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ABSTRACT

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The study demonstrates that heavy mineral analysis of tills has potential as a tool for mineral exploration, geological mapping, and the study of paleogeography.

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APPLICATION OF HEAVY MINERAL ANALYSIS TO
PROBLEMS OF TILL PROVENANCE ALONG A TRANSECT
FROM LONGLAC, ONTARIO TO SOMERSET ISLAND

by

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A thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment
of the requirements for the degree of Master
of Arts
in Geography

Department of Geography

Carleton University

Ottawa

December 13, 1982

IN MEMORIAM

Jeanette Perras

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Relative percentages of heavy minerals (> 3.3 s.g.) were calculated for 55 till samples from cores along a north-south transect across the Canadian Shield. Siderite and pyrite percentages of heavy mineral fractions were calculated for a further 51 till samples from 14 cores between the Seal and Severn rivers. The results allow the definition of five zones based on heavy mineral assemblages. Two vertical variations of regional extent and several local lateral and vertical variations are also described. The mineral assemblages and local variations in heavy mineral abundance, reflect provenance from distinctive bedrock up-ice of sample sites. Regional and local ice flow directions inferred from these results support multidome glaciation in central North America, precluding the possibility of a single ice dome over Hudson Bay.

The study demonstrates that heavy mineral analysis of tills has potential as a tool for mineral exploration, geological mapping, and the study of paleogeography.

RÉSUMÉ

Les pourcentages relatifs des minéraux lourds (gradient de densité $> 3,3$) dans les tills ont été établis pour 55 échantillons, prélevés le long d'une coupe transversale nord-sud au travers du Bouclier canadien. Cinquante et un échantillons additionnels, prélevés entre les rivières Seal et Severn, ont été analysés pour leur concentration en pyrite et en sidérose. Les résultats d'analyse mettent en évidence cinq zones, basées sur les assemblages des minéraux lourds. Sur une base régionale, deux variations verticales sont différenciées alors qu'à un niveau plus local, plusieurs variations latérales et verticales sont identifiées. Les différents assemblages minéralogiques et les variations locales des minéraux lourds peuvent être associés à des formations géologiques bien distinctes qui permettent de retracer les mouvements locaux et régionaux de la glace au cours de la dernière glaciation. Les résultats indiquent la présence de plus d'un dôme principal pour le centre de l'Amérique du Nord et s'oppose donc au modèle d'un seul dôme, centré sur la baie d'Hudson.

L'étude suggère le potentiel de l'analyse des minéraux lourds pour l'exploration minière, la cartographie géologique et les études paléogéographiques.

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CHAPTER I

INTRODUCTION

1.1 General Statement

Heavy mineral analysis is a well established technique in sedimentary geology and geomorphology, but it has been sparingly used in the study of tills. It seems probable that there are many instances in which the heavy minerals present in tills can be used successfully for establishing the regional and local paleogeography in an area of glaciated terrain. Moreover, if this is the case, the resulting knowledge of ice flow patterns, stratigraphy, till mineralogy could make a considerable contribution to mineral exploration (Lee 1963; Shilts 1975; and Brundin and Bergström 1977). In order to determine the value of this technique to Quaternary geological studies and mineral exploration this investigation has considered the distributions of heavy minerals at various depths in till along a traverse across the Canadian Shield from Somerset Island to Longlac, Ontario (Fig. 1.1).

The heavy mineral fraction of the tills which cover most of the Canadian Shield reflects the heavy mineral composition of the bedrock and sediments from which they were removed by glaciers (Derry 1933; Dreimanis *et al.* 1957; Shilts 1973; Brundin and Bergström 1977). Even though these grains often make up less than 2% of the sand-size fraction of the till, they consist of a much greater variety of minerals than is normally present in the light mineral fraction. Furthermore, heavy minerals are more diagnostic of provenance.

Tills, particularly those of northern Canada, would appear well suited to this type of study. In contrast to other sediments, their original composition, especially in areas of permafrost, is rarely altered by selective sorting or deep weathering. As a result, the heavy mineral composition of the till closely reflects that of the parent rock.

1.2 Acquisition of Data

The samples used in this study were provided by the Geological

Figure 1.1. Location of samples.

Survey of Canada, which had in turn, obtained them from EBA Engineering Consultants Limited of Edmonton. In 1975, 1976 and 1977 EBA carried out an overburden drilling survey under contract to the Polar Gas Consortium to provide geotechnical data along the route of a proposed natural gas pipeline to run to the west of Hudson Bay from the Sabine Peninsula on Melville Island to Longlac, Ontario (Fig. 1.1). Continuous, undisturbed core samples were obtained from most of the 425 holes drilled along the transect. These cores (many still naturally frozen), along with the core logs and geotechnical reports, are held by the Geological Survey of Canada. One hundred and sixty-six of these holes were drilled in till and it is from these cores that the samples investigated in this study were selected.

A regional study was favoured over a detailed study of a specific problem because information over a broad range of situations was desired in order to illustrate the use of heavy mineral analysis in the study of tills. Cores were chosen 1) to provide an even distribution of samples from along the transect; 2) to include tills that are underlain by a variety of geological terrains; 3) to examine cores from boreholes which penetrate multiple units of till; and 4) to investigate tills containing clays or heavy mineral fractions that have been shown by Shilts (1980b) to be geochemically anomalous either laterally or vertically. Thirty-three cores, from Longlac, Ontario to Somerset Island, District of Franklin were selected. The heavy minerals from 1 to 4 different depths in each core were separated from the sand size fraction using methylene iodide (3.31 specific gravity). These grains were mounted in Araldite and the mineral proportions determined by point counting. A more detailed investigation of two indicator minerals, siderite and pyrite, was also carried out between the Seal and Severn rivers. This involved determining the siderite and pyrite contents of 51 samples from 14 cores.

1.3 Objectives

The objectives of this study were related to defining the value of heavy mineral analysis as a tool for establishing the provenance of tills of northern Canada.

The specific objectives were:

- (a) To establish a reference collection of heavy minerals from till.

The study of heavy minerals from tills is still in the descriptive and collective stage. There is a paucity of information on the recognition of minerals or the various forms that they assume as a result of glacial abrasion. The author has prepared a collection of 80 reference slides. It is intended that these slides, available through the Geological Survey of Canada, be of help to other researchers.

- (b) The establishment of a methodology.

No thorough methodology for working with heavy minerals in tills has been published. Thus, a methodology was carefully devised for this study and the procedures are presented here.

- (c) To determine regional trends and vertical distribution of heavy minerals.

Another objective of the study was to define the regional trends of lateral and vertical variations of heavy minerals and heavy mineral assemblages of the till. By isolating indicator minerals of various tills this may prove useful as a tool for correlation. An attempt was also made to relate heavy minerals and heavy mineral suites to bedrock geology. These mineral provenance results may lead to conclusions on ice flow patterns.

- (d) To detect the presence of economic minerals.

It was also an objective of this study to identify the presence of minerals that are of economic interest. This has a bearing on the usefulness of heavy minerals in tills as a tool in prospecting.

1.4 Previous Work on Heavy Minerals in Tills

Heavy mineral investigation of sediments has, for the most part, been applied to the study of sedimentary rocks and fluvial, beach, and marine sediments (Boswell 1933; Milner 1962; and Parfenoff *et al.* 1970). Although heavy mineral analysis was once a standard tool in petroleum geology, as well as in sedimentary petrology in general, its ineffectiveness in solving correlation problems of a detailed nature resulted in its fall from popularity (Andel 1959; Griffith 1967, p. 203).

The first quantitative study of heavy minerals from Canadian tills was of Pleistocene deposits at Toronto (Derry 1933). In Alberta (Bayrock 1962), in Minnesota (Kruger 1937), and in Wisconsin (Murray 1953) it was found that the tills were too homogenous for heavy mineral analysis to be of much use in differentiating till sheets. The relatively homogenous nature of the bedrock and the incorporation of older tills into the younger tills were possible reasons for the inefficacy of the technique in these studies.

On the other hand, Dreimanis and Reavely (1953), Dreimanis *et al.* (1957) and Gwyn and Dreimanis (1979), on the basis of heavy mineral assemblages, were able to distinguish among glacial lobes in the Great Lakes region by defining their sources as being in the Superior, Southern, and Grenville structural provinces.

Heavy mineral analysis of tills has been successfully employed in a number of other studies of glacial sediments in North America and Europe. Some examples are: Sitler (1963) in Ohio and Pennsylvania; Cannon (1964), and Shilts (1965) in Vermont; Connally (1966) in New-York; Nielson (1967) in Nova Scotia; Shilts (1973) in southeastern Québec; and Lindén (1975) in Sweden.

Dilabio (1982) studied the dispersal of gold and tungsten (scheelite) in various size fractions of till near a former gold mine in Nova Scotia. Grains from the 63 to 250 μ m fraction were examined using scanning electron microscope techniques. He found a strong relationship between abundance of these minerals and mineralization in the bedrock in this size range.

Heavy mineral analysis of tills, eskers, and alluvial gravels has been used to define indicators of kimberlite pipes in the Moose River Basin and James Bay Lowland (Wolfe *et al.*, 1975) and of gold mineralization in the Kirkland Lake area (Lee 1963). Both these studies were of a qualitative nature and only selected heavy minerals were examined.

In brief, few studies have been done on the heavy minerals found in Canadian tills. Consequently, the heavy mineral zones of Quaternary deposits in Canada are far from being known.

CHAPTER 2

GEOLOGICAL SETTING

2.1 Physiography

The transect along which the samples were taken crosses several physiographic divisions, as shown in Fig. 2.1. These divisions are described by Bostock (1970) as:

(1) The Abitibi, Severn, and Kazan uplands.

This broad, lake-splattered rolling country is typical of much of the Canadian Shield. The average relief of this region is between 100 and 150 metres. Much of the area is underlain by till. The southern portion of the Kazan uplands, large areas in the southwestern Severn, and most of northern Abitibi Upland are mantled by glacial lake deposits. The northeastern part of the Kazan Upland was submerged and consequently, some marine sediments occur. All three areas are underlain by crystalline Archean and Archean rocks.

(2) The Hudson Bay Lowland.

This area is a low, swampy, flat area underlain by thick till and interglacial sediments. These sediments are covered with post glacial marine sediments. The underlying bedrock consists of Paleozoic sedimentary rocks.

(3) The Wager Plateau.

The Wager Plateau rises gradually from Chesterfield Inlet to an elevation of 700 metres where it is deeply dissected. From Chesterfield Inlet northward the surface consists of low patches alternating with rugged areas of 130-250 metres in relief. The southern and northern extremes of the Wager Plateau are rocky with a discontinuous cover of marine sediments. The higher central portion is covered with a mantle of ground moraine. This region is underlain by crystalline Precambrian rocks.

(4) The Boothia Plateau.

This area merges with the Wager Plateau and declines in elevation towards the north. It consists of a till-mantled Precambrian crystalline core flanked on the east and west by till-covered Paleozoic sedimentary rocks.

Figure 21 Physiography

2.2 Bedrock Geology

The transect crosses areas underlain by Precambrian rocks of Superior and Churchill structural provinces, and Paleozoic rocks of the Hudson and Arctic platforms.

2.2.1 Superior Province

From KP3721 to KP2787 the transect is underlain by Archean metavolcanics and metasedimentary rocks separated by areas of plutonic rocks (Fig. 2.2). The metamorphosed volcanics and sedimentary rocks are usually conformable and often interbedded. The volcanic rocks consist of metamorphosed basalt, pillowed or amygdoloidal basic flows, dacite, pyroclastic rocks, tuff, breccia, and schists. The sediments are made up of greywacke, shale, argillite, and arkose that have been metamorphosed from greenschist up to amphibolite facies. Long thin beds of iron formation, typically composed of grey or red jasper-chert interlayered with magnetite and hematite-rich layers occur throughout these rocks (Gross 1970, p. 170). The sedimentary and volcanic groups were affected by the Kenoran Orogeny which resulted in folding, metamorphism, shearing, and intrusion by granitic rocks (McGlynn 1970, p. 57). The rocks described above are rich in such minerals as garnet epidote, ilmenite, titanite, magnetite, and chlorite (Parfenoff *et al.* 1970).

