, Plate I).
FIGURE 17. Location map showing outcrop belt of the Headquarters Formation, Medicine Bow Mountains, Wyoming; and measured sections. Modified from Karlstrom and Houston (1979).
The Headquarters Formation, and associated metasediments, are between 1.7 and 2.0 Ga old (Allan Hills and others, 1968). They outcrop along the southern edge of an Early Proterozoic (1.4-2.0 Ga) geochronologic province (Allan Hills and others, 1968, Fig. 2). The northeast-southwest trending Nash Fork-Mullen Creek Shear Zone, in the Medicine Bow Mountains (Houston and others, 1968, Plate 1: King, 1976; and Camfield and Gough, 1977) is a major tectonic boundary which separates this age province from a much younger one. No sedimentary rocks similar to those of the Early Proterozoic Libby Creek Group occur southeast of it.

Blackwelder (1928) first ascribed a glacial or glacial aquatic origin to diamictites in the Headquarters Formation. Fenton and Fenton (1957, p. 105) noted units which appeared to be "varved deposits" and "conglomerate lenses which probably formed in stream channels". They cited these as evidence for terrestrial and glacio-lacustrine deposition. Sylvester (1973), in the most thorough sedimentologic study of this formation to that time, concluded that the unit represented several advances and retreats of a grounded and floating ice sheet. But, due to later revision of Sylvester's stratigraphy, his facies associations and correlations, and the conclusions derived from them, should be viewed cautiously. Sylvester was also hampered in his study by the general lack of
knowledge concerning modern glacial marine sedimentary facies.

The Headquarters Formation and the Gogmanda Formation are separated by nearly 2000 km of younger rocks, but several authors have suggested that they are stratigraphically equivalent. Young (1970) correlated these units with each other, with ancient glacial deposits in the Dead River Basin, Michigan, and with exposures in Quebec. He based his correlations on similarities in the lithostratigraphic successions and in whole rock geochemistry. Karlstrom and Houston (1979, Table 2) show correlations between rocks in the Medicine Bow Mountains and Huronian strata in Ontario. They also suggest that the Headquarters Formation is equivalent to the Gogmanda Formation, and base their correlation on stratigraphic similarities and similar inferred environmental conditions.

Such correlations are admittedly tenuous, but they led Young (1970) to postulate a widespread mid-Precambrian glaciation. If a continental-size glacier did deposit the Headquarters and Gogmanda Formations more or less simultaneously, then the Headquarters Formation, like the Gogmanda Formation, should show evidence of continental glaciation. Studies in modern Antarctic sediments yield criteria which enable us to identify deposits from a large ice sheet, and thus enable us to test Young's model.
General Stratigraphy

The stratigraphy of Early Proterozoic rocks in the Medicine Bow Mountains has most recently been refined by Karlstrom and Houston (1979). Table 1 gives general stratigraphic relationships. The Headquarters Formation is the lowest unit in the Libby Creek Group, and unconformably overlies rocks in the Deep Lake Group -- the Rock Knoll Formation. The Rock Knoll Formation consists primarily of quartzite and was previously referred to as the Deep Lake Quartzite (Houston and others, 1968). The Headquarters Formation is conformably overlain by the Heart Formation, also in the Libby Creek Group.

Previous workers (Sylvester, 1973; Lanthier, 1978; Karlstrom and Houston, 1979) have informally divided the Headquarters Formation into a lower arenitic and conglomeratic unit, and an upper phyllitic unit. This division is retained in the present report because the rocks of interest are primarily in the lower unit. The base of the upper unit is a useful stratigraphic horizon.

Description and Distribution of Sedimentary Units

The rocks of the Headquarters Formation are exposed in the southern limb of a northeastward plunging, asymmetric anticline (Sylvester, 1973). Beds are typically steeply dipping and are in placed overturned. This structure forms a northeast - southwest trending
<table>
<thead>
<tr>
<th>LIBBY CREEK GROUP</th>
<th>Heart Formation</th>
<th>siltstone, arenite phyllite, arenite, and diamicrite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Headquarters Formation</td>
<td></td>
</tr>
<tr>
<td>DEEP LAKE GROUP</td>
<td>Rock Knoll Formation</td>
<td>arenite</td>
</tr>
</tbody>
</table>
outcrop belt (Fig. 17) which extends for approximately 16 km. These are the only known exposures of this formation.

Outcrop quality is variable, the rocks being well-exposed in a few localities but poorly exposed elsewhere. Mafic intrusions and extensive faulting obscure stratigraphic relationships within the Headquarters Formation and with surrounding units. In particular, the basal contact with the underlying Rock Knoll Formation is only rarely seen.

Lithologies and lithologic associations within the Headquarters Formation are complex. Many rock units cannot be traced, or confidently correlated, for more than a few hundred meters. Figure 18 shows details of stratigraphic sections, and inferred lithologic correlations. The most widespread lithologic units are highest in the section. The base of the upper chloritic phyllite is recognizable at most localities and was thus used as a marker horizon. That portion of the Headquarters Formation below this horizon thickens tremendously to the south (from 75 m to at least 400 m). In this lower portion the number of distinct lithologic units also increases towards the south; the section is most complex at Headquarters Park (Fig. 18).

