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**The Origin of Drumlins at Bernard Harbour,
District of Mackenzie, N.W.T., Canada**

by

Marion B. Potschin

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

Department of Geography
Carleton University
Ottawa, Ontario
December 24, 1989

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"The origin of Drumlins at Bernard Harbour,
District of Mackenzie, N.W.T., Canada"

submitted by Marion B. Polschin
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in partial fulfilment of the requirement for
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Abstract

This thesis examines the Bernard Harbour drumlin field in the Northwest Territories of Canada. It is based on field work, air photo interpretation and sedimentological and morphological analysis. The findings include:

- 1) Sediment composition indicating lodgement deposition processes operating prior to drumlin forming events;
- 2) the till fabrics indicate a lodgement rather than melt-out origin;
- 3) the drumlins were formed under stagnant rather than active ice;
- 4) the mode of formation appears to have been by subglacial fluvial processes (Shaw, 1983; Shaw and Freschauf, 1973);
- 5) identification of two-dimensional wave-like forms and six distinct morphologic zones within the drumlin field.

Acknowledgements

Canada, a country which has always piqued my curiosity.

In the summer of 1986 I had an opportunity to do fieldwork in the Canadian Arctic for my MA in Geography back in Germany. That year, the field group under the leadership of Dr. Denis A. St-Onge, Geological Survey of Canada, went north to map the Quaternary genesis of the Bluenose Lake Region, District of Mackenzie. In the summer of 1988 the Canadian Arctic and the same field party called me back, this time to the neighbouring region to the east, the Bernard Harbour area.

I thank Dr. Denis A. St-Onge for initiating the thesis topic and for providing logistic support. Many people have contributed to this study. The 'Drumlin City' field group (Denis St-Onge, Ron Avery, Daniel Kerr, and Isabelle McMartin) were generous with their support in the field and were stimulating in their discussions with the author. Back in Ottawa, Isabelle McMartin kept me 'up to date' with the results of the recent 1989 field work in the Bernard Harbour area.

At Carleton, most of all, I would like to express my deepest thanks to my supervisor Dr. Peter Johnson for taking so much time off to discuss both the thesis and the meaning of life. Without his guidance and advice through my studying time at Carleton the whole task would have been much more difficult.

I am indebted to my roommate and friend Diane Spivey, and Stephen Winn, both Graduate Students in the Geography Department Carleton, for their gentle and constructive criticism of my thesis.

I also would like to thank Dr. John Shaw, Queen's University, Kingston, and David Sharpe, Geological Survey of Canada, Ottawa, for their invaluable discussions on the origin of drumlins.

I dedicate this thesis to the Canadian Arctic in hope that humans will not be able to destroy this beautiful landscape.

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C h a p t e r I

I n t r o d u c t i o n

Anyone with an interest in glaciated terrain or glacial landforms is aware of what might be termed "The Drumlin Problem". Perhaps, no other landform has created such fascination and enigmatic interest. Over a hundred years has gone by since the term drumlin was first enunciated, yet the research and literature pertaining to these landforms continues to grow. Often termed collectively as "swarms" or "basket of eggs topography" drumlins draw interest beyond the field of earth science, with poets and novelists proclaiming their flowing lines and sculptured shapes. The academic interest in drumlins is, in many ways, an illustration of the changing field and nature of glacial studies. From the early ventures of Bryce and Close to our present period of understanding of glaciers and subglacial mechanics much remains unknown.

(Menzies, 1984:v)

The geographical literature, as we will see in section 1.1.3 has dealt in detail with most aspects of drumlin distribution and morphology, but the process of formation has never been satisfactorily explained. The proposed answers given in this study to some of the still remaining questions on the origin of drumlins are based on field studies by the writer, the subsequent necessary laboratory work, and an intensive review of the relevant literature conducted before and after the fieldwork. Discussions with investigators who hold opposing views are also included.

What is a 'drumlin'

According to Shepps (1968:293) in Fairbridge's 'Encyclopedia of Geomorphology' a drumlin is

a smooth, stream-lined, dome-shaped hill formed beneath flowing glacial ice. Drumlins have the shape of an inverted spoon elongated in the direction of ice movement with the long gentle slope pointing in the direction toward which the ice moved... Drumlins are built of fine-grained till and in some places have a rock core.

Drumlins vary widely in shape, size and symmetry. They may appear as well-defined elliptical hills or grade to irregular mounds of drift, scarcely different from ground moraine. Extreme forms may be nearly circular or greatly elongated, such as those identified by Lemke (1958). All these features, regardless of their size and shape, have in common a definite streamlined configuration, indicating their formation by a moving medium. The dimension of drumlins vary from 0.1 to 7 km in length and 50 m to 2 km in width, with a height range of 1 to 120 m. The length-width ratio is the most common index of drumlin shape (Lemke, 1958). Normally, the ratio is about 2.5:1, extending up to 3 or 4:1 (Embleton and King, 1975:404).¹

Figure 1 indicates that drumlins are generally elliptical and bear a resemblance to stoss and lee features (crag and tail). However, unlike most *rôches moutonnées*, the

¹Detailed information about the morphometry of drumlins will be provided in Section 5.1 of this study.

stoss (up-glacier or proximal) end of the drumlin is usually higher, steeper and wider than the lee or distal end.

Figure 1: Streamlined glacial landforms (Dionne, 1987:150)

Dionne (1987) discusses in detail the terminology of drumlins and its misinterpretations. His conclusions are summarized in Figure 1.

1.1. Previous work on the origin of drumlins

Theories of drumlin formation have been intensively reviewed by Charlesworth (1957), Gravenor (1953), and more recently by Muller (1974), and Embleton and King (1975) (Miller,

1972:418).

The origin of drumlins is a controversial subject which has been known as 'The Drumlin Problem'. That it is becoming a more interesting subject in glacio-geomorphological research is demonstrated in a bibliography by Menzies (1984) which lists over one thousand references on this topic. Brief overviews on the more important and recently published literature are offered by Sharpe (1985) and Shaw et al. (1989).

A symposium focusing specifically on drumlins² and a whole edition of the journal Sedimentary Geology dedicated to drumlin research (Menzies and Rose, 1989) attest to the fact that Quaternary Scientists feel the urge to solve this question of the origin of drumlins.

1.1.1 Development of drumlin research

Although recognition of depositional activity of glaciers occurred in the late 18th century, it is only within the last 100 years that the study of till has generated much interest. The work of Geikie (1863), Chamberlin (1894) and many of their contemporaries did much to build the foundation of till studies, a precursor of drumlin research.

²Held in Manchester, 16-18 September, 1985, and published under Menzies and Rose (1987).

An overview of the more important landmarks of drumlin research since late in the nineteenth century is suggested below in the contributors' own words.

The term drumlin was introduced by Bryce in 1833 (Flint, 1971:101; Menzies 1984:xi) in his work on Ireland. The term seems to go back to the Irish Gaelic word for hill - "druim". However, it is generally believed that the introduction of the word 'drumlin' into the glacio-geomorphological literature can be attributed to Maxwell Close (1867) who also studied drumlins in Ireland. Menzies (1984: xi), summarizes the early work on drumlins as follows:

- Hypotheses on drumlin origin in the latter half of the nineteenth century that gained some general acceptance were:
- a) formation based upon the overriding of proglacial and/or previous glacial deposits (e.g. Shaler, 1888; Upham, 1892);
 - b) formation due to subglacial debris becoming "lodged" at the glacier sole due to reduced plasticity within the lower ice causing differential sliding and overriding taking place (e.g. Russell, 1895);
 - c) formation as the result of differential pressures at the ice-glacier bed interface resulting in differential erosion and/or subglacial debris traction (e.g. Davis, 1884, Geikie, 1874).

By the turn of the century it was generally believed that drumlins were formed by actively moving ice, which modified material either incorporated in situ or from pre-existing glacial material.