2.2.2 Churchill Province

Precambrian rocks of Churchill Province underlie most of the area from the Nelson River to Somerset Island. These rocks include metamorphosed Archean and Aphebian volcanic and sedimentary rocks, relatively undeformed sedimentary and volcanogenic rocks of Paleohelikian age, and granitic intrusive rocks of various Precambrian ages.

The Archean rocks consist of northeasterly-trending belts of conformable basic to intermediate volcanics such as andesite, dacite, quartz-biotite rhyolite, and amphibolite schist. Archean sedimentary rocks include quartzite, gritty sandstone, pebbly conglomerate, shale, and greywacke (Wright 1955). The Ketyet River Group, located just north of Baker Lake, and believed to be equivalent to the Archean Prince Albert Group (Schau *et al.* 1982), is particularly interesting because it closely resembles mineral-rich Archean units in northern Ontario. In many places these rocks are metamorphosed to migmatite and granitic gneisses (McGlynn 1970).

Belts of Aphebian rocks occur in northern Manitoba and central Keewatin. These consist of conformable units of conglomerate, orthoquartzite, greywacke, siltstone, shale, slate, and argillite. In places these rocks are overlain by basic volcanic rocks. The Aphebian rocks are metamorphosed and moderately folded.

In the centre of Keewatin, the unmetamorphosed, undeformed Paleohelikian Dubawnt Group lies unconformably over Aphebian and Archean crystalline basement rocks. Donaldson (1965) has divided the Dubawnt Group into six formations. These include sandstone and mudstone, conglomerate, arkose, subaerial potassium-rich alkaline volcanics, rhyolitic volcanics, and syenite. All the formations contain some amount of hematite. The Kazan Formation, which is mainly redbeds, and, to a lesser extent, the volcanogenic rocks, contain high amounts of hematite as secondary and primary minerals respectively. (Appendix IV, Fig. 1).

The possible signatures of these various rocks in the heavy mineral fraction of a till are quite varied. The gneiss, schists, and plutonic rocks are generally contributors of garnet, epidote, orthopyroxene, ilmenite, and other minor minerals. The very different mineral composition of a large area of charnockite located just south of the N.W.T.-Manitoba border does, however, have the potential to substantially influence the heavy mineral composition of a till by contributing orthopyroxene. The large hematite proportion of the accessory minerals in some Dubawnt Group rocks (80%) (Kaszycki and Shilts 1980) could also possibly contribute a distinctive assemblage of minerals to tills.

2.2.3 Hudson and Arctic Platforms

Near the Nelson and Churchill rivers and on the Boothia Peninsula the transect crosses areas underlain by Paleozoic rocks of the Hudson and Arctic platforms respectively. These sediments lie unconformably on the Precambrian basement. The Hudson Platform consists of remnants of the Hudson Bay Basin and the Moose River Basin. These basins are separated by a northeast-trending arch in the Precambrian basement (Sanford *et al.* 1968).

The Hudson Bay Basin, presumed to be filled with about 2 000 metres of Paleozoic sedimentary rock (Hobson 1967), is largely covered by Hudson Bay. The smaller Moose River Basin, comprising approximately 800 metres of Paleozoic and late Mesozoic sedimentary rocks, occupies

Figure 2.2 Bedrock geology Modified from Douglas, G.S.C., 1972 (1:29,000,000), Sanford and Norris, 1973

the Hudson Bay Lowland west of James Bay. The succession of Upper Ordovician to Middle Devonian rocks which outcrop in northern Manitoba and northern Ontario is conformable with the lower units of the Moose River Basin. It is believed that the Upper Devonian sediments of the Moose River Basin, which correlate with sediments to the south, are also represented under Hudson Bay (Sanford and Norris, 1973).

The Ordovician rocks consist of basal sandstone, limestones and dolostones. The Middle to Upper Silurian rocks are represented by a sequence of carbonate rocks, barrier and pinnacle reef complexes, red beds, mudstones, siltstones, sandstones, dolostones, and evaporites. The Silurian rocks are succeeded by Lower, Middle and Upper Devonian formations consisting of marine carbonate rocks and dark bituminous marine shales (Sanford *et al.* 1968). Middle Ordovician to Middle Silurian formations of the Hudson Bay Basin are also represented on Southampton and Coats islands (Heywood and Sanford 1976). In the Moose River Basin, the Paleozoic formations are overlain by Mesozoic clastic rocks and lignite-bearing clays (Bennett *et al.* 1967).

Paleozoic rocks also flank the core of crystalline rocks underlying Boothia Peninsula and Somerset Island. The Arctic Platform consists of Upper Ordovician to Lower Devonian limestones, dolostones, shales, evaporites, siltstones, sandstones, and conglomerates (Miall and Kerr 1980). These sediments rest, unconformably, on crystalline rocks of the Boothia Uplift which form the cores of Boothia Peninsula and Somerset Island. Sedimentary rocks, such as those described above, often contain a greater proportion of resistant minerals, such as garnet, zircon, rutile, than other rocks. Varietal differences, such as rounding or textures caused by weathering, are also common in recycled sediments. These rocks can also be sources of authigenic minerals.

2.3 Quaternary Geology

2.3.1 Ice Flow Patterns

At the maximum of the Wisconsin Glacial stage most of the Canadian Shield was covered with ice sheets. Consequently, varying thicknesses of till, as well as other glaciogenic sediments, were

deposited throughout the study area (Prest 1970). The positions of the centres of dispersal and the flow directions of the ice during the Wisconsin maximum have been a source of disagreement since the turn of the century. Two basic models of ice dispersal over central North America have evolved, one consisting of a single ice sheet and the other consisting of several coalescing ice sheets.

2.3.1.1 The single ice sheet model

Although the theory of one large ice sheet centered over Hudson Bay had been proposed by several geologists (Dawson 1886; Chamberlin 1895; and Camsell 1916), the Laurentide Ice Sheet received little attention until Flint (1943) defended its existence (Fig. 2.3a). Flint suggested that: 1) data on isobases of marine and lacustrine strand lines indicate that the area of maximum uplift was over Hudson Bay; 2) climatic conditions favoured one ice mass over central North America; 3) evidence of upwarping towards the centre of Hudson Bay suggests it was there that ice was thickest.

Bird (1953) also supported the single ice sheet hypothesis. He used field data and airphotos to argue against an ice divide over Keewatin. More recently, Hughes *et al.* (1977) and Denton and Hughes (1981), have used numerical models to reconstruct the morphology and distribution of Wisconsin ice sheets (Fig. 2.3b). The input for these models was based on the characteristic of the present Antarctic glaciation. The results suggest that a single ice mass, centred over Hudson Bay, existed in central North America during the Wisconsin maximum.

Mayewski *et al.* (1981) also support this model on the basis that "flowlines radiating from ice domes must all have approximately the same length.". They therefore conclude that a major North American ice dome would have to have had a central location, preferably over Hudson Bay.

Even though the concept of a single Laurentide ice sheet, in particular as proposed by Flint, is not supported by hard evidence, it has been used extensively in textbooks, for example: Tricart and Cailleux (1962), Flint (1971), and Sugden and John (1976).

Figure 2.3 Two versions of the single dome concept as proposed by Flint (1943). (a) Morphology of the Laurentide ice sheet at its maximum (modified from Sugden 1977). (b) Reconstruction of flow patterns of the Laurentide ice sheet at 18 000 B.P. (Modified from Hughes *et al.*, 1977).

2.3.1.2 The multiple ice sheet model

Tyrrell (1898), on the other hand, concluded from such evidence as striae and drumlinoids, that two centres of radial glacial outflow or ice dispersal existed: one northwest of Hudson Bay in Keewatin and one east of Hudson Bay near Labrador. The terms "Keewatin" and "Labradorian" were applied to these centres. This concept was commonly accepted until Flint (1943) popularized the Laurentide Ice Sheet.

An increase in the number of mapping and till sampling programs during the past 15 years has resulted in a better knowledge of the lithology of the tills in northern Canada (McDonald 1969; Skinner 1973; Dionne 1975; EBA 1976, 1977; Cunningham and Shilts 1977). Using these data, as well as data on the orientation of ice inscribed and ice moulded features (Fig. 2.4), Shilts *et al.* (1979) and Shilts (1980a) studied the dispersal patterns of lithologically distinctive erratics around Hudson Bay (Fig. 2.5). It was found that red erratics, carried from their source in the hematite-rich Dubawnt Group rocks to the west, dominated the tills of eastern Keewatin. Furthermore, it was found that no Paleozoic erratics had been transported to Keewatin from the Hudson Bay area. Southwest of Hudson Bay the tills overlying the Precambrian basement are rich in Paleozoic erratics. Southeast and east of Hudson Bay in Québec no Paleozoic erratics were found above the marine limit. Additional study of the composition of tills southwest of the Dubawnt Group led Kaszycki and Shilts (1982) to conclude that many tens of thousands of years had been required for the ice to transport red erratics such a great distance from their source onto the floor of Hudson Bay. These dispersal patterns of Dubawnt and Paleozoic erratics led Shilts *et al.* (1979) to conclude that two independent dispersal centres, one in Keewatin and one in Nouveau Québec-Labrador, existed during the glacial maximum of the Wisconsin (Fig. 2.6). Because no carbonate erratics were found in Keewatin, even a few kilometers west of Paleozoic outcrops, they also concluded that "ice never flowed from Hudson Bay into Keewatin".

Other evidence in support of the multidome hypothesis includes "the rarity of limestone erratics" immediately east of Paleozoic limestone - Precambrian Shield contact on western Baffin Island which would have been crossed by "flow lines from a hypothetical

Figure 2.4. Generalized ice-flow direction. Modified from Prest *et al.* (1968).

Figure 2.5 Dispersal patterns of carbonates, red, and dark erratics from source areas in bedrock. From Shilts (1980a).

Figure 2.6 Flow patterns reconstructed from trends of ice moulded or inscribed features and from dispersal patterns of erratics (see Fig. 2.3). From Shilts (1980a).

ice centre over Hudson Bay" (Andrews and Miller, 1979) and the absence of Paleozoic or Proterozoic erratics in glacial deposits east of the eastern coast of Hudson Bay as well as new interpretations of uplift (Hillaire-Marcel *et al.* 1980).

Yet another interpretation of ice flow indicators, proposed by Dyke *et al.* (1982) would have, in addition to the centres delimited by Shilts (1980a), a centre over southwestern Hudson Bay (Fig. 2.7).

Although the models which suggest a single centre of glacial outflow are quite elaborate, the field data appear to contradict them and show that several centres of ice dispersal existed in central North America during the Wisconsin maximum. Assuming that the multidome hypotheses are correct, as the field evidence suggests, the transect investigated in this study encompasses areas overlain by tills deposited by ice from at least three dispersal centres.

2.3.2 Description and Apparent Sources of Tills Along the Transect

Along the transect from Longlac, Ontario to Churchill, Manitoba, field evidence suggests that ice flow was generally to the west or southwest from a centre or centres to the east (Figs. 2.4, 2.5). There is also evidence that there was later ice flow from the north (Prest *et al.* 1967; Shilts 1980a). Tills along this part of the transect contain much Paleozoic carbonate material derived from the Hudson Bay Basin to the east. Dark grey to black Proterozoic erratics, transported from the vicinity of the Belcher Islands and Sutton Lake areas are also present in the tills (Fig. 2.5). Finally, pre-Wisconsin marine sediments from around Hudson Bay have been incorporated in the till (Shilts *et al.* 1979). Because much of the till in this part of the transect was derived from carbonate rocks and marine sediments of the Hudson Bay area, it is generally fine grained and contains few stones (EBA 1976).

Between the Nelson and Seal rivers the transect crosses an area of contact between ice from Keewatin and ice from an eastern centre. Multiple till sections (EBA 1976; Shilts *et al.* 1979; Shilts 1980a) indicate that glacial deposits in this area consist of till sheets of alternating provenance: carbonate-rich, fine-grained tills deposited by ice from the east alternating with coarse-grained tills of granitic origin from the Shield to the north. This suggests that the contact

Figure 2.7 Flow patterns reconstructed from trends of ice moulded or inscribed features and dispersal patterns of erratics. From Dyke *et al.* (1982).

between ice from the two lobes located in this area was not stationary.