Pebbles consist primarily of lithologically immature, extrabasinal granitic and gneissic clasts, with a smaller percentage of locally derived metasedimentary clasts.
FIGURE 18. Measured sections and proposed correlations, Headquarters Formation.
Pebbles vary in roundness, being well-rounded to sub-rounded low in the formation, and more angular upwards. In general, greater amounts of rounded clasts are present in northern exposures, with clasts being more angular to the south at equivalent stratigraphic levels. Metasedimentary clasts and locally derived rip-up clasts are more angular than extrabasinal clasts. Faceted stones are rare.

**Rock Knoll**

The section at Rock Knoll (Fig. 18) is a composite. A detailed section is given in figure 19. The lower Headquarters Formation in this area ranges in thickness from 75 m to 225 m. This variability is chiefly due to coarse conglomerates filling topographic depressions in the original surface of deposition. The largest depression measured was >100 m deep and at least 200 m wide at the top.

The conglomerates and arenites of these valley-fill units are coarse grained, containing clasts up to boulder size (Unit I; Fig. 20a). Arkosic arenites comprise approximately 20% of this sequence. They too contain clasts, either concentrated in basal pebbly zones or dispersed throughout the arenite. Grain size in these arenites ranges from coarse sand to grit; feldspars constitute approximately 35% of the detrital material.

Stratification is well-developed in both conglomerates and arenites. Beds are lensoid, ranging in thickness
FIGURE 19. Detail of lateral lithologic variability - Rock Knoll Section, Medicine Bow Mountains.
FIGURE 20. a) Boulder conglomerates at base of Rock Knoll Section.
b) Rock Knoll Formation - Headquarters Formation contact - Rock Knoll Section.
from 50 to 500 cm. They are massive or contain large scale (>15 cm) festoon bedding and cut and fill structures. Contacts between beds are sharp.

The conglomeratic valley-fill unit passes transitionally upwards into a more widespread arenite-argillite sequence (Unit II). Lensoid conglomerates make up only a small portion of this sequence. This succession has less lateral thickness variability than does the underlying conglomeratic unit (Fig. 19), but does exhibit local topographic influences upon deposition. Thickness ranges from 40 to 70 m.

The arenite-argillite unit is fine-grained and more argillitic upwards. Argillites, whether pebbly or non-pebbly, are rare near the base of the section. There the unit consists primarily to interbedded medium- to fine-grained, tabular to broadly lenticular arenites. Lenticular beds possess large scale (>15 cm) festoon crossbeds and cut and fill structures, or are massive. Tabular beds display well-developed horizontal stratification and large scale planar foresets. Beds are non-graded or only slightly graded and contacts between them are sharp. Pebbly arenites contain dispersed clasts pebbly zones or have basal pebble zones; angular argillitic rip-up clasts are also present.

Arenites are finer grained, thinner, and more tabular upwards. Pebbly and non-pebbly argillites are also more common. Argillite beds range in thickness from 10 to 60 cm and are lenticular or irregular in shape. They are not stratified but are foliated. Pebbles do not
appear to be tectonically elongated. Texture in these argillites varies. Non-pebbly argillites are much finer-grained than are pebbly units which are more poorly sorted and contain a small percentage of sand-sized material.

The interbedded pebbly argillite-arenite interval is a transition between the predominantly arenitic unit and an overlying ~30 m thick pebbly sandy argillite (Unit III). This unit contains localized thin lenses of arenites. The pebbly sandy argillite is laminated in places but typically appears massive. It is foliated but the pebbles appear unaffected by metamorphism. No well-developed dropstone structures are present.

The pebbly sandy argillite passes transitionally upwards into non-pebbly, laminated argillite (Unit IV). Laminae range in thickness from <.5 to 1.5 mm. They consist of non-rhythmic beds of very fine sand-, silt-, and clay-sized material. The unit is slightly foliated. This uppermost argillite contains no outsized clasts or coarser lenses.

There is a complete textural transition between pebbly arenites and pebbly argillites. The chief distinction in the field is that, where some minimum amount of very fine grained material is present the beds are more well-foliated and chloritic than coarser ones. Pebbly argillites are distinguished by this foliation and by their greenish color.
The sequence as a whole at Rock Knoll becomes finer-grained upwards. Conglomerates, arenites, pebbly argillites, and non-pebbly argillites dominate the section in succession. Pebbles are less common upwards and slightly less rounded. Arenite beds are less arkosic, and individual beds are thinner, more tabular, and more laterally continuous.

Rock Knoll is one of the few places where the sharp erosional nature of the Headquarters Formation—Rock Knoll Formation contact (Fig. 20b, page 79) can be readily observed. The contact is nearly vertical where steep relief was once present, but, in other places the contact is flat-lying.

Vagner Lake

At Vagner Lake, the next section to the south (Fig. 18), the Headquarters Formation is in fault contact with older rocks of the Deep Lake Group. Here, an unknown thickness of the Headquarters Formation is missing.

The lowest unit exposed in this area is a pebbly argillite at least 5 m thick. No stratification is evident but the argillite is contorted and fractured due to faulting. The pebbly argillite is in sharp contact with an overlying massive arenite bed. This bed is lensoid, ranging from 4 to 5 m thick, and is also highly fractured due to faulting.