The drumlin research of the first half of the 20th century was dominated by Alden (1905, 1911), Fairchild (1907, 1911, 1929), Ebers (1926, 1937), and Slater (1928, 1929)³. Alden who studied drumlins in Wisconsin, provided major contributions on the process of formation, morphology, internal composition and structure. Fairchild proposed, on the basis of fieldwork in the New York drumlin field the "accretional theory" hypothesizing that drumlins develop by progressive lodgement on some commonly unrecognized core or nucleus (Muller, 1974:189). Ebers's comprehensive study of the shape and size of drumlins was based on European drumlins. It extended the one sided research in North America. A new period of drumlin research began with Gravenor's research on drumlins in Canada (Gravenor, 1953). His paper was one of the first post-war reviews of drumlin formation hypotheses and as such remains a landmark. His thoughts are summarized in this abstract:

Theories on the origin of drumlins are grouped as either depositional or erosional ... The fact that many drumlins have a small amount of clay and contain stratified materials makes the depositional theory untenable. It is believed that a modification of the erosional theory will fit the known facts on drumlins.
Gravenor (1953:674)

³As cited in Menzies (1984).

Despite the fact that scientists could not agree on one process of formation - depositional or erosional or a combination of both, it was generally believed that drumlins were formed under actively flowing ice and "their form is one which offers the least resistance to ice movement" (Gravenor, 1953:678). A 'descriptive approach on drumlin research' followed. Thus, Kupsch (1955:336) postulated that

...roches moutonnées, crag and tail, rock drumlins, drumlins with till cores would form one series, all composed of modified nuclei with no, a little, or much glacial material lodged on their lee side.

Chorley's (1959) major contribution to drumlin research was his statement on the relationship of drumlin shape to ice pressure and velocity, and till shear stress. His meaningful interpretation of the shape of drumlins was given in the form of an equation:

$$k = \frac{l^2 \cdot \pi}{A}$$

where l is the length of a drumlin's long axis and A is the area of its ellipsoid (Chorley, 1959). This equation is preferred by some authors (e.g., Smalley and Unwin, 1968: 381; Flint, 1971:101) over the one given by Reed et al. (1962):

$$\frac{x^2}{a} + \frac{y^2}{b} + \frac{z^2}{c} = 1.^4$$

⁴In areas like Eastern Ontario or Bernard Harbour area these techniques have uncertain values because only the top, not the whole feature can be measured, since the lower part is buried under younger sediments or lakes. Since most morphometric studies like these are made from topographic maps, it means one should know something about the stratigraphy before proceeding.

Reed et al. produce an ellipsoid with its centre at the origin; a, b, and c are the semi-axes and x, y, and z are the rectangular coordinate direction. Their research on drumlins generated measurements of distribution, orientation and spacing between drumlins; it also dealt with the form of the drumlins.

The paper by Smalley and Unwin (1968) marks the beginning of the "geotechnical approach to drumlin research" (Menzies, 1984:76) and was used in the next decade as the seminal work⁵. The abstract of Smalley and Unwin's (1968:377) paper, introducing the 'dilatancy' hypothesis, reads as follows

If glacial till contains more than a certain minimum boulder content, it is dilatant and requires a much larger stress to initiate shear deformation than to sustain it. If the stress level at the glacier-terrain interface drops below a certain critical level, or till reaches its critical boulder-content density, then the till beneath the glacier packs into stable obstructions. These are shaped into streamlined forms by the glacier and are found distributed at random in drumlin fields. Due to drumlin coalescence there is a normal distribution of drumlin axes about the direction of ice movement.

Smalley and Unwin (1968:377)

⁵"The classical hypothesis" is in contrast to the "alternative hypothesis" developed by John Shaw in 1983. This topic will be discussed in more detail in Section 1.1.2.

However, this view was questioned by numerous researchers and even Smalley in time modified his early ideas. Thus

The 'dilatancy' hypothesis (Smalley 1966, Smalley & Unwin 1968) sought to explain the formation of the characteristic low smooth hills of a drumlin landscape by invoking certain critical stress levels which affected the deformation of the till, typically under the thinning ice sheets of the continental glaciation. ... We propose, in this paper, that although the basic idea of critical stress levels can still have validity, the actual dilatant nature of the ground material is not strictly required.

(Smalley and Piotrowski, 1987:81)

Lundqvist (1970) has noted the similarity of drumlins and erosional forms, such as 'sichelwannen'⁶.

Flint (1947) argued that drumlins were formed by the erosive activity of ice, but later he supported the 'depositional theory' (Flint, 1971).

Shaw and Freschauf (1973) and Aario (1977) used the concept of secondary flow⁷ (helical) to explain drumlins/ flutings. While Shaw and Freschauf developed their theory in Canada, Aario worked independently in Finland. The difference between them is how this secondary flow is initiated. Shaw and

⁶"Features similar in form to rat tails also occur on a variety of bedrock types. Sichelwannen (Dahl 1965) occur commonly on felsic intrusive rocks of the Canadian Shield... Such sichelwannen are about 1-2m in width. Furrows extend for 2-3 m and are a few tens of millimetres deep" (Shaw and Sharpe, 1987:2318). These authors also provide pictures of these features; they will be discussed in Chapter 5.

⁷The relation between secondary flow and primary flow (unidirectional current) is illustrated in Figure 4.

Freschauf suggested that the spiral flow in the basal ice which accounts for drumlin formation was formed by melting-out of debris previously carried up into the ice by spiral flows (Boulton, 1987:76), while Aario believed that the spiral flow was caused by movement of subglacial sediment into the drumlin ridges. Both theories contributed to Shaw and Sharpe's (1987) 'glaciofluvial erosional hypothesis', which will be discussed in more detail in the following chapter.

Muller (1974) discussed in detail 1960's research on drumlin origin and morphometry. Although his research was not based on field work he developed the idea that the "drumlin form is affected by protrusion in the glacially overridden topography and by character and abundance of glacial load" and "till fabric analyses indicate depositional modification of such drift cores by accretion..." (Muller, 1974:187).

Clayton and Moran (1974), on the other hand, presented evidence of erosion rather than deposition and found support from Goldthwait (1974).

A second group of theories has been developed since 1983 (Boulton 1987:76). "As an alternative explanation, it has recently been proposed that the formation of some drumlins involved subglacial fluvial processes" (Shaw et al. 1989:177).

Dardis and McCabe (1983), who worked in Ireland, suggest that glacial deposition in subglacial cavities plays an important role in drumlin formation. However, they do not believe that the shape of the drumlins was produced by meltwater, but "only that stratified sediment within drumlins was deposited by subglacial flood events, with the form being subsequently moulded by ice " (Shaw et al. 1989:177).

Shaw (1983) and Shaw and Kvill (1984) assert that the drumlins they studied in Saskatchewan "were formed directly by subglacial meltwater that first eroded cavities into overlying ice and subsequently infilled these cavities during declining flow" (Shaw et al. 1989:177/78). The subglacial meltwater theory can be divided into the glaciofluvial depositional hypothesis, developed by Shaw (1983) and supported by Shaw and Kvill (1984) and Sharpe (1987), and the glaciofluvial erosional hypothesis suggested by Shaw and Sharpe (1987). Shaw and Sharpe (1987:2316) argued that "drumlins might also form as remnant ridges resulting from erosion of the glacial substrate by subglacial meltwater sheets" (Shaw and Sharpe, 1987:2316).

Since 1969, Boulton has been working on till fabrics and genesis, and in 1979, 1982, and 1987 he made major contributions to drumlin research.

This chapter can be summarized with a quote from Boulton (1987:31).

Several major sets of processes have been invoked to account for the origin of drumlins and related forms, of which the following are current:

1. Drumlins as the product of subglacial deformation (Smalley & Unwin 1968, Evanson 1971, Boulton 1982).
2. Drumlins as the product of subglacial lodgement (Fairchild 1907, Boulton 1982).
3. Drumlins as the product of melt-out of basal debris-rich ice (Shaw 1980).
4. Drumlins as fluviatile infillings of subglacial cavities (Shaw 1983, Dardis and McCabe 1983).

He also provides an overview of recent theories on drumlin formation⁸, which he divided into two groups. Thus:

There are two principal groups of drumlin formation theories; those which assert that drumlins are produced by glacial transport of bed material or basal debris, and those which assert that they are intimately related to subglacial fluvial activity.

Boulton (1987:74)

Jones (1982), too provides a good analysis of the theoretical debate among drumlin researchers.

Figure 2 on the following page summarizes the attention given in the literature to drumlin research over the last 200 years.

⁸ For more information see Boulton (1987:74-78).