From the Seal River to Baker Lake, ice flow was generally to the south or east from one or more centres in Keewatin (Prest *et al.* 1967). Till in the southern two-thirds of the segment is derived mostly from Shield rocks and sandstones of the Thelon Basin. They are, consequently, sandy to stoney. The northern third of this segment crosses an area underlain by clayey red till. This till is dominated by red erratics transported from red beds of the Proterozoic Dubawnt Group (Fig. 2.5) (Shilts 1980a).

Between Baker Lake and Rae Strait, the predominant ice flow was eastward or westward, depending on the position of the Keewatin Ice divide, which is believed to have shifted from west to east (Cunningham and Shilts 1977). Tills in this segment of the transect are sandy to gravelly and reflect sources in granitic and metamorphic Shield rocks.

From Rae Strait to the north coast of Somerset Island, ice flow evidence indicates that the principal source of the tills is the Paleozoic rocks to the west over which the M'Clintock ice divide was positioned (Dyke, in press). The texture of the till in this area reflects both the crystalline rocks of the Boothia Arch and the sedimentary rocks of the Arctic Platform. They vary from coarse to fine grained respectively.

It is evident from the above description that the bedrock and surficial geology of this sizeable area is varied and complex. Some aspects of the geology which are not contained within this chapter will be covered in Chapter 4.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology described below was conceived to meet the requirements of a regional study on the distribution of heavy minerals in tills overlying a large area of complex geology. The methodology is based on many standard techniques described in sedimentary petrology textbooks (Krumbein and Pettijohn 1938; Milner 1962; Parfenoff et al. 1970; Carver 1971; Boswell 1933; and Griffiths 1967). It differs from most heavy mineral studies of sediments (including till) in that: the > 3.3 specific gravity (s.g.) fraction is analysed rather than the > 2.8 s.g. fraction; a stereoscopic (binocular) microscope, instead of a petrographic microscope, is used to count the grains; and clinopyroxene and hornblende results have been excluded in calculating the heavy mineral totals. The > 3.3 s.g. fraction was chosen for analysis in order to exclude micas and most amphibole and pyroxene grains from the separate. These minerals vary widely in abundance, particularly in metamorphic and igneous terrains, and can mask other, more interesting minerals, thereby making comparison of results difficult. The stereoscopic microscope was chosen over the petrographic microscope since heavy mineral counts take less time, and opaque and turbid minerals can be more easily identified. Clinopyroxenes and hornblende percentages were not calculated or included as part of the total because it was felt that insufficient care had been taken to insure uniformity of separation of the heavy minerals. The density of many clinopyroxene (principally diopside) and hornblende grains is the same or close to that of Methylene Iodide (3.3 s.g.). Therefore, a slight change in the routine of the separation method could affect comparisons of the results of one sample with another. Fig. 3.1 is a flow sheet of operations used in the preparation of the samples.

3.2 Pretreatment of Samples

The original till samples used in this study were segments of

Figure 31 Laboratory operations

dry or frozen drill cores. From 200 to 400 gm of sediment was taken from each sample at selected depths along the core. When necessary, the samples were disaggregated by being soaked, for 12 hours, in a solution of sodium metaphosphate. The 63-250 μ m (fine to very fine sand) fraction was obtained by wet-sieving the sample through stainless steel sieves. After drying overnight in an oven, the 63-250 μ m fraction was dry-sieved to ensure that the separation was complete. The -63 μ m (silt and clay) fraction was discarded. The +250 μ m fraction (medium sand and coarser) was stored in vials.

3.3 Separation of Heavy Minerals

Heavy minerals were separated from the 60 to 250 μ m fraction of the till by gravity settling in glass separatory funnels, employing the method used at the Sedimentology Laboratories of the Geological Survey of Canada (Fig. 3.2).

The procedure followed was:

- (1) A 500 ml separatory funnel, placed inside a fume cabinet, was filled with 100 ml of methylene iodide.¹
- (2) The 63-250 μ m fraction was added to the methylene iodide. If more than 50 gm of sand was used the quantity of methylene iodide was increased.
- (3) The mixture was then agitated thoroughly with a glass rod. Before removing the glass rod from the funnel, the glass rod and the sides of the funnel were washed clean of adhering grains with a jet of methylene iodide from a plastic squeeze bottle.
- (4) After 10 minutes the mixture was again agitated without disturbing the accumulation of heavy minerals that had settled above the valve.
- (5) After 10 minutes or whatever time it took for all the heavy mineral grains to sink, the following procedure was used to drain the separatory funnel.
- (6) A vacuum funnel apparatus with a #1 Whatman filter paper was placed under the separatory funnel. With the vacuum pump operating, the valve was quickly turned to the open position and then back to the closed

¹ Methylene iodide is toxic. It should not be allowed to come into contact with the skin and its vapours should not be inspired.

Figure 3.2. Apparatus for heavy mineral separation by flotation in heavy liquids.

position several times until all the heavy minerals that had accumulated over the valve had been extracted.

(7) Once the methylene iodide had drained through the filter paper the funnel was removed and the filtered methylene iodide was returned to the methylene iodide bottle.

(8) The heavy minerals were washed thoroughly with acetone.

(9) Steps 6 through 8 were repeated, to remove all the light minerals to a separate filter paper.

(10) The magnetic grains were separated from the heavy minerals with an auto magnet.

3.4 Identification of Minerals

A significant part of this study involved designing a method to deal with the problems of sorting, identifying, and collecting heavy minerals from tills. The establishment of a collection of heavy mineral varieties, in the form of reference slides, is important to the achievement of complete and accurate identification of the mineral assemblages of the study samples. This is particularly true of studies in which mineral grains are counted using a stereoscopic microscope.

Identification of minerals with a stereoscopic microscope depends almost entirely on physical appearances such as colour, cleavage, fracture, luster and so on. These properties are much more difficult to quantify or describe than the optical properties observed with a petrographic microscope. The techniques outlined below were used to identify the minerals in the tills of the study area. The results appear in Appendix II.

3.4.1 Sorting for Identification and Reference Slide Preparation

A small amount of heavy mineral residue was removed from its vial, using a knife, and sprinkled onto a separation tray or a glass slide. The heavy-minerals were examined under reflected light with a stereoscopic microscope. A hypodermic needle was found to be the most suitable instrument for sorting the grains. Generally the grains would adhere to the needle, because of static electricity, and could be removed by gently tapping the needle on the side of the

receptacle to which they were being transferred. When a glass slide was used, the desired grains were either picked out one at a time with the needle or pushed over the edge onto another slide. Grains difficult to distinguish from one another or not plentiful, were grouped near the edge of the slide. They were then compared and segregated on the basis of colour, morphology, cleavage, fracture, relief, crystal form, lustre, opacity, streak, and hardness. Streak was determined by placing the tip of the hypodermic needle gently over the grain and, with the finger over the shaft of the needle, crushing the grain. The resulting powder indicated the colour of the streak. For example, a red powder remains when hematite is crushed, while green or brown slivers remain when hornblende is crushed.

Grains kept for subsequent positive identification or for mounting as reference slides were stored in cardboard microfossil slides.

Positive identification of minerals was achieved by examination with a petrographic microscope, X-ray diffraction, and by examination with a scanning electron microscope (SEM) with energy dispersion capabilities (Appendix IV Fig. 2).

3.4.2 Petrographic Microscope

A petrographic microscope was used to verify the identity of non-opaque grains before making reference slides, and during counting to verify the identity of grains which were difficult to identify with a binocular microscope.

Use of the petrographic microscope is limited because grains are often too thick, lack thin edges, or are opaque or turbid. Therefore, X-ray diffraction results are necessary for positive identification.

3.4.3 X-ray Diffraction

X-ray identification was done by 57.3mm Debye-Scherrer cameras employing Ni filtered Cu radiation. Three or four grains in each group suspected of being the same mineral were selected for X-ray study. The grains were chosen to represent the range of characteristics exhibited by each group of minerals to assure that all were, in fact, the same mineral. They were ground to a powder and bonded together

by an amorphous glue, onto a needle-like spindle. The spindle was then placed in a powder diffraction camera. The diffraction pattern produced was compared with patterns for standard minerals from the G.S.C. reference file. This method provided non-ambiguous identification.

3.4.4 Scanning Electron Microscope

The heavy minerals described in this study were examined, at the Geological Survey of Canada, with a scanning electron microscope (SEM) equipped with a Kevex X-ray dispersive system (EDS). The SEM was useful in studying surface textures of mineral grains. The X-ray energy dispersive capabilities of the SEM allowed qualitative analysis of elements making up any part of the mineral grain that could be observed in the SEM display. The technique is also useful in determining the identity of inclusions in grains.

Photographs were taken of the surface texture and elemental spectrum of all the minerals reported in this study. The elemental compositions of the minerals, as determined with X-ray EDS, are listed in Appendix II.

3.4.5 Reference Slides

Eighty reference slides of 60 different minerals and mineral varieties were made for this study.¹ The following procedure was developed for preparing reference slides:

- (1) The grains to be mounted were transferred to the centre of a clean slide. If a certain distribution and orientation was desired, a thin film of solution of gum-arabic was placed on the slide before the grains were positioned. After the solution had evaporated the grains were firmly attached to the slide.
- (2) An epoxy resin was prepared by mixing 5 parts Araldite 502 ($n = 1.56$) to 1 part Hardener 956 in a test-tube and then stirring vigorously with a glass rod for 1 minute.

1 The slides were prepared by the writer while employed by the Geological Survey of Canada. They may be examined by contacting Dr. W.W. Shilts, Terrain Sciences Division, G.S.C., 601 Booth Street, Ottawa, Canada, K1A 0E8.

- (3) This mixture was placed in a centrifuge for 8 minutes at 2 500 r.p.m. to remove air bubbles.
- (4) The thin film which formed on the surface of the epoxy was removed with a spatula.
- (5) Tweezers were used to carefully place a clean No. 1 thickness, 1.8mm round cover glass over the mineral grains on the microscope slide.
- (6) A drop of the epoxy resin was placed on either side of the cover glass and allowed to be drawn, by capillary action, underneath the cover glass.
- (7) The slide was immediately examined under the binocular microscope and any air bubbles in the drops of epoxy were removed with a needle before they could be drawn under the cover glass.
- (8) The epoxy resin was cleaned from around the coverslide using tissue paper and alcohol.
- (9) After drying overnight, excess glue on the cover glass or slide was removed using a knife.

3.5 Point Counting

Heavy minerals from each sample were mounted in Araldite for point counting. The following method was used:

- (1) Six to eight drops of epoxy were spread evenly on a clean microscope slide.
- (2) A small amount of the heavy mineral residue was removed from the vial with a knife and sprinkled evenly onto the Araldite from a height of 10cm.
- (3) A No. 1 thickness, 24 X 40mm cover glass was put in place, pressed down until there was only the thickness of the grains between it and the microscope slide. The Araldite was then allowed to dry overnight.
- (4) Excess epoxy that had been squeezed out from under the cover glass was not removed. Its presence may reduce cracking of the Araldite underneath the cover glass as it ages.

A modified form of point counting was developed by the writer in order to arrive at a number percent rather than a percent frequency. A Swift mechanical stage, fitted with an automatic counter, was mounted on the stage of a stereoscopic microscope. A total of 450 grains were counted along equally spaced linear traverses parallel to the long axis of the slide.

As the stage advanced at constant interval, the grain, whose

Figure 3.3 Method of counting heavy mineral slides. Only the shaded grains (the grains whose centres are closest to the crosshairs (+) as indicated on the imaginary transect) are counted.

centre was closest to the crosshairs, was counted (Fig. 3.3). In this way larger grains were not preferentially counted to smaller grains.

3.6 Significances of Changes in Abundance of Mineral Species

- To determine the significant point of change in the abundance of a heavy mineral, from one sample to another, the probable error in observations was calculated, for values 5 - 96%, using the formula (Galehouse 1971):

$$PE_{95.4} = 2 \cdot \sqrt{\frac{P(100-P)}{N}}$$

where PE = probable error in percent,
N = total number of grains counted,
P = percentage of N of an individual mineral.

For observations of individual minerals making up <5% (as well as >96%) of the sample, calculations were based on Poisson distribution. The formula:

$$PE = P$$

was used (Kelley 1971). Table 3.1 summarizes the probable error at the 95.4 confidence level for a mineral present at various percentages.