A thick (~20 m), poorly exposed non-pebbly
argillite sharply overlies this arenite. This argillite appears non-laminated, but is strongly foliated. An arenite sequence overlies this argillite but the nature of the contact is unknown. This arenite section is approximately 50 m thick and differs from that at Rock Knoll in that the majority of the beds are tabular. Horizontal stratification and grading are more well-developed. Contacts between beds are sharp but cut and fill structures are common. Beds range in thickness from .5 to 1.5 m.

These arenites consist of coarse- to medium sand-sized material, but commonly grade upwards to very fine sand-sized arenites or siltstones. Varying amounts of chlorite are present, perhaps indicating that they originally contained a significant amount of clay-sized material. Pebbles, either dispersed or in basal zones, are rare.

Some thin, non-pebbly argillites are interbedded with these arenites throughout the section. But, they account for less than 10% of the sequence. Massive, chloritic pebbly graywackes, the only other significant lithology in this arenite sequence, also constitute a very small percentage of the lithologies present. These rocks occur as thin (<1 m), isolated, lenticular beds near the top of the sequence.

No pebbly argillite unit is present at Wagner Lake analogous to that overlying the arenite sequence at Rock
Knoll. Arenites and scattered interbedded pebbly gray-wackes grade upwards into finer-grained phyllites and siltstones, which grade in turn into overlying chloritic phyllites. This uppermost unit probably correlates with the uppermost non-pebbly, laminated argillite at Rock Knoll.

The Vagner Lake section is, overall, finer grained than the Rock Knoll section. There are no conglomerates and only rare paraconglomerates. Arenites are more tabular, and are more chloritic. Like the Rock Knoll section, the Vagner Lake sequence becomes finer-grained upwards.

North Twin Lake

The North Twin Lake section (Fig. 18) is also incomplete. At the base is a poorly exposed sequence, of unknown thickness, of interbedded medium- to fine-grained tabular arenites grading upwards into non-pebbly argillites. Basal arenite contacts are sharp. A laminated sparsely pebbly argillite (approximately 10 m thick) outcrops above this arenite-argillite sequence. Laminations consist of interbedded argilitic and siltier layers.

Above this pebbly argillite, and in sharp contact with it, is a thick section of interbedded arenites and conglomerates. Argillites are not present in this sequence. Beds are tabular and lenticular, and range in
thickness from 1 to 3 m. Contacts between beds are sharp and irregular; cross-cutting relationships are common. Few primary sedimentary structures are present except grading, many beds grading upwards from cobbles to silt-sized material (Fig. 21). The entire sequence is finer-grained upwards with conglomeratic units being thicker and more abundant at the base, whereas arenites are more prominent towards the top. Arenites are either non-pebbly or contain dispersed clasts. Typically, those with dispersed clasts are more poorly sorted than non-pebbly graded units.

Unlike the succession at Rock Knoll the arenite-conglomerate sequence at North Twin Lake does not pass gradationally upwards into an overlying pebbly sandy argillite. Rather, at North Twin Lake, the contact is sharp and irregular. The argillite is extensively fractured and, except for some pebble-rich zones, appears massive. It is at least 20 m thick at this locale. This pebbly argillite is overlain by a thick non-pebbly chloritic phyllite but the contact relationships are unknown.

**Headquarters Park**

The Headquarters Park section is the thickest and most southerly section studied. It is relatively complete, though exposures in places are poor. There, the basal Headquarters Formation-Rock Knoll Formation contact can
FIGURE 21. Graded arenites and orthoconglomerates - North Twin Lake Section.
again be seen. It is sharp and marked by a granite cobble lag layer (Fig. 22). Directly overlying this contact is a thin (<8 m), well-foliated pebbly argillite. No laminations are present in this unit.

A thick (>75 m) sequence of poorly exposed arenite overlies this argillite but contact relationships are unknown. Boulders in the float suggest that some pebbly argillites or pebbly arenites are interbedded with these arenites, but this could not be confirmed. Isolated outcrops indicate that arenite beds are either tabular, in places displaying horizontal stratification or small scale ripples; or lensoid, with large scale festoon bedding. Individual beds are commonly normally graded.

Towards the top of this succession, non-pebbly argillites and thinly-bedded, cross-stratified arenites crop out. These pass into a thick (~60 m) laminated pebbly argilite. Laminae consist of non-rhythmic silty and argillitic layers (Fig. 23). Dropstone structures are common and well-preserved (Fig. 23).

The upper contact of the pebbly laminated argillite with a non-pebbly laminated argillite is gradational. But, this transition is marked by the presence of several lenticular arenite, conglomerate, and diamictite beds which are interbedded with the pebbly argillites. Contacts between these beds are sharp and irregular. The entire interbedded interval is less than 5 m thick.

The laminated, non-pebbly argillite is poorly exposed
FIGURE 22: Pebbly lag at Rock Knoll Formation - Headquarters Formation contact - Headquarters Park Section.
FIGURE 23. Dropstone in laminated pebbly argillite - Headquarters Park Section.
and of unknown thickness. Laminae consist of non-rhythmic silty and argillitic layers (Fig. 24). No outsized particles were observed in this unit. Laminations are not horizontal, but consist of large amplitude, low angle crossbeds (Fig. 24), and small scale ripple or wavy bedding. The contact with the overlying unit is covered.