Several periods of drumlin research can be recognized. They are:

- ☐ Formation due to subglacial debris becoming 'lodged' at the glacier sole due to reduced plasticity within the lower ice and leading to differential sliding and overriding
- ☐ Formation based upon the overriding of proglacial and/or previous glacial deposits
- ☐ Formation as a result of differential pressure at the ice-glacier bed interface resulting in the differential erosion and/or subglacial debris traction
- ☐ Period of the ideas of Fairchild, Ebers, and Alden
- ☐ 'New Phase' in drumlin work following the publication of the work in Canada of Gravenor (1953)
- ☒ Periods since 1953. Descriptive accounts of drumlins continue to appear
- ☒ The analysis of till fabrics from drumlins has led to further understanding of drumlin sediments and to several hypotheses of formation

Figure 2: Histogram of published papers on drumlins (1815-1984), modified according to Menzies (1984)

1.1.2 Introduction to the 'alternative theory'

Sharpe (1988: 274/5) considers 'the classical interpretation of drumlins' to be the "conventional hypothesis" and the recent one, developed by Shaw (1983) as "the alternative view". The writer accepts this view.

Sharpe (1985:370) also offers a brief but comprehensive discussion of streamlined features and shows the discrepancy between his findings about the drumlins on Victoria Island and the existing conventional hypothesis⁹. He finds a more appropriate explanation for these drumlins in the alternative hypothesis.

The glaciofluvial depositional hypothesis

It has been recently proposed that the formation of some drumlins involved subglacial fluvial processes (Dardis and McCabe, 1983; Shaw, 1983; Shaw and Kvill, 1984). Shaw et al. (1989:177) concluded that drumlins in northern Saskatchewan were formed directly by subglacial meltwater that first eroded cavities into overlying ice and subsequently infilled these cavities during declining flow. Sharpe (1987) also interpreted drumlins as cavity fills. As a third mechanism, Shaw and Sharpe (1987) described bedrock drumlins which they

⁹ For further information see also Menzies (1984), Menzies and Rose (1987), and Menzies and Rose (1989).

interpreted as residual ridges standing between furrows caused by the abrasive action of sediment laden meltwater. "Both the glaciofluvial depositional hypothesis ... and the glaciofluvial erosional hypothesis ... require deep and broad sheetflows of meltwater" (Shaw et al., 1989:178).

The meltwater origin of drumlins is based on the analogy between the shape of drumlins and strikingly similar forms created by water erosion (Allen, 1969). "Erosion marks are considered to form on the underside of glaciers by subglacial meltwaters that ultimately filled in the eroded cavities" (Sharpe, 1985:370). Deposition by water currents and/or mass flow would result in interbedded massive or stratified units and diamictons. Shaw (1983) found these kinds of features at Camden East, Ontario. In addition, he has identified a mechanism for subglacial cavity formation and filling.

Figure 3: Stages in the glaciofluvial depositional formation of drumlins (Shaw and Kvill, 1984:1543)

"If this hypothesis is true, then the drumlins should look like infilled erosional marks" (Shaw et al. 1989:185). This is what Shaw found. The spindle form had an appropriate length/width ratio of approximately 5:1. He also notes that parabolic and transverse asymmetrical forms¹⁰ are also possible.

Analogies between erosional marks in bedrock and the form of the drumlins appear also as "Flutes on the bed of a turbidite bed", "Flutes cut in snow by wind direction" or "Flutes cut in limestone" (Shaw et al., 1989:186-8). These discoveries have been supported by Baker and Csiro (1987:640) who found form analogies in Australia which were produced by "sand carried by flood flows". Shaw and Sharpe further report erosional marks on the shore of Georgian Bay (personal communication, 1989; papers in preparation). This evidence of the same principle of dynamics, even from places where no glaciation took place, demonstrate that forms like drumlins can be produced by meltwater erosion, and that glacial activity is not necessary.

The glaciofluvial erosional hypothesis

This theory can be best introduced by the researchers, who developed it.

¹⁰ Terminology developed by Shaw (1983).

Some drumlins are shown to belong to a family of ~~remant~~ erosional ridges associated with subglacial meltwater. The length of these ridges vary in scale from a few tens of millimetres to over 5 km. Similar form elements are illustrated for three scales of forms. It is concluded that some drumlins are composed of preexisting sediment or bedrock¹¹ left upstanding in ridges as a result of the removal of surrounding materials. This erosional theory is related to an earlier theory in which drumlins are held to result from the infilling of subglacial cavities. The unifying factor for both theories is the role of sheets of subglacial meltwater.

Shaw and Sharpe (1987:2316)

The secondary flow responsible for the formation of such drumlins is illustrated in the Figure below.

Figure 4: The secondary flow. Sketch of flow around an obstacle in unidirectional flow. (Shaw and Sharpe, 1987:2318).

Scientific research involves interpretation. In physical geography, and particularly in glacial geomorphology, we

¹¹ "Or a combination of both" and "A surface veneer of till or other deposits may drape such drumlins but, unless it is deformed by glaciotectonic action, the internal structure need not relate to the external forms" as stated in Shaw et al. (1989:181).

have only residuals of the 'Great Ice Age' to deal with, i.e., we have incomplete facts, and we seek explanations for them. Certainly, there are many different ways to explain the origin of drumlins, but the ones described above are the principal ones.

Considering the amount of literature on drumlins, there has been a surprising lack, until relatively recently, of attempts to create and establish a theoretical basis for drumlin research. Even Menzies (1984) neglects to mention supporting literature for the alternative theory. A recent paper by Habbe (1988) demonstrates a lack in awareness of work reported in the English literature by Germans and vice versa. Although citing the Drumlin Symposium (Menzies, 1987) in his bibliography he ignored totally the alternative hypothesis¹² established in 1983.

It should be evident that if the origin of drumlins is to be understood, the alternative hypothesis should also be given serious consideration.

1.1.3 Conclusion

A broad and intensive literature study has been

¹² "Zwar besteht Übereinstimmung insoweit, als Drumlins allgemein als durch fließendes Gletschereis geformte Stromlinienkörper betrachtet werden, doch ist nach wie vor offen, ob dabei Erosion oder Akkumulation oder beides zusammen das Hauptagens war..." (Habbe, 1988:34/35).

conducted on the subject of this thesis. Firstly, literature was reviewed before the field work to enable reasonable hypotheses to be formulated, and secondly, afterwards to relate the observations and facts obtained in the field to one or more of the prevailing theories on the origin of drumlins. The writer believes that field work should only be done when one is familiar with all possible and existing theories on the topic in mind in order to be open to the evidence acquired in the field.

To achieve a better overview on the vast amount of literature on this topic the major thoughts of each author were summarised. The writer used the bibliography by Menzies (1984) for this purpose. As Menzies focuses more on the conventional theory, the research for this study has been extended to address the alternative hypothesis. The results of the writer's literature study are summarized in the Table in Appendix A which also includes recently published material¹³. The table contains the name of the author, the year of publication, the location of field work and whether or not the facts being reported or hypothesis of drumlin formation being presented are more closely associated with the conventional (C) or alternative hypothesis (A). Another column provides information about each author's detailed

¹³ Menzies (1984) closes his review on the literature in 1983.

description of drumlin formation. The writer follows the 'Drumlin Hypothesis of Formation' given by Menzies (1984:xvii) for the first four points and Shaw et al. (1989:178) for the last two:

1. Erosion of preexisting glacial materials;
2. Deposition "en masse";
3. Accretion / Deposition (with or without a core);
4. Subglacial Bed Deformation;
5. Glaciofluvial depositional; and
6. Glaciofluvial erosional.

The next column indicates, if the author found some stratified material in his/her section or not. The following column provides a list of authors who support or refer to this topic in their own work. This column is mainly used to demonstrate if the specific publication is mainly used by supporters of the conventional or alternative hypothesis.

As this chapter demonstrates, the dynamics of drumlin formation are by no means fully understood. A wider knowledge of till fabrics and also drumlin morphology, sedimentology and distribution is necessary to find the right answer. This thesis is another step towards providing useful answers concerning the genesis of drumlins and streamlined features in general.

1.2 Goal and Objectives

The drumlins studied in this thesis belong to the drumlin fields of the Bernard Harbour area west of Dolphin and Union Strait in the western Northwest Territories of Canada (Figure 5). The writer was able to conduct studies on individual drumlins of this spectacular field as part of the 1988 field programme of the Terrain Science Division of the Geological Survey of Canada (G.S.C.).