TABLE 3.1 Number of grains counted of a particular mineral species and the probable error of the number at the 95.4 level of confidence.

Total number of grains counted 450	Percent of a particular mineral species present														
	1	2	3	4	5	10	20	30	40	50	60	70	80	90	95
	±1	±2	±3	±4	±5	±2.8	±3.7	±4.3	±4.6	±4.7	±4.6	±4.3	±3.7	±2.8	±2

morphology, and chemical composition. Varieties were not differentiated in this study.

Rutile

There are three areas where rutile is found in relative abundance. These are: between KP2836 and KP2442 (.3 to 1%), from KP1703 to KP1540 (.3 to 1%), and at KP645 (3%).

Zircon

From KP3721 to KP1703 values for zircon vary between .2 to 2% and show no regional consistency. Between KP1621 and KP645 values are uniformly higher, ranging from 1 to 4%. Samples from KP1237 and KP645 are particularly rich.

Monazite

Monazite occurs in proportions that range from .2 to 2% at KP2939 to KP2347. There is also 1% monazite at KP1325. Other than in these cases the mineral occurs only in a few cores in amounts less than .5%.

Magnetic fraction

In general, the percent by weight of magnetic minerals of the heavy mineral fraction varies greatly from core to core. There are two areas that have consistently high values. These are: from KP2347 to KP1966 which has an average of 33% and from KP1787 to KP1237 where there is an average of 29%.

The magnetic fraction of the samples examined in this study consisted mostly of magnetite. Grains of other minerals, such as epidote or titanite, were sometimes trapped because they contained magnetic inclusions. The proportion of these grains never exceeded 1 or 2% of the total number of magnetic grains. Pyrrhotite, also magnetic, constituted part of the magnetic fraction in some samples (KP2939, 13.1m; KP1384, 5.0m; KP1325, 5.9m; KP1237, 5.3m).

Percent heavy minerals of fine sand fraction

The heavy mineral content of the fine sand fraction varied from .4 to 2.1% by weight, with most values in the .6 to 1.5% range. The average value was 1%. The only deviation from these ranges was at KP1044 where the heavy minerals represented 8.5% of the weight of

CHAPTER 4

VARIATIONS IN THE ABUNDANCE OF HEAVY MINERALS - RESULTS AND DISCUSSION

4.1 Introduction

Heavy mineral analysis of the uppermost samples from cores along the transect from Longlac to Somerset Island are presented as Fig. 4.1. The diagram illustrates how the relative proportions of 17 minerals and mineral varieties vary. Fig. 4.2 shows how the relative proportions of these minerals change with depth in selected cores. It is important to note that clinopyroxenes and clinoamphiboles (principally diopside and hornblende), although counted, were excluded from the percentages of heavy minerals calculated and are not represented in the diagrams.

The large area covered by the samples and the lack of detailed geological information available for much of the study area have resulted in discussions of the results being limited to regional patterns and selected local variations of heavy mineral distribution. For purposes of comparison with locations along the transect, a sample from Coats Island was also investigated and the results are presented in Fig. 4.1.

The term significant, as used in the following discussion, applies to changes in abundance greater than the probable sampling error described in section 3.6 (see Table 3.1).

4.2 Variation in Near-Surface Samples

4.2.1 Description

Hematite

From KP3721¹ through KP2347, the percentage of hematite (Appendix II) in the heavy minerals of the tills is fairly uniform, with no value exceeding 22%. At KP2836 however, the tills is relatively poor in hematite. The most common variety of hematite in these samples is specularite. It occurs as angular, equidimensional platy grains with a highly metallic lustre. Many of these grains also contain quartz, some

¹ Polar Gas Consortium notation which indicates the kilometer post south of the proposed starting point of the pipeline on Melville Island (Fig. 1.1). The corresponding Polar Gas Borehole notations and their geographic coordinates are listed in Appendix I.

Figure 4: Heavy mineral diagram of near surface samples. 3%, 4%, 7%, 10% (when above a bar, these symbols represent the subclass) 1, 0.5% weight of heavy minerals, 1, 0.5% weight of 63-250µm fraction, 1, alluvium

Figure 4.2 Heavy mineral diagram of vertical variation in cores 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31, 33, 35, 37, 39, 41, 43, 45, 47, 49, 51, 53, 55, 57, 59, 61, 63, 65, 67, 69, 71, 73, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 97, 99, 101, 103, 105, 107, 109, 111, 113, 115, 117, 119, 121, 123, 125, 127, 129, 131, 133, 135, 137, 139, 141, 143, 145, 147, 149, 151, 153, 155, 157, 159, 161, 163, 165, 167, 169, 171, 173, 175, 177, 179, 181, 183, 185, 187, 189, 191, 193, 195, 197, 199, 201, 203, 205, 207, 209, 211, 213, 215, 217, 219, 221, 223, 225, 227, 229, 231, 233, 235, 237, 239, 241, 243, 245, 247, 249, 251, 253, 255, 257, 259, 261, 263, 265, 267, 269, 271, 273, 275, 277, 279, 281, 283, 285, 287, 289, 291, 293, 295, 297, 299, 301, 303, 305, 307, 309, 311, 313, 315, 317, 319, 321, 323, 325, 327, 329, 331, 333, 335, 337, 339, 341, 343, 345, 347, 349, 351, 353, 355, 357, 359, 361, 363, 365, 367, 369, 371, 373, 375, 377, 379, 381, 383, 385, 387, 389, 391, 393, 395, 397, 399, 401, 403, 405, 407, 409, 411, 413, 415, 417, 419, 421, 423, 425, 427, 429, 431, 433, 435, 437, 439, 441, 443, 445, 447, 449, 451, 453, 455, 457, 459, 461, 463, 465, 467, 469, 471, 473, 475, 477, 479, 481, 483, 485, 487, 489, 491, 493, 495, 497, 499, 501, 503, 505, 507, 509, 511, 513, 515, 517, 519, 521, 523, 525, 527, 529, 531, 533, 535, 537, 539, 541, 543, 545, 547, 549, 551, 553, 555, 557, 559, 561, 563, 565, 567, 569, 571, 573, 575, 577, 579, 581, 583, 585, 587, 589, 591, 593, 595, 597, 599, 601, 603, 605, 607, 609, 611, 613, 615, 617, 619, 621, 623, 625, 627, 629, 631, 633, 635, 637, 639, 641, 643, 645, 647, 649, 651, 653, 655, 657, 659, 661, 663, 665, 667, 669, 671, 673, 675, 677, 679, 681, 683, 685, 687, 689, 691, 693, 695, 697, 699, 701, 703, 705, 707, 709, 711, 713, 715, 717, 719, 721, 723, 725, 727, 729, 731, 733, 735, 737, 739, 741, 743, 745, 747, 749, 751, 753, 755, 757, 759, 761, 763, 765, 767, 769, 771, 773, 775, 777, 779, 781, 783, 785, 787, 789, 791, 793, 795, 797, 799, 801, 803, 805, 807, 809, 811, 813, 815, 817, 819, 821, 823, 825, 827, 829, 831, 833, 835, 837, 839, 841, 843, 845, 847, 849, 851, 853, 855, 857, 859, 861, 863, 865, 867, 869, 871, 873, 875, 877, 879, 881, 883, 885, 887, 889, 891, 893, 895, 897, 899, 901, 903, 905, 907, 909, 911, 913, 915, 917, 919, 921, 923, 925, 927, 929, 931, 933, 935, 937, 939, 941, 943, 945, 947, 949, 951, 953, 955, 957, 959, 961, 963, 965, 967, 969, 971, 973, 975, 977, 979, 981, 983, 985, 987, 989, 991, 993, 995, 997, 999, 1001, 1003, 1005, 1007, 1009, 1011, 1013, 1015, 1017, 1019, 1021, 1023, 1025, 1027, 1029, 1031, 1033, 1035, 1037, 1039, 1041, 1043, 1045, 1047, 1049, 1051, 1053, 1055, 1057, 1059, 1061, 1063, 1065, 1067, 1069, 1071, 1073, 1075, 1077, 1079, 1081, 1083, 1085, 1087, 1089, 1091, 1093, 1095, 1097, 1099, 1101, 1103, 1105, 1107, 1109, 1111, 1113, 1115, 1117, 1119, 1121, 1123, 1125, 1127, 1129, 1131, 1133, 1135, 1137, 1139, 1141, 1143, 1145, 1147, 1149, 1151, 1153, 1155, 1157, 1159, 1161, 1163, 1165, 1167, 1169, 1171, 1173, 1175, 1177, 1179, 1181, 1183, 1185, 1187, 1189, 1191, 1193, 1195, 1197, 1199, 1201, 1203, 1205, 1207, 1209, 1211, 1213, 1215, 1217, 1219, 1221, 1223, 1225, 1227, 1229, 1231, 1233, 1235, 1237, 1239, 1241, 1243, 1245, 1247, 1249, 1251, 1253, 1255, 1257, 1259, 1261, 1263, 1265, 1267, 1269, 1271, 1273, 1275, 1277, 1279, 1281, 1283, 1285, 1287, 1289, 1291, 1293, 1295, 1297, 1299, 1301, 1303, 1305, 1307, 1309, 1311, 1313, 1315, 1317, 1319, 1321, 1323, 1325, 1327, 1329, 1331, 1333, 1335, 1337, 1339, 1341, 1343, 1345, 1347, 1349, 1351, 1353, 1355, 1357, 1359, 1361, 1363, 1365, 1367, 1369, 1371, 1373, 1375, 1377, 1379, 1381, 1383, 1385, 1387, 1389, 1391, 1393, 1395, 1397, 1399, 1401, 1403, 1405, 1407, 1409, 1411, 1413, 1415, 1417, 1419, 1421, 1423, 1425, 1427, 1429, 1431, 1433, 1435, 1437, 1439, 1441, 1443, 1445, 1447, 1449, 1451, 1453, 1455, 1457, 1459, 1461, 1463, 1465, 1467, 1469, 1471, 1473, 1475, 1477, 1479, 1481, 1483, 1485, 1487, 1489, 1491, 1493, 1495, 1497, 1499, 1501, 1503, 1505, 1507, 1509, 1511, 1513, 1515, 1517, 1519, 1521, 1523, 1525, 1527, 1529, 1531, 1533, 1535, 1537, 1539, 1541, 1543, 154

of which is stained bright red. There are, in addition, very well rounded grains with smooth surface texture.

The highest concentrations of hematite were noted from KP2226 through KP1703. At KP2226 there is an increase of 13% in the amount of hematite. Concentrations increase to 80% at KP1871 and then descend gradually to 29% at KP1703. Hematite grains in these samples vary from sub-angular to rounded, and have a smoother texture and less metallic lustre than the majority of hematite grains from tills south of KP2226 (Appendix IV, Fig. 1).

At KP1621 hematite content drops sharply to 9%. Low values, which vary from 4 to 16%, are maintained to the end of the transect at KP645. The hematite in this area resembles the specular variety found in the tills from south of KP2226 in the Ontario-Manitoba segment. The till from Coats Island has a relatively high hematite content (25%).

Garnet

In the Ontario portion of the transect, from KP3721 to KP3093, garnet content remains in the vicinity of 15%. From KP2939 to KP2347 contents in cores are higher, less uniform, and range from 21 to 33%. At KP2226 a sharp decrease to 11% was noted. After a rise to 15%, values decrease gradually to 4% at the Thelon River (KP1787). At KP1703 there is an increase to 11%; followed by a sharp increase to 44% at KP1621. From here to the northern end of the transect, KP645, values remain high, ranging from 25 to 67%.

Although several varieties of garnet were observed (Appendix II), only rounded and angular grains were differentiated during point counting. The rounded grains occur primarily in cores from north of Rae Strait (KP1237 - KP645) (Appendix IV, Fig. 5).

On Coats Island values resemble those from the Ontario segment of the transect (20%).

Epidote

The relative proportion of epidote rises gradually from 34% at KP3721 to 49% at KP3414. North of this point, there is a gradual and even decrease to 25% at the Nelson River (KP2787). From KP2610 to KP2347 the 3 samples counted have 11% epidote. At KP2226 a sharp rise in epidote to 33% is followed by a steady decrease to 5% at KP1871, a sharp increase at KP1850 to 23%, and an increase to 55% at KP1787. From

KP1703 to KP1237 changes are random and range from 12 to 26%. At KP1146 values drop from 15% in the previous core to 4% and remain in this range to the end of the transect.