A thick (>100 m) partly covered arenitic sequence overlies the laminated argillite. Near the base, tabular medium to fine-sand-sized arenites grade upwards into non-pebbly argillites. Small scale (<8 cm) crossbedding and flute casts are present. Basal arenite contacts are sharp. Higher in the section, argillites become less common and a sequence of amalgamated, graded, arkosic arenites is present. Units are tabular or broadly lenticular and contacts between beds are sharp. At the highest levels in this unit, pebbles occur as basal zones or dispersed clasts.

These arenites pass transitionally upwards into stratified pebbly sandy argillites (Fig. 25). Stratification is horizontal and is manifested by subtle textural changes, or changes in the percentage of pebbles. Individual layers range in thickness from .5 to 2 m. Contact relationships with the overlying chloritic phyllite are unknown.

The Headquarters Park section differs from the others in that it does not markedly fine upwards within the lower part of the formation. Also, more and thicker discrete
FIGURE 24. Low angle cross-bedsding in non-pebbly laminated argillites - Headquarters Park Section.
FIGURE 25. Granite clast in pebbly arenite near top of Headquarters Park Section.
units are present. Two thick pebbly argillite units were deposited as opposed to only one, or none, at other sites. Pebbles in these argillites are increasingly angular higher in the section. Great thicknesses of arenite are present, but conglomerates are uncommon. The basal unit there is a pebbly argillite, strikingly different from the boulder conglomerate at Rock Knoll.

Origin of the Headquarters Formation

The limited extent and great variability of stratigraphic units in the Headquarters Formation make it difficult to relate its origin to tectonic or climatic conditions. Measured sections are only km apart yet seemingly major lithologic units cannot be confidently correlated to one another. The thickest units rarely exceed 100 m and pebbly argillites are all less than 75 m thick. Proximal to distal facies transitions which probably occur over distances of hundreds of km in Antarctica, or indeed on any continental margin, are present here over a distance of only 16 km. Facies analyses from the Antarctic continental margin (Anderson and others, 1977, 1979), where a continental ice mass dominates glacial marine sedimentation, indicate that sedimentary sequences there are very different from those exposed in the Headquarters Formation. Similar individual lithologic units are present in both settings but their associations and depositional scale are very
different. Thus, hypotheses involving nearby continental glaciation cannot be justified when interpreting the Headquarters Formation.

Tectonic uplift occurred just prior to deposition of basal Headquarters sediments. This is implied by the sudden advent of high energy fluvial transport of arkosic sands and extrabasinal granitic and gneissic clasts. The upraised land mass was dissected as these streams carved v-shaped valleys. Streams flowed southeastward (Young, 1970; Sylvester, 1973; Lanthier, 1978).

Subsidence took place throughout deposition of the Headquarters Formation. This is indicated by the great difference in thickness of the formation at Headquarters Park vs. Rock Knoll. Sedimentary evidences for subsidence in the basal portion of the section include a preserved stream-incised valley at Rock Knoll, and a basal cobble lag, probably a beach deposit, at Headquarters Park which is overlain by a finer-grained (offshore) pebbly argillite. The general fining upward nature of the Headquarters Formation indicates continual subsidence, though deposition at times kept pace with it. There is no sedimentary evidence that the land mass was being depressed by the buildup of a large ice sheet, and a substantial ice mass would not preferentially depress a basin only 3 km from a less affected area. Loading would be more evenly distributed.

Frigid climatic conditions probably prevailed
Initially. Arkosic arenites, large quantities of unstable unweathered clasts, and scattered pebbly argillites indicate this. Thin pebbly sandy argillites probably represent shore ice rafting. Such ice rafting is suggested by the rounded nature of many clasts and by the absence of very large clasts (maximum clast size <40 cm).

Thus, during early stages of deposition of the Headquarters Formation an upraised land mass was being dissected by high energy streams; the region was undergoing differential subsidence; and climate was cold. Valley glaciers may have been present, but they were not reaching the sea or lake.

Deposition was initially in fluvial and fluvial-deltaic environments. Coarse, fluvial arenites and conglomerates pass upwards and southwards into interbedded arenites and argillites. These latter arenites exhibit characteristics of distributary channel deposits -- cross-bedding scour and fill structures, and erosional contacts. More distal deposits are finer-grained, thinner, and more tabular. Thin pebbly and non-pebbly argillites were deposited in interdistributary bays. Rapid proximal-distal facies changes indicate a relatively steep slope and the delta was probably a small one. Fluvial and nearshore fluvial-deltaic conditions prevailed at Rock Knoll for a long period of time. In the more southerly section at Headquarters Park, where subsidence was more rapid, a thick sequence of arenites and offshore
argillites was deposited. Ice-rafting was only a minor process at this time.

The next major episode is marked by the thick pebbly laminated argillite at Headquarters Park (Fig. 18). This unit is fine-grained but does contain ~20% coarse material. All outsized material was delivered to the depositional basin by ice and clasts shapes are well- to sub-rounded indicating passive glacial transport. Well-developed stratification and sandy texture indicate moderate marine current activity. Simultaneous ice-rafting and moderate circulation indicate relatively open water. These, and the limited extent of the outcrop, suggest a valley glacial situation rather than the presence of a large ice shelf. The basal pebbly argillite at Vagner Lake was probably deposited at this time.