The purpose of the investigation was to determine the origin of the drumlins in the Bernard Harbour area. "With respect to drumlins and flutings composed of materials transported by ice, the fundamental issue is to explain how these materials are agglomerated" (Shaw, 1980:287). It might be possible that these drumlins cannot be assigned totally to one theory but the evidence and facts should suggest that one theory, more appropriately explains the origin.

The major procedures used to achieve this goal are:

1. Intensive literature study before and after the field work.
2. Detailed air photo interpretation before the field work to determine the most efficient locations for study (traverses) during the short field season; and after to develop a better understanding of the whole drumlin field on the basis of the knowledge gained in the field.
3. Mapping of the drumlins from air photos and on ground.
4. Measuring of drumlins (Morphology).
5. Cutting deep cross sections to:
 - collect till samples
 - determine pebble orientation
 - to provide a lithology of pebbles.

The purpose of the above programme is to determine if the existing theories of drumlin formation¹⁴ are supported by field or other evidence.

A second goal of the thesis is to provide more information about the Late Wisconsin Ice movements in this area.

This investigation depends on the application of the ideas (many untested or only partially so) to a unique field area. It recognizes that "Out-of-date theories are not in principle unscientific because they have been discarded" (Kuhn, 1962: 3). However, the writer also recognizes that Kuhn's idea of 'scientific revolutions', which "are the tradition-shattering complements to the tradition-bound activity of normal science" (Kuhn, 1962:6) are particularly appropriate to our developing understanding of how drumlins are formed. It always takes much more evidence to convince people of a new theory than to stick with the old one, the Copernican Revolution is a classical example. Therefore, given the level of current debate, it is still a challenge for Earth Scientists to find a satisfactory explanation for the origin of drumlins.

¹⁴ As mentioned in the conclusion (Section 1.1.3)

C h a p t e r I I

The Bernard Harbour Area

2.1 Location and Physiography

The name of Bernard Harbour has been applied to the area between Basil Bay to the south and Dolphin and Union Strait to the north and between longitude 116° to the west and Coronation Gulf to the east (Figure 5).

The Bernard Harbour area comprises approximately 5,500 km², ca. 110 km x 50 km. The southeastern, the eastern and the northern borders of the study area are bounded by the sea. The western limits of the area coincide with the western edge of the map in Figure 5. Fieldwork was conducted by the Geological Survey of Canada in 1986 (St-Onge and McMartin, 1987) in the adjoining area to the west.

The study region is also part of the Horton Plain in the Interior Plains Region (Bostock, 1976).

Figure 5: The Bernard Harbour area, location map, District of Mackenzie
(after St-Onge, McMartin and Avery, 1989:96)

The morphology and orientation of the drumlins (Chapter 5), can be used to divide the Bernard Harbour area into six zones (A-F). The assignment of letters to the zones was done arbitrarily by the writer and they proceed clockwise from the top (Figure 5).

The physiography of the Bernard Harbour area is dominated by the effects of glaciation and marine sedimentation. The land rises gently from the sea towards the southwest corner of the map area (Figure 6) and its highest point occurs in the southwest corner at 290 m (950 ft) a.s.l. The topography is nearly flat to gently undulating and is underlain by Lower Palaeozoic dolomites (Fraser et al., 1960); outcrops are common and drift is usually less than 15 m thick.

Figure 6 : Physiography of the Bernard Harbour area

2.2 Previous Work in the area

Only a few geologists and other scientists have worked in this remote region, so our prior knowledge of the Quaternary history is fragmentary. Chronologically the following investigations were made¹:

1770 Samuel Hearn, starting from the Churchill River travelled over land to the mouth of the Coppermine River.

1789 Alexander Mackenzie followed the Mackenzie River down to the delta and returned.

1819-21 Captain John Franklin and Dr. John Richardson canoed the Coppermine River to Coronation Gulf.

Figure 7: Franklin's first North American Expedition with Back and Richardson, 1819-22 (Berton, 1988:69)

¹Dates and facts, when not indicated otherwise, are taken from various sources; general overviews are given by Kimble and Good (1955:509ff), Berton (1988:300ff), and Lopez (1987:318ff).

1825-27 John Richardson, a member of Franklin's overland expedition to the Arctic Coast, explores the coastline between the Mackenzie Delta and the mouth of the Coppermine River (Figure 8).

Figure 8: Franklin's second expedition, with Back and Richardson, 1825-27; the solid lines. The dotted line indicated the search for Franklin by Collinson, 1850-54 (after Berton, 1988:93).

Most of the geographical names along the coast were assigned by Richardson. "His detailed and precise notes on the flora, fauna, ice conditions, Eskimo and so forth have contributed substantially to the scientific knowledge of the north" (Mackay, 1958:13). The results of this expedition were published by Franklin in 1828.

1837-39 "Hudson Bay Company expedition on land, led by Peter Dease and Thomas Simpson, surveyed most of the remaining unknown areas of the Northwest Passage"

(Berton, 1988:638). However, they only reached the southern tip of the study area.

1850-54 Richard Collinson is sent into the same waters by the British Admiralty in search of the lost Franklin Expedition. There were two ships, the "Investigator" and the "Enterprise", the latter one navigated by Collinson, who passed the study area (See Figure 8, the dotted lines).

1903-05 Roald Amundsen successfully completed the first navigation of the Northwest Passage. In doing so, however, he passed the study area but did not make any investigations.

1913-18 J.J. O'Neil, member of the 'Canadian Arctic Expedition', made numerous and detailed observations of "Pleistocene" features along the coastline; he also collected shells from raised marine sediments and measured the orientation of glacial striae and grooves. O'Neil completed the work, started by Richardson, and published it in 1924.

1958 The first detailed Quaternary study in the District of Mackenzie was made by R.Mackay (1958) in the neighbouring "Anderson River Map Area".

1960 "More recently, Craig (1960), a member of the Geological Survey of Canada's 'Operation Coppermine', mapped major glacial landforms such as drumlins,

morainic ridges and eskers and measured striae. He also collected marine shells which provided the first age estimate for deglaciation. On his map the approximate limit of marine submergence is shown (St-Onge and McMartin, 1987:91).

1981-89 During this period numerous investigations took place near the Bernard Harbour area (St-Onge et al., 1981; Kerr, 1984, 1987a, 1989; Mercier, 1984; and Sharpe, 1984, 1985, in press). St-Onge, began to investigate the Quaternary genesis of the Bluenose Lake and adjacent areas (St-Onge and McMartin 1987; Kerr, 1987b). Additional information about this area is available in the form of theses, especially Avery (1988), McMartin (1988), and Potschin (1987). No known mapping of the Bernard Harbour area was carried out before 1988.

2.3. Bedrock Geology and Quaternary Genesis

A brief review of the geology of the area, from the Precambrian to the Quaternary Periods, is necessary to understand the evolution of the study area and the sedimentological and the glacio-morphological processes

which gave it its present character.

The Bernard Harbour area is located near the northwest edge of the Canadian Shield and belongs in the so called 'Border Regions' of the Shield². During the Cambrian the first marine transgression covered the study area and dolomites and sandstone were formed. These sedimentary rocks are very thin and are not exposed in the area. However, the Upper Ordovician dolomite is exposed throughout the study area (Clark and Stearn, 1960:242; Fraser et al., 1960), Table 1, next page.

The table provides an excellent overview of geological events in the Interior Plains, to which the Bernard Harbour area belongs. The only difference in the study area is the lack of Paleozoic and Mesozoic shales.

According to Fraser et al. (1960) the area contains two different kinds of dolomite; the base of brown dolomite is overlain by fine crystalline, very fine-layered to massive, grey to beige and light brown marmorized dolomite.

Of more interest for this study are the sediments transported and deposited during the Pleistocene. According to Dyke (1984) the Bernard Harbour area was only covered by the Late Wisconsinian lobe, which spread out from the M'Clintock Ice Divide (Dyke, 1984:14).

²Detailed information about the Canadian Shield in the study area can be obtained from Stockwell et al (1976:44-150).