On Coats Island the percentage of epidote is relatively low (13%).

Orthopyroxene

The greatest abundance of orthopyroxene occurs in the Ontario-Manitoba portion of the transect. From KP3721 to KP3170 contents average 10%. At KP3093 there is a rise to 15% followed by a steady decline to 7% at KP2787. Samples from KP2610, 2442, and 2347 (Churchill River to Manitoba-Northwest Territories border) are very rich in orthopyroxene, averaging 18%. At KP2226 there is a sharp drop of orthopyroxene to 5%. This is followed by a steady decline to 7% at KP1703. From KP1621 to KP1394 values average 9.5%, between KP1384 and KP1237 values average 3.5%, and from KP1146 to the north shore of Somerset Island (KP645) the proportions of orthopyroxene vary from core to core and range from 3 to 14%.

A cursory examination of the orthopyroxene under the petrographic microscope indicated that the majority of the grains fall in the hypersthene end of the enstatite-hypersthene series. The hypersthene grains in cores from KP2610 through KP2347 are among the most distinctive along the transect. They are characterized by a waxy, yellow-orange colour and fractures surrounded by areas of cloudiness.

Bronzite

Bronzite, a variety of orthopyroxene, occurs primarily in tills from the Manitoba portion of the transect (KP3093 to KP2347). Proportions range from .5 to 3%. At KP1621 there is 6% bronzite. In other samples bronzite was not noted in amounts exceeding .3% (1 grain).

Pyrite

The first occurrence of pyrite along the transect is at KP3471 (6%). The mineral also occurs between KP3093 and KP2610 (average 2.5%). Most of the pyrite grains in these samples have a granular appearance. There are also grains with botryoidal textures as well as a few which occur as pyritized fossils (forams).

In the sample from KP2226 there is 8% pyrite. Values in the next 7 cores, however, climb, in an irregular fashion from 0 at KP2176

to 19 and 14% at KP1819 and KP1803 respectively. The sample from KP1787 contains no pyrite while that from KP1703 contains 11%. At KP1621 there is a sharp drop of 8% followed by a fairly regular increase in pyrite to maximum of 29% at KP1119.

The pyrite in tills between KP1621 and KP1119, for the most part, resembles that from south of KP2226. Also, in some of the cores east of Rae Strait there are well rounded and very shiny grains of pyrite. These grains are so round and lustrous that they can be mistaken for air bubbles. There are some euhedral grains, mainly in the cores from southern and central Keewatin.

In the 2 northernmost cores, only trace amounts of pyrite were noted. On Coats Island pyrite content was high (18%).

Ilmenite

From KP3721 to KP2939 the proportion of ilmenite in the heavy minerals of the tills ranges from .2 to 7%. In cores from KP2836 to KP2610 values are more constant (average of 8.5%). At KP2442 there is a marked increase to 22% followed by a fairly regular decline to 1% in the till at KP2176. Samples from cores north of this point to KP1703 are relatively deficient in ilmenite. At KP1621 there is an increase to 13%. Along the remainder of the transect values range from .8 to 8% and a consistent pattern does not emerge. On Coats Island 10% ilmenite was noted.

Siderite

A few grains of siderite were noted at KP2939. Between KP2836 and KP2610 values range from 2 to 4%. A grain of siderite, of the same variety as those observed in the south, was also noted in the core from KP1146. The sample from Coats Island showed 4% siderite.

Goethite

Values from goethite are consistently low throughout the transect (ranging from .2 to 4%) with the exception of a sample from KP645 in which 9% goethite was noted. The proportions are slightly higher than average in the area between KP2836 and KP2610 (1 to 2%), at KP2176 (2%), at KP1850 (3%), at KP1787 (3%), and at KP1703 (4%). From KP1621 through KP1044 goethite is either absent or present only in trace amounts. Several varieties of goethite were observed during the study, but are not differentiated in the results presented here.

Barite

At KP3093, near the Severn River, 1% barite was noted. This represents 4 grains of the 450 counted. At KP2226 .2% was noted. At KP1850, 75Km south-west of Baker Lake, there is 6% barite. At KP1312, .7% barite was recorded.

The barite at KP1850 is a distinctive pink-orange, setting it apart from the grey variety observed in other samples (Appendix IV, Fig. 3(a)).

Cloritoid

Cloritoid occurs in trace amounts (.2 to 1%) in several cores from KP3093 to KP1384. It was observed in larger proportions only at KP1819 (4%) and at KP1703 (3%).

Kyanite

Kyanite is found in significant amounts at KP2610 (2%) and at KP1703 (11%). Otherwise, it occurs only in trace amounts in a few samples of the Ontario-Manitoba segment and on the north shore of Somerset Island. The kyanite at KP1703 is quite distinct from that found in the rest of the transect. It is grey, fibrous, elongated, and more closely resembles sillimanite than kyanite.

Titanite

The highest proportions of titanite (2 - 4%) were noted in samples from the area between KP3721 and KP2739. From KP2836 to KP1394 values are significantly lower (0 - 1%) with the exception of KP2087 (20%) and KP1787 (4%). From KP1384 to KP1237 values average 2.2% and then fall to trace amounts in the final 4 cores of the transect. In the case of the samples from KP3471 and KP2087, 1% of the magnetic fraction consists of titanite grains with magnetite inclusions. In several samples grains are partially altered to leucoxene. The titanite at KP2987 was particularly affected by this type of alterations.

Leucoxene

Leucoxene was noted in low proportions, rarely exceeding 2%, in most cores along the transect. It is relatively abundant at KP1819 and KP645 where 3% was noted in each case.

Leucoxene, an alteration product of titaniferous minerals, such as ilmenite, rutile, and titanite, varies widely in colour, texture

morphology, and chemical composition. Varieties were not differentiated in this study.

Rutile

There are three areas where rutile is found in relative abundance. These are: between KP2836 and KP2442 (.3 to 1%), from KP1703 to KP1540 (.3 to 1%), and at KP645 (3%).

Zircon

From KP3721 to KP1703 values for zircon vary between .2 to 2% and show no regional consistency. Between KP1621 and KP645 values are uniformly higher, ranging from 1 to 4%. Samples from KP1237 and KP645 are particularly rich.

Monazite

Monazite occurs in proportions that range from .2 to 2% at KP2939 to KP2347. There is also 1% monazite at KP1325. Other than in these cases the mineral occurs only in a few cores in amounts less than .5%.

Magnetic fraction

In general, the percent by weight of magnetic minerals of the heavy mineral fraction varies greatly from core to core. There are two areas that have consistently high values. These are: from KP2347 to KP1966 which has an average of 33% and from KP1787 to KP1237 where there is an average of 29%.

The magnetic fraction of the samples examined in this study consisted mostly of magnetite. Grains of other minerals, such as epidote or titanite, were sometimes trapped because they contained magnetic inclusions. The proportion of these grains never exceeded 1 or 2% of the total number of magnetic grains. Pyrrhotite, also magnetic, constituted part of the magnetic fraction in some samples (KP2939, 13.1m; KP1384, 5.0m; KP1325, 5.9m; KP1237, 5.3m).

Percent heavy minerals of fine sand fraction

The heavy mineral content of the fine sand fraction varied from .4 to 2.1% by weight, with most values in the .6 to 1.5% range. The average value was 1%. The only deviation from these ranges was at KP1044 where the heavy minerals represented 8.5% of the weight of

the fine sand fraction.

On Coats Island the heavy mineral content was 2%, the second highest content noted in the study.

4.2.2 Heavy Mineral Zones and Assemblages

The tills described in this study have never been classified according to heavy mineral composition. Five heavy mineral zones can be defined from Fig. 4.1 (see Fig. 4.3). These zones can also be easily distinguished in Fig. 4.4, which classifies samples according to abundance of epidote, hematite and garnet, and in Fig. 4.5 which allows comparison of ratios of epidote to orthopyroxene. The heavy mineral zones, from north to south, are defined by assemblages constituted of dominant or characteristic minerals as follows:

- a) Superior zone (KP3721-KP2787): epidote, orthopyroxene, bronzite, and titanite.
- b) Churchill zone (KP2610-KP2347): garnet, orthopyroxene, and ilmenite.
- c) Dubawnt zone (KP2226-KP1703): hematite, epidote, and pyrite.
- d) Northern Keewatin zone (KP1621-KP1237): garnet, epidote, titanite, zircon, and magnetite.
- e) Boothia zone (KP1146-KP645): garnet, ilmenite, and orthopyroxene.

Because of the linear nature of the data only the northern and southern limits of the zones can be established (Fig. 4.3). Future studies will, hopefully, allow further delineation and refinement of these zones.

4.2.3 Lateral Distribution and Provenance

The lateral distribution and provenance of heavy minerals in tills along the transect can be discussed on a regional scale in terms of the heavy mineral zones identified above. In areas where the geology is known in sufficient detail, the study of local variations (i.e. in the abundance of heavy minerals anomalies,) can also be fruitful. The following discussion is based on near-surface samples depicted in Fig. 4.1.

4.2.3.1 Regional patterns

There are several indicators of ice flow direction which point to the source of tills of the Superior heavy mineral zone. McDonald (1969) and Prest *et al.* (1967) define two major flow directions based

Figure 4.3. Heavy mineral zones.

Figure 4.4. Ternary plot of selected minerals from uppermost samples divided into subgroups.

Figure 4.5. Epidote-orthopyroxene ratios in uppermost samples

on drumlins, and striations on bedrock and boulder pavements (Fig. 2.4). These consist of a dominant flow from the northeast and a less significant flow from the north northwest. Shilts (1980a) has recorded high content of "crystalline" erratics (from igneous and metamorphic Shield rocks) in the upper portion of the till in the Nelson River - Churchill area. Shilt suggests that these erratics indicate that the upper portion of the till was deposited by ice flowing from the north northwest (Figs. 2.5, 2.6).

The heavy mineral results presented in this study agree with the conclusion that the upper portion of the till was deposited by ice flowing from the north northwest. The assemblage characteristic of the Superior heavy mineral zone consists of epidote, orthopyroxene, and titanite; minerals which indicate a source in igneous and crystalline metamorphic rocks (Krumbein and Pettijohn 1938, pp. 430-450). Striation, drumlin, and till lithology data indicate that ice flowed from an area to the north-northwest which is underlain by crystalline metamorphic rocks. It is, therefore, reasonable to assume that the provenance of the heavy minerals is the "crystalline" rocks of the Shield to the north-northwest (Fig. 2.2).

The source of tills in the Churchill heavy mineral zone has been established by studying the distribution of glacial erratics (Shilts 1980) (Figs. 2.5, 2.6) and the orientation of glacial landforms and striations (Prest *et al.* 1967) (Fig. 2.4). These indicators show that, except for just north of the Nelson River, where ice flow was to the west, flow was to the south during most of the Wisconsin stage.

The bedrock source of the heavy minerals in the till is, however, more difficult to define. The principal minerals in the assemblage which characterizes this zone, i.e. orthopyroxene (including bronzite) and ilmenite, are often derived from basic and ultrabasic rocks (Milner 1962, pp. 127, 129). The centre of dispersal for tills deposited in this area lay immediately north of a large region of basic hypersthene-bearing charnockite-mangerite (Manitoba Mineral Resources Division 1979). The till at KP2347 lies directly over charnockite-mangerite. The samples from KP2442 and KP2610 are from till deposited 5 and 100 km down-ice from the rock respectively. Since hypersthene is the principal constituent of the orthopyroxene category, the hypersthene characteristic of this zone may be

amounts of siderite such as found in the Moose River Basin (Bell 1877, Baker 1911, Bennett *et al.* 1967, Shilts 1980b and others). Varieties of siderite identical to some of those noted in the till have also been observed in amounts of up to 25% in several samples of mature Cretaceous sediments south of James Bay (S. Averill, personal communication). The source of the pyrite and siderite in the lower part of the tills examined in this study is probably the Devonian Stopping River and Kwataboahagan formations under Hudson Bay (Fig. 2.2). Varieties of siderite which resemble those in Cretaceous sediments south of James Bay, may suggest the presence of units under Hudson Bay as well. It is also likely that the absence of these minerals in the upper parts of the core reflects a source in the crystalline rocks of the Shield to the north and north northeast. These rocks would also provide the epidote and orthopyroxene which are more abundant in the upper portion of the tills. Any siderite or pyrite in the upper portion is probably derived from underlying siderite and pyrite-rich tills which have been reworked by the glacier that deposited the upper till.