That valley glaciers had finally reached the water, might indicate that climate was becoming colder. However, there are no similar deposits at Rock Knoll where nearshore fluvial deltaic deposition continued. Valley glacial aquatic deposition could reflect increasing subsidence. At Rock Knoll, where subsidence was less, valley glaciers never reached the water. At more southerly locales, where subsidence was greater, rising sea level flooded coastal valleys to the level at which valley glaciers became floating. Such floating valley glaciers may have existed along glaciated coasts during the Pleistocene (e.g. Fyles, 1963) and many Alaskan valley glaciers have floating
termini (Powell, 1979). The valley glacier or glaciers probably occupied different valleys from that at Rock Knoll. Thus deposits from several valleys are interbedded in this depositional basin. This accounts in part for the lateral discontinuity of sediment facies.

At both Wagner Lake and Headquarters Park the upper boundary of the pebbly argillite is marked by a series of mass flow deposits. These sediments probably indicate a single catastrophic event because they are in turn overlain by deep water argillites at both locales. No other similar deposits are near them in the section; no shoaling upward sequence was deposited. Glacier disintegration or retreat with accompanying introduction of large volumes of unstable material into the aquatic environment probably caused the mass flows. Whether the glaciers receded because of climatic conditions, or became unstable due to rising water levels, is unknown.

After glacial recession, fluvial runoff again became the dominant erosional process on land. Streams delivered large volumes of sediment into the aqueous environment, suggesting that some relief still remained. The resulting turbidites, mass flow deposits, and fluvial-deltaic sediments formed the thick, post-glacial shoaling upward sequence. Initially these clastics were probably deposited in estuaries, thus argillite deposition continued for a time in deeper waters. During the progradational stage, sedimentation probably kept pace with subsidence.
Though the glaciers were diminished, climate remained cool. Lenticular pebbly argillites in shoaler portions of this prograding succession indicate that fast ice-rafting was still taking place.

Subsidence continued and, perhaps with peneplanation of the adjacent land mass, marine transgressions occurred. A thin retrogressive sequence at the top of the progradational unit records this. Ice-rafting also resumed at this time. These pebbly sandy argillites are coarser than similar deposits lower in the section and may be nearshore deposits. Because the pebbles are rounded and relatively rare, fast ice-rafting again seems likely. Plenty of material was available for ice-rafting from progradational coastal plain deposits. This apparent increase in ice-rafting may reflect renewed climatic cooling or merely lower fluvial-deltaic sedimentation rates. Or, rising water level over a gently sloping coastal plain may have created a lower energy coastline than had previously existed. Greater quantities of fast ice might freeze under such circumstances, and might remain close to shore upon freezing.

Deep water choritic phyllites were the final sediments to be deposited. Ice-rafting ceased, either because of climatic warming, or because the shore ice zone transgressed northward.

The fascinating aspect of the Headquarters Formation is that, given the initial conditions of tectonic uplift,
cold climate, and subsidence, the entire sequence could have been deposited during the normal subsequent course of events. There is no need, nor is there any basis, to postulate a marine transgression, renewed tectonism, repeated climatic fluctuations, or the build-up of a major ice sheet. With regard to Young's (1970) hypothesis then, there is no evidence in the stratigraphic succession in the Headquarters Formation, when it is compared with Antarctic facies associations, which suggests the presence of a continental glacial event. However, the origin of the rocks in this formation is not incompatible with simultaneous continental glaciation in Ontario. Deposition in both places could well have been affected by the same climatic events.

The differences in glacial regime between the Headquarters Formation and the Gowganda Formation casts doubt upon Karlstrom and Houston's (1979) correlation of the two units. Early Proterozoic rocks in the Medicine Bow Mountains and Ontario represent different climatic and tectonic conditions. Correlation between them, even on the basis of lithostratigraphic successions, is difficult at best.
BLACK HILLS METACONGLOMERATES

Introduction

Metaconglomerates have been known from the Black Hills since Darton and Paige (1925) first described the rocks in this region. The metaconglomerates outcrop at several stratigraphic levels, but regional Precambrian stratigraphy in the Black Hills has yet to be worked out.

These metasediments were studied in an effort to evaluate Young's (1970) hypothesis concerning a middle Precambrian glaciation. Though he studied and correlated tillites from several localities in North America, he did not examine the metaconglomerates in the Black Hills. Yet, if the thick metasedimentary sequence in this area is equivalent to early Proterozoic glacial rocks, and a continental glaciation did occur, then one would expect to find sedimentary evidence of this event there. Unfortunately, the strata are too tectonically deformed and, the stratigraphy is too sketchy to do a thorough study in a short time. Many years of work still remain before such sedimentologic questions might be answered. Nevertheless, possible glaciogenic units do outcrop in the Black Hills, and this chapter constitutes a short, very preliminary report dealing with their lithologic character and possible genesis.
Previous Work

These metaconglomerates have been studied at several localities by various workers (Redden, 1968; Ratte and Wayland, 1969; Shaddrick, 1971). Each of these has applied different stratigraphic names to the rocks in question. Table 2 gives general correlations.

Metasediments in the Black Hills unconformably overlie the Little Elk Granite (Ratte and Zartman, 1970) and were intruded by the Harney Peak Granite and associate pegmatite dikes. The Little Elk Granite yields an age of 2.56 Ga (Zartman and Stern, 1967). The Harney Peak Granite has an K-Ar age of 1.64-1.68 Ga (Goldich and others, 1966). Thus, the most precise age determination possible for the tilloid units is between 1.62 and 2.56 Ga.