CON	ERA	PERIOD	TIME	M.Y.	INTER OF PLAYS	ROCK
					ANDERSON R	
					HORNADAY R	
					22	
CENOZOIC	TERTIARY	PALEOCENE	UPPER	15.2	erosion	silt, clay
				15.2	Laurentide Drift	
				20		
				20	REINDEER	clay, silt, shale
				20	sand, ash, gravel	
				20		
				20		
				20		
				20		
				20		
MESOZOIC	CRETACEOUS	UPPER	UPPER	70		shale
				70		
				70		
				70		
				70		
				70		
				70		
				70		
				70		
				70		
PALEOZOIC	JURASSIC	UPPER	UPPER	141		
				141		
				141		
				141		
				141		
				141		
				141		
				141		
				141		
				141		
PHANEROZOIC	TRIASSIC	UPPER	UPPER	250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
PHANEROZOIC	PERMIAN	UPPER	UPPER	250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
PHANEROZOIC	PENNSYLVANIAN	UPPER	UPPER	250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
PHANEROZOIC	MISSISSIPPIAN	UPPER	UPPER	250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		
				250		

PALEOZOIC	DEVONIAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
PALEOZOIC	SILURIAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
PALEOZOIC	ORDOVICIAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
PALEOZOIC	CAMBRIAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
PROTEROZOIC	HADRINIAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
PROTEROZOIC	HELKIAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
PROTEROZOIC	APHEBIAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
PROTEROZOIC	ARCHEAN	UPPER	UPPER	353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		
				353		

Table 1: Geology of the Bernard Harbour area

Figure 9: Configuration and dynamics of the northern part of the Laurentide Ice Sheet showing flow patterns and ice streams of the M'Clintock Dome, the Foxe Dome, and the Keewatin ice remnant. The final position of the Keewatin Ice Divide is shown. (Dyke, 1984:14)

Glacial till, up to 60 m thick (St-Onge, 1987:1)³, erratics, sandy gravel, outwash and glaciomarine sand, silt, and clay form a discontinuous cover so that bedrock outcrops are extensive.

Figure 10, illustrates a model of the geological conditions in the Bernard Harbour area.

³Usually less than 15 m (Fraser et al., 1960).

Figure 10: Model of the geological conditions in the study area

2.3.1 Late Wisconsin Ice Situation

The Late Wisconsin lobe reached its western limit at the east slope of the Melville Hills, west of Bluenose Lake. With the help of distinct flow patterns, identified from drumlins (?!?), flutings and striae, and by ice frontal positions associated with morainic ridges and other ice contact features, McMartin and St-Onge (in press) have developed four phases of ice retreat, from the Melville Hills to the Coronation Gulf, Figure 11.⁴

⁴Isabelle McMartin is working on this subject in an upcoming M.A. Thesis at Université Québec à Montreal.

Figure 11: Late Wisconsin retreat phases south of Dolphin and Union Strait (McMartin and St-Onge, in press-Figure 1).

The westerly flowing ice left a large moraine system within which glacier ice has been preserved to the present day (St-Onge and McMartin, 1989). These moraines define the "Phase I - Bluenose Lake Moraine Complex". The shrinking ice mass gradually retreated and split into two distinct lobes flowing northwestward into Dolphin and Union Strait and westward into the Richardson and Rae Rivers basins. During this retreat three further stages can be defined: "Phase II - The Inman River Phase, Phase III - The Harding River Phase, and Phase IV - Stapylton Bay Phase" (McMartin and St-Onge, in press). The whole Bernard Harbour area is located within the last, the Stapylton Bay Phase.

Eventually, the ice moved along a corridor open between the ice mass and mainland, and penetrated as far as the upper reaches of the Richardson River. The marine limit is the Bernard Harbour area is 160 m a.s.l. McMartin and St-Onge (in press) suggest that rapid calving into the water body generated numerous minor surges and changes in iceflow direction. Once the area was completely ice-free, marine action in the form of wave washing of emerging landforms occurred along the present-day coastline.

Field evidence in the form of the remaining glacial landforms and marine sediments is summarized in Figure 11.

2.4 Climate and Soil

The entire Bernard Harbour area lies north of the 10° July isotherm and therefore belongs to the polar tundra zone which is underlain by continuous permafrost. According to the Köppen climatic classification system it has a "Dfc" climate and in the Troll system a "II,2" one.

Weather records are available from Coppermine (67°50'N, 115°07'W, 9m) to the south, and at Cape Young (68°56'N, 116°55'W, 18m), a DEW-line station⁵ west of the study area.

CAPE YOUNG A 68° 56' N 116° 55' W 18 m														JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Daily Maximum Temperature														-26.2	-27.7	-23.4	-14.5	-3.3	5.6	10.5	9.8	3.6	-4.5	-15.6	-21.7	-9.0
Daily Minimum Temperature														-34.2	-34.4	-32.7	-24.4	-11.2	-0.8	2.7	3.1	-0.9	-10.4	-23.5	-30.2	-16.4
Daily Temperature														-30.3	-31.6	-27.9	-19.3	-7.2	2.4	6.8	6.5	1.4	-7.5	-19.8	-25.6	-12.7
Standard Deviation, Daily Temperature														2.7	3.2	2.3	2.6	2.3	2.1	1.4	1.6	1.7	2.9	2.1	3.2	1.1
Extreme Maximum Temperature														-3.9	-5.5	-5.0	4.4	13.3	23.3	29.4	25.6	20.6	8.3	5.6	-2.8	29.4
Years of Record														20	21	20	23	23	24	22	24	24	24	24	27	
Extreme Minimum Temperature														-48.3	-47.8	-46.7	-43.3	-30.6	-15.0	-4.0	-3.3	-15.0	-30.0	-38.9	-44.4	-48.3
Years of Record														23	23	23	23	23	24	23	24	24	24	24	24	
Rainfall														0.0	0.0	0.0	0.0	1.5	14.2	28.6	32.5	16.4	0.4	0.0	0.0	93.6
Snowfall														3.8	3.5	3.4	5.7	6.6	0.8	0.2	1.0	6.5	17.7	12.7	6.5	68.4
Total Precipitation														3.8	3.5	3.4	6.2	8.8	15.1	28.8	33.5	23.0	18.0	12.7	6.5	168.1
Standard Deviation, Total Precipitation														2.8	3.5	3.5	12.1	8.2	13.0	22.0	18.5	14.0	12.2	9.1	6.3	52.2
Greatest Rainfall in 24 hours														0.0	0.0	0.0	T	6.9	17.5	41.1	35.1	17.3	4.1	T	0.0	41.1
Years of Record														23	22	22	20	21	22	22	23	23	23	24	23	
Greatest Snowfall in 24 hours														5.4	7.6	5.1	23.5	11.4	5.1	4.6	6.4	9.4	12.7	11.8	12.7	23.5
Years of Record														21	20	20	20	21	23	22	23	23	22	23	22	
Greatest Precipitation in 24 hours														5.4	7.6	5.1	23.5	11.4	17.5	41.1	35.1	17.3	12.7	11.8	12.7	41.1
Years of Record														21	20	20	20	21	22	22	23	23	23	23	22	
Days with Rain														0	0	0	0	1	4	7	8	6	1	0	0	26
Days with Snow														3	2	3	3	3	1	0	1	4	8	6	4	38
Days with Precipitation														3	2	3	3	4	4	7	8	9	8	6	4	61

Table 2: Weather records from Coppermine and Cape Young⁶
(Atmospheric Environment Service, 1982)

⁵ Distant Early Warning station.

⁶ Units and symbols: temperature in [°C], rainfall in [mm], snowfall in cm, total precipitation in [mm]. M = missing data, T = a trace amount, i.e., less than 0.1 mm of liquid or less than 0.1 cm of snow.