The ice flow directions implicit in these conclusions are consistent with conclusions on ice flow patterns and till provenance reached by McDonald (1969) and Prest *et al.* (1967) based on drumlins and striations and by Shilts *et al.* (1979) and Shilts (1980a) based on distribution of erratics.

An alternative hypothesis is that the siderite and pyrite are not from the Devonian rocks underlying Hudson Bay, but were formed in the till or some other sedimentary environment. These minerals form under reducing conditions. Reducing conditions can occur when decomposing organic matter on the ocean floor causes depletion of oxygen and development of H_2S . Under such conditions, pyrite or marcasite is formed. Reducing conditions can also occur on land where there is a large accumulation of plant debris. This type of highly reducing environment can lead to the formation of ferrous carbonates such as siderite (Berry and Mason 1959). It is doubtful that these conditions occurred in the till over such a large area as delimited by the occurrence of pyrite and siderite in this study. Furthermore, the mineral's presence in such high concentrations in many of the till and bottom sediments from Hudson Bay (Henderson, in press) makes it difficult to support any hypothesis that states that the siderite or pyrite was formed in a location west (down-ice) of Hudson Bay. It is also significant that authigenic siderite grains do not occur in other tills along the transect, or elsewhere in

solutions in the form of etch textures (Appendix IV, Fig. 5), are most likely derived from the Paleozoic sedimentary rocks that flank Boothia Peninsula (Fig. 2.2). The scarcity of epidote may be due to the lack of volcanic rocks which are one of the principal sources of this mineral in tills in other zones studied.

Studies of ice flow indicators, and till geochemistry and petrography by Dyke (in press) show that ice flow, during most of glaciation, was from a centre over the Paleozoic basin to the west of the Boothia Peninsula. This supports the conclusion that the major source of the heavy minerals in the till of the Boothia heavy mineral zone is Paleozoic sedimentary rocks.

The northernmost sample, KP645 contains higher amounts of stable minerals than any other sample along the transect. Stable minerals, such as rutile, zircon, monazite, and garnet (many of which are well rounded), indicate a sedimentary source; perhaps the Paleozoic rocks to the west or local fluvial sediments. These observations, however, are based only on one sample.

The heavy mineral zones described in section 4.2.2 appear to be compatible with the areas of provenance described above. Further sampling and a greater knowledge of the bedrock mineralogy would, undoubtedly, permit a better definition of these heavy mineral zones as well as provide more information on the distribution and provenance of the heavy minerals.

4.2.3.2 Local variations

Several local variations in the proportion of various heavy minerals are evident in Fig. 4.1. At KP1703, 11% of the heavy mineral fraction is kyanite; 5.5 times higher than in any other sample counted. In addition, several kyanite grains were noted in the magnetic fraction. Some grains are of the usual type, i.e. clear, colourless, bladed, with conspicuous cross cleavage, but most of the kyanite occurs as long, grey, fibrous grains and is distinct from the kyanite observed in the other cores. There are also red, yellow, and khaki stained grains of both types. Examination of all the varieties, using an X-ray energy dispersive system, revealed nothing but Al and Si in similar proportions.

Ice inscribed and ice molded features indicate that at least the upper portion of the till in this area was deposited by ice flow

from the southeast (Fyles 1955). About 15 km up-ice from the borehole, Fraser (personal communication, 1982) has observed an outcrop of medium grade amphibolite facies schist. Still unconfirmed, preliminary inspection of a hand specimen of this rock, suggests that the same variety of kyanite as described above is present in bedrock. If this is the case, it is reasonable to conclude that the kyanite in the till is from these rocks, and possibly, from the vicinity of the outcrop described above. This is a tentative conclusion, since the extent of the schist in question is not known, as the geology of the region has been mapped only on a reconnaissance scale. Callahan (1980) has shown how heavy minerals in stream sediments from Labrador characterize metamorphic zones, as well as, particular lithologic units. A more detailed study of the distribution of kyanite in this area could prove helpful in mapping the bedrock geology. The position of kyanite isograds could have implications for regional metamorphism in the area.

The sample from 2.7 metres depth on the north shore of the Thelon River (KP1787) consists of alluvium (EBA 1976). It is of interest because a grain of free gold was found in the heavy minerals and because of the absence of pyrite. The X-ray energy dispersive spectra of the grain shows that gold is the only element present.

The discovery of the gold grain adds to mounting evidence of mineralization in the area. This evidence includes: (1) the occurrence, near the sample location, of the Ketyet River Group metasedimentary rocks which bear a strong resemblance to rocks of the Archean Prince Albert Group (Schau *et al.* 1982); these rocks include highly folded fuchsite-bearing iron carbonate horizons within chloritic greywackes; an association characteristic of gold deposits in Archean rocks of the Kirkland Lake area of Ontario; (2) the occurrence of arsenopyrite with iron formation in rocks of the Ketyet River Group, an association also typical of Archean gold deposits (Ashton 1982); (3) a report by uranium prospectors of a gold anomaly (3ppm) associated with iron carbonates and iron formation in the same area as sample location KP1850 (Indian and Northern Affairs 1970).

The absence of pyrite in the heavy minerals of the sample, particularly in an area where pyrite is abundant in the till, demonstrates the inability of this mineral to tolerate oxidation in a fluvial environment (Parfenoff *et al.* 1970). This sample provides an example of the type of variation in the proportion of a heavy mineral which should cause one to question the origin of the material.

4.3 Vertical Distribution and Provenance

4.3.1 Introduction

Samples from various depths of several cores were analysed to determine vertical variation in heavy mineral abundance. Depths were selected to represent the range of depth; differences observed in clay or sand-sized heavy mineral geochemistry (Shilts, unpublished notes 1979; Shilts 1980b); and differences observed in the physical characteristics of the till (EBA 1976, 1977). The results of these analyses are presented in Fig. 4.2.

Although the vertical variation of heavy mineral abundance within a till can be a useful indicator of changes in ice flow direction, there are several other possible causes of variation. Some of the more important of these are: (1) exhumation or exhaustion of a heavy mineral source, (2) covering of a source of heavy minerals by sediments, (3) formation of authigenic heavy minerals in the till, (4) depositional changes, (5) glaciotectonic changes during deposition, and (6) weathering (Shilts 1980b).

4.3.2 Regional Patterns

In the Superior heavy mineral zone, cores KP2939, 2836, and 2787 (Fig. 4.2) represent the most clearly defined regional vertical change along the transect. In all three cores pyrite and siderite values increase sharply with depth. Upper samples averaged 2% pyrite and 2% siderite while samples taken in the lower part of the core averaged 14.6% pyrite and 20.8% siderite. The pyrite in the samples from 13 and 13.2m at KP2939 has a framboidal form and is quite distinct from other pyrite grains along the transect. A decrease with depth of the abundance of epidote in all three samples was also noted. The decrease is particularly large at KP2939 (22%). Cores from KP2836 and KP2787 showed decreases of 8% epidote each.

In these cores, the till is dominated by two different mineral assemblages: an assemblage dominated by epidote, garnet, and orthopyroxene in the upper till and an assemblage dominated by siderite, garnet, and pyrite in the lower till. The clearest and strongest distinction between the mineralogy of the upper and lower part of the core in each case can be based on the abundance of pyrite and siderite.

Fig. 4.6 illustrates the results of a detailed study in which pyrite and siderite were used as index minerals to determine the lateral and vertical extent of the lower till. Abundance of pyrite and siderite as percentages of the heavy mineral fraction¹ were determined for 51 samples in 14 cores from the Severn River to the Manitoba-Northwest Territories border (KP3170 to KP2347), a distance of 582 km. Samples from a depth of 5 m or less contain no more than 4% pyrite and 5% siderite. Between 5 and 12 m there is a sharp increase in pyrite and siderite in all cores, and till at depths greater than 5 m contains up to 24% pyrite and 26% siderite. The greatest contrast occurs over the 176 km between KP2939 and KP2787 (Fig. 4.6). Geochemical analysis of the tills through this segment of the transect by Shilts (1980b) also showed that siderite was a major component of the heavy mineral fraction.

Varietal features of the pyrite and siderite, which are peculiar to certain rocks, provide clues to the provenance of the till. Much of the pyrite is in the form of framboidal, fossiliferous, or rounded grains. These forms are characteristic of minerals derived from sedimentary rocks. Henderson (in press) has observed abundant grains of identical form in tills and other bottom sediment overlying Paleozoic rocks beneath Hudson Bay. She has also observed, in similar sediments in the vicinity of the Belcher Islands, high concentrations of the same distinctive botryoidal pyrite observed in the lower tills described above. It is unlikely that any of the varieties of pyrite were formed as authigenic minerals within the till, since the pyrite does not cover other mineral grains; much of it appears to have been broken from larger pieces, and many of the grains are pyritized Paleozoic fossils.

The siderite found in association with pyrite in the lower assemblage occurs as framboidal, botryoidal, globular, and euhedral grains and as composite crystals, often twinned. Skinner (1973) encountered the same variety of siderite in tills of the Moose River Basin. He concluded that the siderite had not formed in the tills but was derived from siderite-filled solution cavities in the Devonian Stopping River and Kwataboahagan formations of the Moose River Basin. Both of these units are present in the Hudson Bay Basin (Fig. 2.2) and likely contain large

1 Includes clinopyroxenes and clinoamphiboles.

Figure 4.6 Variation with depth of pyrite and siderite, Ontario-Manitoba segment

amounts of siderite such as found in the Moose River Basin (Bell 1877, Baker 1911, Bennett *et al.* 1967, Shilts 1980b and others). Varieties of siderite identical to some of those noted in the till have also been observed in amounts of up to 25% in several samples of mature Cretaceous sediments south of James Bay (S. Averill, personal communication). The source of the pyrite and siderite in the lower part of the tills examined in this study is probably the Devonian Stopping River and Kwataboahegan formations under Hudson Bay (Fig. 2.2). Varieties of siderite which resemble those in Cretaceous sediments south of James Bay, may suggest the presence of units under Hudson Bay as well. It is also likely that the absence of these minerals in the upper parts of the core reflects a source in the crystalline rocks of the Shield to the north and north northeast. These rocks would also provide the epidote and orthopyroxene which are more abundant in the upper portion of the tills. Any siderite or pyrite in the upper portion is probably derived from underlying siderite and pyrite-rich tills which have been reworked by the glacier that deposited the upper till.

The ice flow directions implicit in these conclusions are consistent with conclusions on ice flow patterns and till provenance reached by McDonald (1969) and Prest *et al.* (1967) based on drumlins and striations and by Shilts *et al.* (1979) and Shilts (1980a) based on distribution of erratics.

An alternative hypothesis is that the siderite and pyrite are not from the Devonian rocks underlying Hudson Bay, but were formed in the till or some other sedimentary environment. These minerals form under reducing conditions. Reducing conditions can occur when decomposing organic matter on the ocean floor causes depletion of oxygen and development of H_2S . Under such conditions, pyrite or marcasite is formed. Reducing conditions can also occur on land where there is a large accumulation of plant debris. This type of highly reducing environment can lead to the formation of ferrous carbonates such as siderite (Berry and Mason 1959). It is doubtful that these conditions occurred in the till over such a large area as delimited by the occurrence of pyrite and siderite in this study. Furthermore, the mineral's presence in such high concentrations in many of the till and bottom sediments from Hudson Bay (Henderson, in press) makes it difficult to support any hypothesis that states that the siderite or pyrite was formed in a location west (down-ice) of Hudson Bay. It is also significant that authigenic siderite grains do not occur in other tills along the transect, or elsewhere in

Canada (W. Shilts, personal communication 1982; S. Averill, personal communication 1982).

Although the most likely source of the pyrite and siderite is the Devonian rocks under Hudson Bay, the provenance of these minerals cannot be ascertained until identical varieties have been identified in bedrock.