Metasediments associated with these diamictites consist of schists, phyllites, and metagraywackes, with minor metabasalts, quartzites, and meta-iron formations. They probably represent a eugeosynclinal sequence and attain a thickness of at least 1200 m (Shaddrick, 1971). The sequence is highly deformed. All of the units have been folded into tight, slightly overturned isoclinal folds plunging towards the south (Darton and Paige, 1925). Associated high angle faulting a second phase of folding also occurred. The later intrusion of the Harney Peak Granite upwarped them and metamorphosed those rocks nearest
TABLE 2

Stratigraphic Relationships Between Metaconglomerates and Surrounding Units in the Black Hills

<table>
<thead>
<tr>
<th>Xg (youngest)</th>
<th>Harney Peak Granite</th>
<th>Harney Peak Granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bugtown Formation</td>
<td>Bugtown Formation (diamictites)</td>
<td>Quartz Schists</td>
</tr>
<tr>
<td>Xd (tilloids)</td>
<td>Loues Formation</td>
<td>Oreville Formation</td>
</tr>
<tr>
<td>Vanderlehr Formation (diamictites)</td>
<td></td>
<td>&quot;Bluebird Formation&quot; (tilloids)</td>
</tr>
<tr>
<td>Xc (oldest)</td>
<td>Meta-iron Formation</td>
<td>Amphibolite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(from Kurtz, in press)</td>
</tr>
</tbody>
</table>
the intrusion to staurolite and sillimanite grade (Shaddrick, 1971).

Shaddrick (1971) showed that the clasts in the "Bluebird Formation" were sedimentary and that their orientation was due to tectonic alignment. He interpreted the metaconglomerates as mass flow deposits associated with normal eugeosynclinal deposition, ruling out a glacial origin because no dropstone structures are preserved.

Unit Descriptions

The present report deals only with metasediments in the "Bluebird Formation", in the east-central Black Hills near Keystone (Fig. 26). Outcrops are poorly exposed. Widths of outcrop patterns range from a few tens to as much as 300 m; they generally extend less than a km along strike.

Intense metamorphism has destroyed most primary sedimentary structures, though poorly preserved stratification and gross textural variations may remain. Metaconglomerates appear to be conformable with surrounding rocks, though local faulting has altered these relationships in places. A generalized section, from the Keystone area, is given in figure 27.

Metaconglomerates are difficult to recognize in the field but are readily identified on a fresh exposure or in the lab. Diamictites occur at several stratigraphic levels, interbedded with non-pebbly units. Commonly no
FIGURE 26. Location map showing Black Hills study area and outcrops of metaconglomerates (X). From Kurtz, in press.
FIGURE 27. Schematic measured section of Black Hills metaconglomerates near Keystone, South Dakota.
non-pebbly
strongly foliated
quartz mica schist

foliated
diamictite

non-pebbly
strongly foliated
quartz mica schist
definite contact is present between pebbly and non-pebbly zones. Rather, a transition exists where the percentage of pebbles and the grain size of the matrix gradually decrease. Regional stratal variations are unclear; tills often are typically tabular units but in some areas the units may be lens-shaped. Unit thicknesses range from 20 to 150 m. Individual clast-bearing beds commonly appear discontinuous.

Stratification in schistose rocks is poorly preserved and is due to variations in pebble content and matrix texture. Size grading is not present in metaconglomerates. Dropstone structures, if they were once present, have been eliminated. However, isolated clasts are present in otherwise non-pebbly, fine grained schists (Fig. 28).

Pebbles are dispersed in a finer-grained matrix and occupy from 5-40% of the rock by volume (Fig. 29). All particle sizes are present, ranging from the finest silt-sized matrix material to boulders at least 3 m in diameter. No pronounced size modes have been reported.

Pebble lithologies include quartzite, schist, amphibolite, chert, and mica-chlorite rock fragments (Shaddrick, 1971). Quartzite and schist pebbles are most abundant but locally other lithic types may be more numerous. In some sequences crude segregation of clast lithologies is evident. Pebble lithologies resemble those of rocks found in the Black Hills but their source is unknown. No granitic or gneissic clasts have been reported.
FIGURE 29. Black Hills metaconglomerate - showing tectonically elongated clasts.
but untwinned feldspar is a common constituent of the matrix in all areas. Stones are angular to rounded, being more rounded in areas of highest metamorphism. Lithologic variety and textural characteristics of stones are closely related to the degree of metamorphism, both features being most variable in the least deformed rocks (Shaddrick, 1971).

Genesis of Metaconglomerates

The genesis of metaconglomerates in the Black Hills is problematical. There is no unambiguous evidence for glaciation but several factors favor this hypothesis over the mass flow model proposed by Shaddrick (1971). Metaconglomerates are interbedded with and pass transitionally into laminated argillites. This suggests some form of continuous deposition. The presence of scattered lonestones in argillites also suggests ice-rafting. No stratigraphic 'up' indicators or dropstone structures are preserved, and therefore the metaconglomerates could represent thick graded units or mass flows of some sort.