COPPERMINE	JAN	FÉV	MAR	AVR	MAI	JUIN	JUIL	AOÛT	SEPT	OCT	NOV	DEC	ANNEE	
Daily Maximum Temperature	-2.4	-2.2	-22.9	12.1	15	16	13.8	1.2	5.2	5	15.8	22.0	19	2
Daily Minimum Temperature	-33.8	-34.4	-3.3	22.3	12	0.2	5.6	5.0	-0.3	3.6	23.4	29.8	-1.3	2
Daily Temperature	-30.5	-31.1	-27.1	-17.5	-5.3	3.8	9.7	8.7	2.5	-6.6	-18.7	-25.9	-11.6	2
Standard Deviation Daily Temperature	10.7	11.1	11	13.3	2.5	1.9	1.4	1.7	1.7	2.1	2.0	3.6	1.0	2
Extreme Maximum Temperature	-2.4	-2.2	-2.1	7.8	20.3	27.8	32.2	25.4	20.1	13.9	4.4	4.4	32.2	
Years of Record	40	40	40	40	40	40	40	40	40	40	40	40	40	
Extreme Minimum Temperature	-47.8	-50.0	-48.9	-43.9	-31.1	-15.0	-0.6	-3.3	-20.0	-33.3	-41.1	-45.0	-50.0	
Years of Record	40	40	40	40	40	40	40	40	40	40	40	40	40	
Rainfall	0	0	0.0	T	3.5	14.3	25.3	38.2	18.6	2.8	T	0.0	102.1	2
Snowfall	9.2	6.4	10.4	10.2	8.1	2.6	0.5	0.4	5.3	21.0	15.1	11.5	100.7	2
Total Precipitation	9.3	6.2	9.8	11.0	12.0	17.0	25.8	38.6	24.0	22.2	14.3	11.1	202.3	2
Standard Deviation Total Precipitation	6.2	5.2	7.4	12.4	9.0	14.2	15.7	25.6	13.3	13.3	8.1	6.3	53.5	2
Greatest Rainfall in 24 hours	0.0	0.0	T	3.8	18.8	63.5	34.3	57.2	21.1	14.0	0.5	T	63.5	
Years of Record	40	40	40	40	40	40	40	40	40	40	40	40	40	
Greatest Snowfall in 24 hours	22.9	20.3	14.5	19.8	15.5	25.9	14.0	4.6	13.0	20.6	16.8	25.7	25.9	
Years of Record	40	40	40	40	40	40	40	40	40	40	40	40	40	
Greatest Precipitation in 24 hours	22.9	20.3	14.5	21.3	18.8	63.5	34.3	57.2	22.9	20.6	16.8	25.7	63.5	
Years of Record	40	40	40	40	40	40	40	40	40	40	40	40	40	
Days with Rain	0	0	0	0	2	6	9	10	8	2	0	0	37	2
Days with Snow	9	6	8	7	6	2	1	1	4	12	12	9	75	2
Days with Precipitation	9	7	8	7	7	7	9	10	11	13	12	9	109	2

Table 2: to be continued

Figure 12: Climate diagrams for Coppermine and Cape Young

The two stations experience similar weather patterns, as can be seen in Figure 12; they have long, cold, dry winters and brief, cool, damp summers. Freezing temperatures can occur in any month. On average, the frost-free period ranges from 40 to 60 days. In the summer of 1988 temperatures as high as 20°C were recorded.

Snow covers the ground for at least 8 months of the year. By the end of June in 1986 and 1988 snow had stopped falling but could be expected to begin again by September. The greatest snowfall occurs in October and November (Table 2 and Figure 12). However, in this region snowfall is between 68.4 cm (Cape Young) and 100.7 cm (Coppermine) annual. The greatest amount of precipitation falls in the summer and early autumn. On average, there are only 75.3 mm (Cape Young) and 89.4 mm (Coppermine) of rainfall during the months of June, July and August, the growing season. The Bernard Harbour area may be classified as a (cold) desert.

In terms of soils the whole study area belongs to the so called "Tundra zone" (Charlier, 1969:1992) or "Cryic Regosol" (Soils of Canada Map, 1972). Due to its persistent cold climate, there is hardly any chemical weathering and the soil consists mainly of frost shattered debris. The slow rate of plant decomposition is reflected in the very thin humus layer (organic horizon - H). Tundra soils in general do not have a continuous profile, they are mostly a combination of thin

layered sandy clay and humus (Strahler, 1975:310). The surface is covered with a combination of lichens and mosses. According to Tedrow and Cantlos (1958:178) and Charlie (1969:1992) the soil in the study area can be described as "Arctic Brown".

2.5 Flora and Fauna

There is a vast literature describing the flora and fauna of the Low Canadian Arctic of the District of Mackenzie (Porsild, 1957; Reger and Péwé, 1976; Schmeil/Fitchen, 1982; and Ritchie, 1984)⁷. For the flora and fauna described in this study, the writer only lists the plants and animals observed in the Bluenose Lake and Bernard Harbour region during the summers of 1986 and 1988.

A list of the flora is provided in Appendix A (Table ii). The ones possible to dry-press were identified after the writer returned from the field. Sylvia A. Edlund⁸, Geological Survey of Canada, identified doubtful samples; larger plants were identified directly in the field. The first name in the list indicates the family name (Latin); they are in alpha-

⁷The Department of Culture and Communication, Government of the Northwest Territories has publications on fauna and flora which include the latest data.

⁸Her work concentrates on the flora of the arctic. Edlund (1983), Edlund and Alt (1989).

betical order and are followed by the Latin suborder name and then the English terminology. The flora in the Bernard Harbour area indicate an alkaline environment, as calciphilous species are dominant⁹.

Besides these vascular plants, many different mosses and lichens can be found in the study area; they were not identified due to a lack of knowledge about all possible subspecies. However, it can be postulated that the majority of these belong to the family of "Cladonia" and "Cetraria".

Fauna observed in 1986 and 1988 are listed in alphabetical order in the appendix A (Table iii). Kimble and Good (1955:519) and Lopez (1987:400) identify the kinds of fauna that 'can be expected' all year round in the low arctic.

⁹Edlund, personal communication to Avery, another member of the field party.

C h a p t e r I I I

M e t h o d o l o g y

"Today it is apparent that three main areas of drumlin research are foremost: theoretical, sedimentological and morphometric" (Menzies and Rose, 1987:1). Like Boulton (1987), Harry and Trenhaile (1987) and Krüger (1987) the writer has used theory, sedimentology and morphometry to investigate the origin of drumlins in the Bernard Harbour area. Most papers on drumlin research employ only one approach. It is asserted here that the combination of all three can provide a more complete picture.

3.1 Air Photographs and Maps

National Topographic Series maps of scale 1:50,000 (87A) and 1:250,000 (87) and 1968 aerial photographs having a scale of 1:63,200 were used to select and study the field area. The aerial photographs were used also to select potential sites for sediment sampling and fabric analysis (Figure 13) and to

examine the relationships of the glacial landforms to each other and for the measurement and subsequent morphometric analysis of the drumlins. For the latter the length, width and orientation of drumlins were calculated from the photos. Although it is recognized that measurement errors may occur at this scale, it is generally believed to be sufficient for the classification and positioning of drumlins. The Landsat Image¹ provided an ideal overview of the area but was not used for mapping or other morphometric analyses.

Both aerial photographs, and the personal photographs taken during a low-level reconnaissance flight were used to map the drumlins of the area, of which all (2145) were plotted onto a smaller scale map. More detailed information was obtained from ground investigations of selected drumlins.

3.2. Field work and its limitation

Traverses were made on a Honda tricycle around the base camp at Bernard Harbour, and a helicopter was used to reach specific drumlins for cutting sections. At the end of the field season fly-overs in a float plane provided an oppor-

¹Provided in the back pocket of the cover.

tunity to explain outstanding regional questions by viewing all drumlins.

Limitations to the field work were caused mainly by the ground material itself and the presence of permafrost. Cutting sections was sometimes very slow and tedious, especially when shingle beach sediments were present (P75, Zone C). Work on these sections had to be done as fast as possible, as the nature of this material when thawing causes the slopes to collapse very quickly, so that the trench widens rapidly. Photographs taken during the summer field-work of 1989, one year after the sections were dug, show that the sides had totally collapsed. Problems also arose due to the depth of the section. Generally, the permafrost table was between 100-150 cm depth; the average depth was 130 cm depth.

3.2.1 The Sections

On the basis of detailed air photo interpretation which preceded the field work, the Bernard Harbour area was divided into six zones, according to orientation and morphology of the drumlins. Trenches were excavated in drumlins from each zone to provide geological sections of sub-surface material.

The selection of the six sections (trenches) to be excavated, was based on the "areal-sampling method" (Krumbein and Graybill, 1965:147ff)². The selection was randomly determined and each drumlin form is represented by at least one section (trench) and sample site.