The presence of large concentrations of siderite in rocks underlying Hudson Bay has important economic significance. First, the siderite examined in this study has a high concentration of manganese (Shilts 1980b), (Appendix IV, Fig. 2(b)), a metal which is relatively rare in Canada and is of "strategic" importance. Second, siderite is often precipitated because of the presence of methane gas (Postma 1982). Methane gas is often associated with petroleum.

Northern Keewatin, east of Rae Strait, constitutes the only other area crossed by the transect where vertical variation can be extended laterally. Tills at KP1312 1237, and 1146 show an increase in abundance with depth of rounded garnet grains relative to angular garnets. The rounded and angular grains vary from colourless to red. The rounded grains are characterized by rectangular surface patterns which vary greatly in scale (Appendix IV, Fig. 5). No other differences in the characteristics of the heavy minerals with depth were noted. The minerals from the lower part of the cores are similar to those in the near surface samples described in section 4.2.1. The majority of hematite grains are angular and have a strong metallic luster. Some very well rounded hematite grains with smooth surface texture were also noted. Pyrite grains are similar to those noted in the Superior zone of the transect. They have a granular appearance with some having botryoidal textures, and others occurring as perfect balls. It was also noted that many of the zircon grains in this area are rounded in contrast to the more angular zircon grains observed in other cores along the transect.

There is other evidence that in at least two of these cores there are multiple tills. Shilts (unpublished notes; 1980) has noted two tills separated by a weathered zone at KP1312 and by water-laid silty-sand at KP1146. He further defines these tills by their clay and heavy mineral geochemistry (Shilts 1980b). At KP1312, clay in the upper till is richer in Zn and Fe than the clay in the lower till. At KP1146

the only difference between the two tills is an increase in the amount of Fe in the heavy minerals of the lower till (9.95-13m). The core from KP1237 does not show any textural changes with depth (EBA 1977) nor does it have depositional breaks as in the other two cores. The deepest sample recovered (5.4-5.6m) however, shows a decrease in the amount of Fe in the clay (W. Shilts, unpublished notes).

The characteristics of many of the heavy mineral grains indicate a source in sedimentary rocks. Many garnets, for example, are rounded and in a few cases, attached to pyrite. The rounded garnets show a well-developed rectangular pattern which may be due to the effects of etching by intrastratal solutions (Bramlette, 1929; and Gravenor and Leavitt 1981). Another indicator of sedimentary source is the presence of rounded zircons. And, finally, most of the pyrite grains bear a remarkable resemblance to those noted in the Superior heavy mineral zone where they are thought to be of Paleozoic origin. The most obvious sedimentary source of these minerals is the Paleozoic rocks that surround the Boothia Arch (Fig. 2.2).

Since ice flow was eastward from the proposed M'Clintock Ice Divide (Fig. 2.7) (Dyke, in press) the source of minerals in the lower till would appear to be the Paleozoic rock to the west.

The increase in the proportion of angular garnets in the upper samples however suggests that its provenance is the crystalline rocks to the south. This is consistent with the pattern of deglaciation envisaged by Dyke (in press) for this area.

4.3.3 Local Variations

Several vertical variations, which are limited to one core, can be observed in Fig. 4.6. Two examples of these changes in heavy mineral proportions were investigated and are discussed below.

KP3721

In the southernmost borehole, drilled 30km north of Longlac, Ontario, the relative amount of magnetite increases from 5% at 2.6m in the core to 27% at 5.8m. Titanite drops from 3% in the upper sample to 0% in the lower sample. These are the only known differences between the upper and lower portions of the core. Shilts (unpublished notes) did not find any differences with depth in texture and colour of the till or geochemistry of the clays.

Figure 4.7. Provenance of heavy minerals on the basis of bedrock lithology and ice flow direction.

certain if these rocks extend as far as the location of the borehole. Much of the area near KP1850 and as far as the known outcrops of the Christopher Island Formation, is drift covered and the geology largely unmapped (Blake 1980). Immediately north and northwest of the site the basement is exposed and there are few Dubawnt Group outcrops.

Studies of ice-inscribed and ice-moulded features by Fyles (1955) and Cunningham and Shilts (1977) show that in the area of KP1850 ice flow was southeastward, west, or northwestward depending on the position of the eastward moving ice divide (Fig. 2.4). Southeastward flowing ice would have carried detritus from basement rocks to the north and would not likely have contained barite. A shift in the ice divide could have resulted in westward or northwestward flow which might have carried detritus containing barite from some nearby source in Christopher Island Formation rocks. Another possibility is that the change in abundance in barite simply represents a local shift in ice flow direction from a source of barite not associated with the Christopher Island Formation. Nevertheless, this well defined, and easily observed, vertical variation in abundance of a heavy mineral which is often associated with economic minerals such as uranium, tin, and tungsten could have potential as a prospecting tool.

4.4 Regional Synthesis of Provenance and Ice Flow Patterns

Fig. 4.7 illustrates the probable sources of heavy minerals and heavy mineral assemblages observed in cores along the transect. Ice flow patterns that can be interpreted from heavy mineral provenance alone are consistent with the multidome reconstruction of Central North America ice sheet (Tyrrell 1898; Shilts 1980a; Dyke *et al.* 1982; Andrews 1982) rather than the single dome theory (Flint 1943; Hughes *et al.* 1977). The heavy mineral results also support the reconstruction of ice flow patterns in Northern Keewatin and Boothia Peninsula proposed by Dyke (1982).

In the lower tills of the Superior heavy mineral zone, the high proportion of pyrite and siderite indicate provenance from Paleozoic rocks underlying Hudson Bay. There is also a limited amount of these minerals in the Churchill heavy mineral zone south of the Seal River (Fig. 4.1). In tills of the Churchill zone north of the Churchill River and the Dubawnt zones, however, there is no siderite to indicate ice flow from Hudson Bay. Instead, in the Churchill zone, a high proportion of hypersthene indicates ice flow towards the south from hypersthene-rich charnockites to

Figure 4.7. Provenance of heavy minerals on the basis of bedrock lithology and ice flow direction.

the northwest. In the Dubawnt zone, high concentrations of hematite indicate ice flow from the Proterozoic Dubawnt red beds that lie to the northwest. On Coats Island, analysis of one till sample shows that there is siderite and pyrite (4% and 18% respectively) which are of the same variety as those in cores from KP3170 through KP2610. The presence of these minerals would suggest transport from the centre of Hudson Bay. These results clearly support Shilts' model (Fig. 2.6) as well as the alternative model of multidomed glaciation suggested by Dyke *et al.* (1982) (Fig. 2.7). There is, nevertheless, evidence that favours the former of these models. The presence of many grains of botryoidal pyrite, of a distinctive character identical to grains found in abundance in tills and other bottom sediments of Hudson Bay near the Belcher Islands by P. Henderson (personal communication, 1982), would suggest that ice flow was, as Shilts (1980a) has proposed, from a centre over Nouveau Québec-Labrador, and not as Dyke *et al.* suggest, from a local centre over the southwestern end of Hudson Bay.

The increases in epidote and decreases in pyrite and siderite in the upper 5m of the till between the Severn and Churchill rivers in the Superior heavy mineral zone indicate that the source of this till was crystalline rocks to the north and that ice flow was likely moving as speculated by Shilts (1980a), from the northwest during the later stages of glaciation.

In the southern part of the Northern Keewatin heavy mineral zone, the absence of hematite indicates that ice did not flow from the south. Other ice flow indicators such as directional landforms and features, show that ice flow was from an essentially north-south ice divide (Craig 1961) which is consistent with the heavy mineral results.

In the northern part of the Northern Keewatin zone, the abundance of rounded garnet grains, many of which were possibly affected by intrastratal solution, and rounded zircons, in all but the uppermost levels of the tills indicates provenance from sedimentary rocks that lie east and west of most of this segment of the transect. These results agree with Dyke's (in press) suggestion that ice flowed east from an ice divide over M'Clintock Channel which is underlain by Paleozoic sedimentary rocks. The increase of angular garnets relative to rounded garnets in the uppermost samples from cores taken east of Rae Strait may reflect northward

ice flow from the Keewatin Ice divide during late deglaciation, an event also suggested by Dyke (in press).

In the Boothia heavy mineral zone the provenance of the abundant rounded zircons and garnets appears also to be the Paleozoic sedimentary rocks to the east.

It is clear from the reconnaissance study described above that several problems of provenance and ice flow direction can at least be partially solved on the basis of heavy mineral analysis. The heavy mineral results also proved useful in providing new evidence to help resolve the multidome and single dome arguments.

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diamonds, one grain can be of great geological significance. At KP1787 the presence of a grain of gold is, therefore, quite interesting, particularly since other evidence suggests mineralization in the environs.

Minerals associated with economic mineralization can also be useful. The barite noted at KP1850 may well be from fracture fillings in which barite is associated with pitchblende. Pitchblende, because it is fine grained and extremely mobile in an oxidizing environment, is not likely to be present among sand-sized heavy minerals. Therefore, barite may possibly serve as a mineral "pathfinder" for uranium mineralization.

5.2 Recommendations

The study of many of the problems described here could be furthered with more detailed sampling programs. They could also benefit from approaches that are better tailored to individual problems. But perhaps the greatest consideration for further understanding of the results is a greater knowledge of the bedrock, and the accessory minerals that it has likely contributed to the till. This could be partly accomplished through studying the mineralogy and origin of the pebbles in the till.

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APPENDIX I

Geographic Coordinates of Boreholes

Kilometer post	Polar Gas notation	Geographical coordinates (to nearest 10")
3721	3-1-1	50°01'00"N, 86°39'00"E
3538	17-2-1	51°04'30"N, 88°29'00"E
3471	21-2-1	51°28'30"N, 89°10'00"E
3414	26-1-1	51°52'30"N, 89°40'00"E
3275	35-2-1	52°52'30"N, 90°31'40"E
3170	44-2-1	53°38'00"N, 91°17'00"E
3150	45-2-1	53°46'00"N, 91°27'30"E
3093	49-2-1	54°08'45"N, 92°03'00"E
2939 b	R59-1-4	55°27'00"N, 92°38'00"E
2939 a	R59-1-5	55°27'00"N, 92°38'00"E
2836	R65-4-3	56°12'00"N, 93°32'00"E
2844	R67-1-2	56°25'20"N, 93°57'00"E
2787	R68-1-1	56°32'30"N, 94°00'00"E
2610	80-3-5	58°00'00"N, 94°55'00"E
2536	R85-3-1	58°23'30"N, 95°50'00"E
2442	91-1-2	59°08'20"N, 96°21'30"E
2421	92-1-1	59°18'00"N, 96°27'00"E
2364	96-5-1	59°45'50"N, 96°55'00"E
2347	98-3-1	59°54'50"N, 96°59'00"E
2226	106-3-1	60°57'45"N, 97°02'30"E
2176	109-2-1	61°21'00"N, 96°45'00"E
2087	116-3-1	62°05'30"N, 96°50'00"E
1966	124-1-1	63°07'00"N, 97°05'00"E
1871	129-1-1	63°54'00"N, 96°52'00"E
1850	131A-1-1	64°06'00"N, 96°47'00"E
1819	133A-4-1	64°20'00"N, 96°33'45"E
1803	K134-2-1	64°20'10"N, 96°32'30"E
1787	135-1-3	64°36'25"N, 96°28'00"E
1703	142-3-1	65°18'00"N, 96°05'00"E

APPENDIX I (cont'd)

Kilometer post	Polar Gas notation	Geographical coordinates (to nearest 10")
1621	147-1-1	65°58'15"N, 95°43'00"E
1540	152-4-1	66°38'10"N, 94°56'30"E
1394	162-4-1	67°51'00"N, 93°53'00"E
1384	RI63-3-2	68°00'30"N, 93°41'30"E
1312	166-2-1	68°25'45"N, 93°15'00"E
1325	RI66-2-1	68°21'45"N, 92°50'20"E
1237	RI71B-3-2	69°03'45"N, 93°14'00"E
1146	177-4-1	69°51'15"N, 93°34'00"E
1119	180-3-1	70°04'00"N, 92°47'00"E
1044	185-6-1	70°44'00"N, 94°18'00"E
645	211A-4-1	74°04'30"N, 94°22'00"E

APPENDIX II

Description of Heavy Minerals

ANATASE 3.9 s.g.¹ EDS²

Rounded to subangular, very light to medium blue, adamantine lustre.
Some grains show octahedral form. Very rare; found only at KP645.