Apparent lithologic segregation of clasts, a possible evidence for debris flow deposition, is not present in thin section, where a wide variety of lithologies occur in all samples. The absence or rarity of extrabasinal clasts does not rule out a glacial origin, nor does it support mass flow deposition. A metasedimentary
terrain would yield only metasedimentary clasts; clasts collected from Antarctic icebergs near the George V Coast consisted of slates (Anderson and others, in press, J. Glaciol.).
SUMMARY AND FINAL DISCUSSION

The study of modern glacial marine sediments, even though widespread vertical and horizontal facies relationships cannot be directly observed, is of great value in interpreting ancient strata. Modern sedimentary textures, sedimentary structures, pebble characteristics, and facies spatial distribution all reflect glacial and marine processes and their relative influences. Furthermore, these sedimentary processes can be related to large scale climatic or tectonic phenomenon.

Middle Precambrian Glacial Aquatic Sedimentation

Careful facies analysis with a view towards understanding the fundamental phenomenon affecting sedimentation can yield relatively detailed interpretations for ancient sequences. Two examples of this are the interpretations presented in earlier chapters concerning the Gowganda and Headquarters Formations.

The Gowganda Formation has been interpreted to represent deposition during several glacial cycles (Lindsey, 1971; Young, in press). The model in this report agrees with these authors in that a large ice mass was present but postulates only one major glacial event. Considerations leading to this hypothesis are:

1) facies are widespread and thick - this suggests regional control of sedimentation.
2) sediment stratification and texture is comparable to that characteristic of Antarctic paratills and orthotills—these indicate not only a similarity in origin but also a substantial GLACIAL influence on sedimentation. This is in contrast to well-laminated glacial aquatic metasediments in the Headquarters Formation where deposition was controlled largely by AQUATIC agents.

3) the terrestrial sediment — orthotill — paratill — non-glacial aquatic sediment succession records only one glacial cycle. Minor fluctuations might have occurred but repeated major events should have left an entirely different suite of sediments.

Sedimentologic characteristics of the Gowganda Formation yield clues as to the probable ice sheet conditions. These features include:

1) pre-glacial fluvial deposits that have not been removed through erosion;

2) evidence for a large floating ice shelf;

3) thick sediment sequences which indicate continual terrestrial erosion and glacial aquatic deposition throughout glaciation;

4) rapid initial transition from grounded to floating ice; and

5) rare striated and faceted stones.

These features indicate net deposition in the study area but continual erosion in the hinterland. Boulton (1978) discussed the implications of this to glacial
thermal regime. Net deposition occurs beneath floating ice, but only occurs beneath grounded ice when the ice sheet is wet-base. Erosion is most effective when water freezes onto the sole of the moving ice, and debris-laden regelation ice forms. But, for this type of erosion to be effective the substrate must consist of loose porous material. Long term erosion in this manner suggests that the ice was overriding unconsolidated sediments rather than crystalline rocks. Pebble shapes also indicate this type of erosion. Though in general they become more angular upwards, many are nevertheless rounded, and only few exhibit signs of glacial reworking. Passive glacial transport in basal zones of a large ice sheet can occur, however, when regelation ice is continually forming. Debris is lifted upwards due to the constant freezing of more ice, and little debris-substrate interaction takes place. Under wet-base conditions repeated reworking of sedimentary material occurs because sediment remains near the ice-substrate interface. A supraglacial origin for sediment is unlikely because frost riving would not have been active to generate talus slopes.

These conditions appear to have lasted for a considerable length of time, and to have resulted in substantial sediment erosion. A rough computation as to the size of the glaciated landmass affecting Gogwanda sedimentation can thus be made. A minimum of 2000-4000 cubic km of material was deposited by ice in the Gogwanda Formation.
This is equivalent to a soil of regolith zone ~10m thick over an area 200,000 to 400,000 square km. At maximum glaciation the Gowganda ice shelf occupied an area of at least 30,000 square km (Ross Ice Shelf ~700,000 square km). So, the ice drainage (200,000-400,000 square km) basin was probably from 5 to 15 times the size of the Gowganda ice shelf. Modern Antarctic ice drainage basins are from 4 to 30 times the size of their outlet ice shelves. Thus the glaciated area contributing to the Gowganda Formation was probably from one fourth to one half the area of northern Ontario. Of course, a larger total area was probably actually glaciated.

The Headquarters Formation had previously been interpreted as representing several major glacial events, with numerous associated sealevel changes (Sylvester, 1973). Herein, however, a much simpler model based on the interaction between relief and fluvial erosion, cold climate, and subsidence is proposed. Key observations which led to this model are:

1) the tremendous lateral and vertical facies variability over short distances - similar facies transitions are present over hundreds of km in the Antarctic. There, the "averaging" effect of large scale glacial processes result in more gradual facies transitions;

2) the abundance of rounded ice-rafted clasts, particularly in the thinner, pebbly sandy argillites -
this suggests passive transport by ice rather than transport in basal debris zones. Passive transport does not alter pebble shape whereas transport in basal debris layers forms a distinct clast character (Boulton, 1978);

3) the well-stratified to laminated nature of glacial deposits - this indicates vigorous circulation and probably open marine conditions. Such deposits are uncommon on the Antarctic continental shelf (Anderson and others, 1979);

4) the coarse texture of glacial aquatic deposits - this texture is also an indication of current winnowing; similar valley glacial deposits are present in the Puget Lowlands (Cole, 1979);

5) fluvial sediments were deposited throughout much of this time - such deposition is compatible with a temperate or subarctic climate but not with the presence of a continental ice sheet.