After arrival in the field it was discovered that there was insufficient water near some of the drumlins selected for the hydraulic work of cutting sections, and so substitute drumlins had to be picked³. In some cases the slopes of the drumlins were much flatter than estimated from the air photo study so that there was insufficient drainage for cutting sections. Six drumlins were studied intensively.⁴

Figure 13 on the next page illustrates the distribution of samples in the Bernard Harbour area. Where sections were cut (●), samples and height measurements are included; taking samples (▲) also means measuring the height⁵.

²For the selection of drumlins the "Nested sampling at three levels, all randomized" was chosen (Krumbein and Graybill, 1965:161).

³The latest air photos available were taken in 1968, and there have been subsequent changes in the landscape, especially in the ground water level and lakes.

⁴Time restraints, lack of human resources and accessibility problems limited the number of drumlins that could be examined in detail.

⁵In the field, measurements were made of the height and angle of slope for the morphometric analysis of 87 drumlins; the length and width was calculated from the air photos of all drumlins in the Bernard Harbour area (2145).

A list of the exact locations of the samples and the elevation is provided in the appendix A (Table iv).

The downward cutting of the section was a tedious job as can be seen from Plate 1.

Plate 1: Method of cutting deep sections in drumlins

The sections were always cut as deeply as possible. The depth was limited by the thickness of the active layer, usually 130 cm deep. Further excavation would have caused constant slumping of walls cut into permafrost, because they would be melting all the time. This would have disturbed the material and made it impossible to make any useful observations and measurements, and samples would have been contaminated. The only effective way to get below the permafrost table and so

into the heart of the "remaining drumlin", what is left after the rework by the sea, would have been a tunnel. This would keep the temperature of the tunnel below freezing so that one could work on the walls. Unfortunately, the resources to do this were not available. The major part of the cutting was done with the help of a pump. However, larger boulders had to be removed by hand. Problems were also encountered when the slope of a drumlin was less than 10° . In such cases, the loosened material could not be completely removed by the water pressure, and channels had to be made manually. The cutting of one section took at least a whole day. The following day, the face of the section was dried out. As soon as the sections were cleaned they were measured and described. Special attention was given to the kind of material, stratification, and orientation of clasts. The results were recorded in both note and sketch form. The relation of the section to drumlin orientation was also determined.

The next step was to investigate the macrofabrics, a process which involved measurement of the orientation⁶ and plunge of the long axis of pebbles in place. The writer always measured as many pebbles as possible (i.e., until the

⁶Afterwards, the measurements of pebble size - long, intermediate and short axes - was taken to assure that no round example was chosen.

sides of the section collapsed). However, in each case there were at least 45 (on average more than 50) examples taken⁷. In this respect, the position of the pebble within the section - distance in length and depth from a relative null-point - (for example Figures 19 and 21) was also determined to identify any possible differences within one drumlin. Measurements were always below 30 cm from the pump's last action on material to make sure that the pebbles measured had not been disturbed.

The pebbles' azimuths were plotted on a two-dimensional rose diagram and contoured diagrams⁸, this was done by hand in the evening of the day the data was collected in order to attain an overview and to decide if additional or different measurements of the same drumlin (section) ought to be taken⁹. Afterwards, the contoured diagrams were plotted by computer¹⁰. Figure 14 illustrates how these diagrams should be read.

⁷For example, compare data in Jones (1982:61), Shaw and Freschauf (1973:26), Haldorsen and Shaw (1982:272), Shaw (1979:415; 1982:1566) and Kamb (1959:1896).

⁸For the orientation diagrams all bearings are given in degrees azimuth.

⁹The contoured diagrams were plotted manually according to Illies (1949).

¹⁰ Using a program provided by Prof. John Shaw, Queen's University, Kingston.

Figure 14: An example of a contour diagram of till fabrics

For the till fabric analysis the author used the "eigen-vector method" devised by Mark (1974) which "has been established in the earth science literature for more than a decade (see Fara and Scheidegger, 1963)". Here the azimuth (A) of the principal eigenvector gives a measure of the preferred orientation¹¹ and the normalized eigenvalue (S_1) associated with this eigenvector is used as a relative measure of the strength of the preferred orientation. The values for S_1 range between 0 for random and 1 for uniform.

The contour lines demonstrate the degree of randomness of the orientation value; contour intervals equal 2 standard deviations; the black area indicates maximum deviation from a random distribution (Ardith and Johnson, 1986). The mean plunge (P_m) and the mean orientation of pebbles (O_m) is added, also the section number (P_{xx}) and the number of observations (n).

¹¹ The mean plunge is added by the author of this study, also the section number (P_{xx}) and the number of observations (n).

The rose diagrams were not plotted by computer as they are only two-dimensional and do not incorporate the plunge; however, in the field, they provided a clearer overview than the contour diagrams.

In the final analysis the contour line method has its limitations (Mark, 1974), but they are still used because "...the results provide theoretical guidelines to attaching physical meaning to the statistical measures" and "to match processes of till fabric formation to resulting fabric types" (Mark, 1974:101). Mark's classification of till is based primarily on the work by Boulton (1972a, 1972b).

A sample of approximately 1000 grams¹² of till was collected at each fabric side for textural analysis. Additional samples were collected from numerous small sections situated throughout the study area (Figure 13). The location of the samples applied the principle used for choosing the sections (Krumbein and Graybill, 1965:147ff). In some instances, this methodology was not followed strictly in order not to neglect unexpected and interesting sites. Shaw and Freschauf (1973:26) also discuss sampling points within a section. Their methods seem to be for ideal cases, and could not be applied in the Bernard Harbour area, as no complete section through a drumlin could be obtained.

¹² According to Folk (1965:16) 100 grams are needed when gravel is included in the sample.

Altogether, 53 samples were collected from the Bernard Harbour drumlins for sizing by sieving and pipette analysis (Section 3.3).

The last step in the field work process for each section was to take a random selection of pebbles to study clast size, lithology and degree of roundness¹³. The roundness of the clasts was determined through visual estimation according to the six classes of the roundness scale according to Powers (1953). He discusses roundness scales in his review of Wadell (1935), Russell and Taylor (1937), Pettijohn (1949) and Krumbein (1941); he also debates the disadvantages and advantages of each method and provides a new scale. According to Kühnen (1956:336) roundness measurements by Cailleux's method (Cailleux, 1952) tend to give values which are too high. Krumbein (1941 - Table 4) investigates the difference between the exact mathematical roundness definition by Wadell and a visual "rapid method for measuring roundness". His results show no major difference in results from both of these methods, and, therefore the visual estimation of pebble roundness in the field by Powers was accepted for determination of roundness.

¹³ According to Stäublein (1970:14) 100 pebbles should be studied for lithology.

3.3 The laboratory work and its limitation

-- Particle-size distribution --

Graphic or statistical analysis is necessary to show (1) the variation of grain morphology with size, which is nearly always present, and (2) environmental, spatial, or stratigraphic differences between samples.
Folk (1965:12)

Particle-size analyses can be presented and used in several ways; the most common one is the particle-size distribution curve. The writer plotted the results for her size analyses in two forms - the histogram and the cumulative curve. The histogram was used, because it is clear and easily interpreted, and the cumulative curve was used because of its use to obtain statistical parameters, and in order to compare results with other work reported in the literature. According to Gee and Bauder (1986:384), "Particle-size distribution curves are used extensively by geologists in geomorphological studies to evaluate sedimentation and alluvial processes...". For comprehensive descriptions Krumbein and Pettijohn (1938) and Irani and Callis (1963) provide details of the use of these curves. In the use of these curves for geomorphology¹⁴ the graphs start with the fine grains (clay) plotted on the left hand side of the abscissa, and the coarse material

¹⁴ See Stäblein (1970) and Hillel (1982).

(gravel) on the right hand side, just the opposite of the way in which geologists traditionally present this data¹⁵. For the sake of comparison with earlier studies by the writer (Pctschin, 1987) the first approach is used here.

In addition to analysis for grain-size distribution x-ray diffraction analysis was considered as a means to investigate the composition of minerals for the purpose of ice lobe location study (Section 2.3.1). Therefore, samples from at least two drumlins from different parts of the Bernard Harbour area were taken. However, as members of the Geological Survey of Canada field group returned to the same area in 1989 to investigate this and other topics, the results of McMartin and St-Onge (in press) are used instead for this study.

3.3.1 The sieving method

Particle-size analysis (PSA) is a measurement of the size distribution of individual particles in a soil sample. The major features of PSA are the destruction or dispersion of soil aggregates into discrete units by chemical, mechanical, or ultrasonic means and the separation of particles according to size limits by sieving and sedimentation.