BARITE 4.5 s.g. EDS: yellow-brown S Ba Si - Al - K Ca

Subangular to subrounded, clear, vitreous lustre, close match to refractive index of Araldite. Some varieties have a feathery appearance or earthy texture and are yellow-brown or off-white (Appendix IV, Fig. 3).

BRONZITE 3.3 - 3.5 s.g. EDS: Si - Fe Mg Al - K Ca

Variety of hypersthene. Prismatic, flattened parallel to (100) or (010), colourless to pale brown and pale green (core), perfect cleavage at about $97 - 88^\circ$, fair cleavage parallel to (100) and 101). Can be distinguished from other varieties of hypersthene by the presence of Schiller structure which is due to dark brown-bronze blade-like inclusions parallel to either the C or B axis. Attempts to determine the EDS of these inclusions were unsuccessful.

CHLORITOID 3.3 - 3.6 s.g. EDS: Al Si - Fe - Mg K

Tabular to flake-like, perfect cleavage, may have a sugary texture, and is light to bottle green. A flake-like grey variety with sugary texture has also been identified.

1 s.g.: specific gravity

2 EDS: Fe Si - Al Mn Ca - P Ti: X-ray energy dispersive spectra:
major elements - minor elements - trace elements.

APPENDIX II (cont'd)

DIOPSIDE 3.5 - 3.6 s.g. EDS: Si Ca - Mg Fe - Al Na

Perfect prismatic (110) cleavage at about right angles, angular to rounded, very pale green to dark "bottle green", vitreous lustre.

EPIDOTE 3.4 - 3.5 s.g. EDS: Si Al Ca - Fe

Angular to rounded, parallel cleavage, step-like fracture, very pale yellow to pistachio green, vitreous lustre to pebbly texture, translucent to cloudy, rarely euhedral.

GARNET

Almandine 4.1 - 4.3 s.g. EDS: Si Al - Fe Mg - Ca Mn

Angular to rounded, conchoidal fracture, rarely euhedral, colourless to dark red, translucent, vitreous to adamantine lustre. Rounded grains often have frosted features composed of geometrical shapes (Appendix IV, Fig. 5).

GOETHITE 4.3 s.g. (approx.) EDS: Fe - (Si, Al, K, Ca, Mg,)

Angular to euhedral (pseudomorphs after pyrite: cubic, octahedron, striated cubes) botryoidal, yellow to dark brown, red, earthy texture to resinous lustre.

HEMATITE 5.2 s.g. EDS: Fe

Angular to well rounded, flaky, botryoidal, rarely euhedral, dull to metallic grey, red, earthy texture to metallic lustre, pebbly to smooth texture (Appendix IV, Fig. 1).

APPENDIX II (cont'd)

HORNBLende 3 - 3.5 s.g. EDS: Si - Al Ca Fe Mg - Ti K Na

Prismatic, angular to rounded, perfect cleavage (124°), irregular fracture which is often step-like, very dark green (almost black), vitreous lustre.

ILMENITE 4.4 - 4.8 s.g. EDS: Ti Fe - - Mn

Orthorhombic (rarely euhedral), angular to rounded, conchoidal fracture, opaque, black to brown-black, metallic to vitreous lustre; often in part altered to leucoxene. Ilmenite may be confused with hematite, though the latter has a red streak as well as a subtle difference in texture of rounded or angular grains.

KYANITE 3.6 - 3.7 s.g. EDS: Al Si - -

Perfect pinacoid, (100) and (010) (001) parting (nearly at right angles) resulting in step-like cross cleavage, colourless (rarely stained grey, yellow, khaki, or red), may occur as long deformed or fibrous grains.

LEUCOXENE (alteration product)

3.5 - 4.5 s.g. EDS: white, Ti - Si Al Fe - Mg
grey, Si Ti (Ca) - Al Ca (Fe) - Fe
brown, Ti - Fe - Mn Si Al

The composition of this material is variable.

Often occurs as pseudomorphs of ilmenite, titanite, rutile, or anatase, angular to rounded, conchoidal to irregular fracture, easily crushed, opaque. Off-white to grey, cream-yellow, tan to chestnut brown, matte texture to varnished lustre.

APPENDIX II (cont'd)

MAGNETITE 4.9 - 5.2 s.g. EDS: Fe -

Octahedral, angular to rounded, some grains euhedral or with some crystal faces, sub-conchoidal to conchoidal fracture, may be twinned, black. Highly magnetic, grains are attracted to the dissecting needle and form a network of attached grains when placed on a glass slide.

MONAZITE 5 - 5.3 s.g. EDS: P - Ce La Th -

Tabular parallel to (100), perfect basal (001) cleavage good (100) and imperfect (010), most often occurs as broken angular to equidimensional well rounded grains, transparent to turbid, yellow to orange (often mottled with red), high relief (even under binocular microscope), resinous lustre.

OLIVINE 3.2 - 3.4 s.g. EDS: Mg Si - Fe

No olivine grains were noted in samples from the study area. Olivine grains from a till sample taken from a section on the Samson River, Québec have the following characteristics: angular to rounded, transparent, colourless, vitreous lustre. Often characterized by a step-like texture and by overgrowths that result in jagged terminations.

ORTHOPYROXENE

hypersthene 3.4 - 3.7 s.g. EDS: —

Orthorhombic; prismatic, flattened; good 90° cleavage; irregular fracture or fracture along cleavage; rarely rounded; transparent; light to dark khaki or varying degrees of yellow; vitreous to waxy lustre.

APPENDIX II (cont'd)

PYRITE 4.9 - 5 s.g. EDS: S - Fe -

Cubes and pyritohedra, often striated, conchoidal fracture, rare penetrating twins or iron cross, opaque, metallic lustre pale brass-yellow, often tarnished or covered with goëthite or quartz. May occur as multicrystalline aggregates, botryoidal, framboidal or polyframboidal grains.

PYRRHOTITE 4.5 - 4.9 s.g. EDS: S - Fe -

Tabular to platy crystal form (rare), angular to sub-rounded, irregular to sub-conchoidal, opaque; brass-yellow, metallic lustre, magnetic.

RUTILE 4.2 - 5.5 s.g. EDS: Ti - -

Grains often elongated prismatic forms with rounded pyramidal ends, angular to rounded, oblique groove or rounded step common; translucent to nearly opaque, orange-red to deep cherry-black, very high relief.

SIDERITE 3.9 s.g. EDS: resinous brown-orange,
Fe Si - Ca Mn Al - Mg
light brown framboidal,
Fe Si - Al Ca - Mn P

Crystalline aggregates (framboids); botryoidal, globular, and spherulitic masses, rarely euhedral (rhombohedral); acicular, fibrous grains; rounded grains with sugary texture; some grains are twinned. Colour varies from pale tan to grey to brown-orange. Transparent, turbid or opaque. Vitreous, to resinous lustre or earthy texture.

APPENDIX II (cont'd)

CHROME SPINEL 5 s.g. EDS: Cr Fe - Al - Mg

Angular to rounded, concoidal fracture with associated rib features, nearly opaque (thin edge often translucent deep burgundy red), black, adamantine lustre, non-magnetic.

STAUROLITE 3.6 - 3.8 s.g. EDS: Al Si - Fe - Mg

Angular, rarely rounded, irregular to sub-conchoidal fracture, vitreous lustre, candy orange, transparent. Can be distinguished from titanite by its low birefringence.

TITANITE (Sphene) 3.4 - 3.5 s.g. EDS: Si Ca Ti - - Fe Al

Wedge or envelope shaped, angular to rounded, sub-conchoidal to concoidal fracture, yellow to bright orange, translucent, vitreous lustre. May be partially altered to leucoxene. Can be distinguished from staurolite by high birefringence.

ZIRCON 4.6 - 4.7 s.g. EDS: Zr Si - -

Tetragonal, short to long prisms with pyramids; euhedral to well rounded; transparent; adamantine lustre (particularly in colourless varieties); very high relief; colourless, yellow, orange, red, brown; fine zoning, fractures, and rod-shaped inclusions common.

Figure 4.2 Heavy mineral diagram of vertical variation in cores. +, 3%, x, 7%, —, 1% (when above a bar, these symbols represent the subclass).
+ .05% weight of heavy minerals, + .05% weight of 63-250µm fraction

APPENDIX III

Results of point counts of heavy minerals
on replicates samples from 3 cores

SAMPLE	MINERAL	RANGE OF VALUE % (3 duplicates)	MEAN	s.d.	PROBABLE ERROR	
					Binomial $PE_{95} = 2\sqrt{P(100-P)/N}$	Poisson $PE = P$
KP1044	goethite	0 - 0.4	0.2	0.2		0.4
	leucoxene	0.4	0	0		0.4
	zircon	0 - 0.9	0.9	0.9		0.9
	hematite	1.0- 3.0	2.0	1.0		2.0
	epidote	2.0- 4.0	3.0	1.0		3.0
	ilmenite	3.0- 7.0	5.0	2.0	2.0	
	orthopyroxene	11.0-14.0	12.5	1.5	3.1	
	garnet	63.0-70.0	67.0	3.5	4.4	
KP2347	zircon	0.4- 1.0	0.7	0.3		0.7
	titanite	0 - 0.7	0.7	0.7		0.7
	goethite	0.4- 0.7	0.5	0.2		0.5
	leucoxene	0.2- 0.9	0.5	0.2		0.5
	hematite	12.0-15.0	13.0	1.3	3.4	
	epidote	8.0- 9.0	8.5	0.5	2.6	
	orthopyroxene	13.0-20.0	16.5	3.5	3.5	
	ilmenite	9.0-15.0	12.0	3.0	3.0	
	garnet	20.0-26.0	23.0	3.0	3.9	
KP3093	kyanite	0.2	0.2	0		0.2
	siderite	0.4- 0.7	0.5	0.2		0.5
	leucoxene	0.4- 0.7	0.5	0.2		0.4
	pyrite	0.7- 3.0	1.8	1.1		1.8
	ilmenite	3.0- 4.0	3.5	0.2		3.5
	titanite	1.0	1.0	0		1.0
	zircon	0.7- 1.0	0.8	0.2		0.8
	hematite	11.0-12.0	11.5	0.5	3.0	
	garnet	14.0-19.0	16.5	2.5	3.5	
	orthopyroxene	12.0-13.0	12.5	0.5	3.1	
	epidote	34.0-35.0	34.5	0.5	4.5	

PLATE 1

1967

Figure 1. Glacially abraded sandstone pebbles with specular hematite clasts. Tulawnt Group.

Figure 4.2 Heavy mineral diagram of vertical variation in cores. +, 3%; x, 7%; —, 1% (when above a bar, these symbols represent the subclass).
 †, 0.5% weight of heavy minerals; ‡, 0.5% weight of 63-250µm fraction

Figure 3. SEM micrograph of striated barite grain from KPl871 (Shilts, unpublished).

Figure 4. SEM micrograph of feathery textured (plumose) barite grain from KPl871 (Shilts, unpublished).

Figure 5 (a). SEM micrograph of a garnet grain which shows a well-developed rectangular etch pattern, KP1119.

b). SEM micrograph of a garnet grain which shows a well developed rectangular etch pattern, as well as, a relatively unaffected surface. This image would appear to preclude the possibility of the texture being a result of overgrowth.

Figure 6(a). Heavy mineral fraction of till sample from KP2836 (2.5m) viewed through stereoscopic microscope (100X). Yellow-green grains are epidote.

Figure 6(b). Heavy mineral fraction of till sample from KP2836 (9.5m) viewed through stereoscopic microscope (100X). Brown, turbid grains are siderite. Brass-yellow, metallic grains

Figure 4.2 Heavy mineral diagram of vertical variation in cores. 0.3%, x, 0.7%, 1.0% (when above a bar, these symbols represent the subclass) 1.0% weight of heavy minerals, 0.3% weight of 63-250µm fraction

Figure 4.1. Heavy mineral diagram of near surface samples. * 3% x, 7% —, 1% (when above a bar, these symbols represent the subclass) †, as % weight of heavy minerals; ‡, as % weight of 63-250µm fraction; §, alluvium

END

1	2	1	0	9	1	8	4
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FIN