These observations strongly suggest deposition in a nearshore setting with a great deal of sediment being transported primarily by ice. Climate was cold but running water was present. The complex but conformable facies pattern indicates local influences upon sedimentation. Glacial deposition was by valley glaciers and shore ice. There is no evidence that a major ice age, or multiple glaciations occurred.
Middle Precambrian Continental Glaciation

The depositional models proposed for the units studied herein are compatible with Young's (1970) model, but only facies in the Gowganda Formation actually support it. The Gowganda Formation reflect deposition from the floating terminus of a large ice mass. It seems unlikely that a single drainage basin would be glaciated while surrounding areas were ice-free, primarily because a large ice mass influences surrounding climate and weather patterns (Schwerdtfeger, 1970). A minimum estimate for the extent of the Gowganda ice sheet, based upon the observation that Antarctic ice shelves drain approximately 40% of the ice sheet, is 1,000,000 square km. This is approximately 10 times the area of the Iceland ice cap, but only one half the size of the Greenland ice sheet.

Rocks of the Headquarters Formation were deposited under cold climatic conditions but running water was an active sedimentary agent throughout that time. Tectonics, associated uplift, and subsidence were the major factors affecting sedimentation. There is no evidence for the presence of a large ice mass.

The genesis of diamictites in the Black Hills is problematical but extrabasinal clasts are rare. If glaciers were present they were eroding a much different kind of substrate than the Gowganda glaciers.

The Reany Creek Formation represents glacial
aquatic paratill deposition below wave base under the influence of vigorous currents. Extrabasinal clasts are common. There is no evidence in these rocks for or against an ice sheet in Ontario at that time; however it is unlikely that these sediments were deposited from a floating ice shelf.

**Tilloids vs. Tillites**

The distinction between glacial tillites and non-glacial tillite-like rocks, tilloids, is a difficult and important one. Tilloids commonly owe their deposition to tectonic or gravity-driven processes. The situation is complicated by the realization that tectonic, gravity-driven, and glacial processes have operated in conjunction with others in the past. Numerous authors have emphasized the tendency for post-glacial slumping of tills (Boulton, 1976; Bentley and Smalley, 1978; Kurtz and others, 1979). Gravity-induced slumping due to isostatic instability may be particularly important in this regard. Initially, glaciation and glacial deposition may be controlled by tectonically generated relief (Flint, 1971), and hence, glacial and tectonic diamicritites may be closely associated.

Though the problem is a difficult one, it is not unsolvable in many cases. Several important sedimentologic features of glacial and tectonic settings must be kept in mind. A most important parameter to identify is the
the position on the continental margin where deposition took place. On the continental slope and rise, in either tectonic or glacial settings, gravity-driven processes dominate.

Antarctic continental slope and rise sediments consist in large part of turbidites, debris flow deposits, and intermediate forms of sediment gravity flows (Anderson and others, 1979; Kurtz and Anderson, 1979a; Wright and others, in press). Paratills are rare and thin. Thus, except for the possible occurrence of pebbly laminites, there are no sedimentologic criteria which can be used to identify outer margin sediments as "glacial" even in modern environments. Thus, slope and basin sedimentary sequences should be interpreted with caution.

Glacial and tectonic sediments deposited nearshore and on the continental shelf can be more easily differentiated. There, a number of important sedimentologic influences are acting whose effects are not masked by gravity-driven processes. These are:

1) the presence or absence of running water - reflected by the differences in sediment character when delivered to the marine environment by ice or rivers;

2) the relative importance of chemical vs. physical weathering - reflected in clast and particle shape and lithologies;

3) the presence or absence of a suite of facies documenting glacial buildup, advance, and retreat, and
post-glacial eustatic and isostatic adjustments.

Where fluvial transport and chemical weathering are important, the depositional setting is non-glacial. Glaciers may be present but their distribution and size is controlled principally by tectonically generated relief and external climatic conditions. The texture and mineralogy of sediments reaching the sea, the sedimentary structures and facies deposited, and the complex lateral and vertical association of depositional environments will all reflect non-glacial conditions. Glacial sediments will be localized, thin, and interbedded with a variety of different types of deposits. In this setting tills thus reflect the localized, and relatively minor, influence of glaciers. The Headquarters Formation is a good example of deposition in such a setting.

In a glacial setting, glacial processes completely overshadow all other processes in the coastal and shelfal environments. All sediment reaches the sea via ice. Sediment textures and mineralologies reflect the inefficiency of glacial processes in sorting and breaking down material. Tills are common. Their vertical and lateral distributions reflect the "depositional inertia" of a large ice sheet. Spatial and temporal variations in glacial conditions, and primary factors affecting sedimentation, are subtle and occur over relatively great distances or long periods of time. Textural changes in tills are thus also subtle. These are in
contrast to the rapid facies changes that would be caused by rugged relief, varying climatic conditions, coastline irregularities and the like. In an ideal situation, facies development in glacial marine sediments should record glacier advance and retreat. With the exceptions of pre-glacial fluvial sediments and receding glacier mass wasting deposits no other clastics are interbedded with these tills. Post-glacial eustatic and isostatic changes also influence deposition, resulting in first deep water then shoaling upward sedimentation. The Gowganda Formation displays all these features.
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