Gee and Bauder (1986:383)

¹⁵ Krumbein (1932, 1941), Reineck and Singh (1973), Andrews (1975), Bouvier (1975), Lindholm (1987)

To start with grain-size analyses, one has to choose the scale first. The arithmetic scale, "devised by Udden, is based on a constant ratio of between two successive classes; names of the class intervals were proposed by Wentworth" (Folk, 1965:3). Krumbein devised the phi-scale "as a logarithmic transformation of the Wentworth scale".

A review of the literature indicates that different countries use different class intervals and scales¹⁶. As the writer did her laboratory work in Canada, the class intervals used for this study were determined by the sieves available at Carleton University (See Table 3). For the purpose of this study, 9 sieves for the dry sieving method were selected, according to the particle-size limit classification of the "Canada Soil Survey Committee"¹⁷. In their table Gee and Bauder (1986:384) also present a good overview and comparison of the "Particle-size limits according to several current classification schemes". The limits used in this study and a transformation into the phi-scale for comparison are illustrated in Table 3.

¹⁶ Folk (1965), Flüchbauer and Müller (1970:12), Stäblein (1970:7), Griffiths (1967:76), Hartge (1978:7).

¹⁷ McKeague, 1978 in fig.15-1, in Gee and Bauder (1986:384).

0.0002	FINE CLAY	phi-scale
0.001	COARSE CLAY	
0.002		9.0
0.003	FINE SILT	
0.004		8.5
0.006		
0.008	MEDIUM SILT	
0.01		5.5
0.02		
0.03	COARSE SILT	
0.04		4.25
0.06	VERY FINE SAND	
0.08		3.25
0.1	FINE SAND	
0.2		2.0
0.3	MEDIUM SAND	
0.4		1.0
0.6	COARSE SAND	
0.8		0
1.0	VERY COARSE SAND	
2.0		-1.0
3.0		
4.0		-2.0
6.0		
8.0		-3.0
10	GRAVEL	
20		-4.0
30		
40		
60		
80		
	COBBLES	

Table 3: Particle-size limits according to CSSC in mm, and the corresponding phi-scale (only used border lines). After Gee and Bauder (1986:383)

As the given samples contain a relatively large amount of clay, a pretreatment of the samples to enhance separation of the clay particles from the coarser gravel parts had to be done. For this purpose, three sieves (0.053 mm, 0.35 mm and 1.41 mm) were used for wet sieving. The material finer than 0.053 mm was collected in cylinders for later analysis and the coarser material was oven dried (80°C) for the dry sieving procedure. For this method nine sieves between 0.053 mm and 16 mm were utilized (Table 3).

3.3.2 The Pipette Method

According to Folk (1965:27) and Gee and Bauder (1986) the pipette method is the most common and most accurate procedure for analyzing finer grained sediments. These authors also discuss the older procedures such as the hydrometer method and decantation, and they consider the advantages and disadvantages of their use. In addition, they note possible working errors of the pipette method which is shown to be preferable to the other two methods.

The procedure used for diagnosing the samples and carrying out pipette size analyses were according to procedures described in Folk (1965) and Gee and Bauder (1986), no deviations were observed.

3.3.3 The Statistical Parameters

A large number of geomorphologists¹⁸ have written about the statistical parameters used for sedimentological analyses. The following is a list of the statistical parameters used in this study and the formulae with which they were calculated. Average grain size is measured in several ways, Table 4 summarizes all used parameters.

¹⁸ See footnote 15 in this chapter

Median The diameter corresponding to the 50% mark on the cumulative curve

Graphic mean

$$M_z = \frac{\phi_{10} + \phi_{50} + \phi_{90}}{3}$$

Inclusive graphic standard deviation

$$\sigma_1 = \frac{\phi_{84} - \phi_{16}}{4} = \frac{\phi_{95} - \phi_5}{6.6}$$

< 0.35	very well sorted
0.35 to 0.50	well sorted
0.50 to 0.75	moderately well sorted
0.75 to 1.00	moderately sorted
1.00 to 2.00	poorly sorted
2.00 to 4.00	very poorly sorted
> 4	extremely poorly sorted

Inclusive graphic skewness

$$S_{ki} = \frac{\phi_{10} - \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 - \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$$

-1.0 to -0.3	very fine-skewed
-0.3 to -0.1	fine-skewed
+0.1 to +0.3	near-symmetrical
+0.3 to +0.5	coarse-skewed
+0.5 to +1.0	very coarse-skewed

Graphic kurtosis

$$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$$

< 0.6	very platykurtic
0.6 to 0.90	platykurtic
0.90 to 1.11	mesokurtic
1.11 to 1.50	leptokurtic
1.50 to 3.00	very leptokurtic
> 3.00	extremely leptokurtic

Table 4: Formulas and verbal scales for graphic size parameters (after Folk & Ward, 1957), cited in Lindholm (1987:171)

For the calculations of these values, the percentile values (ϕ_i) are taken from the graphs themselves. ϕ_i for example equals the diameter in the phi units at the 25th percentile which equals the first quartile (Q_{25}). Figure 15 illustrates these relations.

Fig. 15: Frequency curves showing distributions differing in skewness (B & C) and kurtosis (D & E).
Lindholm (1987:167)

Flüchbauer and Müller (1970:53) discuss in detail why the indices by Folk and Ward (1957) are more precise and should be used over Inman's (1952) characteristics.

The best measure for the spread is the standard deviation. Sorting, "as a measure of the total spread of grain-size distribution" (Flüchbauer and Müller, 1970:53) is not used in this study, as the established formula by Trask (1932) should be applied only to very clayey sands and not to till. Furthermore, the Inman calculation for sorting is unsatisfactory for bimodal and/or skewed distributions (Folk, 1966).

The following chapters apply these tests to the data collected in the field, and provide a discussion of their limitations in answering the principal hypothesis.

C h a p t e r I V

The sedimentology of the drumlins in the Bernard Harbour area

During the investigation of drumlins of the Bernard Harbour area a systematic study was made of materials from different drumlins and different locations within the same drumlin. There were two reasons for doing this. First a more precise description of the material was necessary than that provided by visual examination; geomorphic interpretation of the kind of till is often based on the character as well as form of the deposition. The second reason was to determine if any of the morphologic features had distinguishing characteristics.

To understand the terminology of the following section, a short description is necessary. P-numbers indicate the site number of drumlins and follow the description of the writer's fieldwork; for example P28, Zone A means, the 28th investigated drumlin, located in Zone A. All locations for sections, drumlins and zones are provided in Figure 12¹.

¹They are also provided on the map in the back envelope for reference while reading this chapter.

4.1 The sections

Deep sections (trenches) were cut in six different parts of the Bernard Harbour area during the summer of 1988 (see Figure 13 and in rear envelope). The first section, P28 - Zone A shows an upward coarsening sequence. This was interpreted as modified by the sea and will be described separately in Section 4.1.1. To obtain another example from Zone A, a further section was later cut in P55 - Zone A. The sections of the area are described below.

P 2 9 - Z o n e D

Figure 16 shows the three exposures, the elevation and their relation to each other, also the drumlin direction.

Figure 16: Location of exposure trenches, P29, Zone D

Plate 2 and 3 illustrate the environment of the section.

Plate 2:
Sections in Drumlin P29
and their environment in
Zone D, orientations:
drumlin 75°-255°, section:
85°-265°, view west,
14.7.1988

Plate 3:
Natural slope before work
started, P29, Zone D,
view north, 13.7.1988

The surface of drumlin P29 is characterized by hummocky terrain, mudboils and numerous cobbles and boulders resting on top and protruding through the surface. Most of the boulders are dolomite and frost-shattered. The following figures and plates of sections illustrate the material of drumlin P29.

location of sample SV(P)-88-9A
samples will be indicated with
(▼) in the following exposures

Figure 17:
Section 1, P29, Zone D

Section 1 in P29 has two different units. On top is a sandy peat (Unit A). The lower 2-5 mm of this unit contain thin layers of sand interstratified with the peat. A sharp contact separates this from the underlying diamicton. Unit B is a matrix-supported, silty sand diamicton with clasts ranging from granules to boulders, the latter being angular to well rounded.

Plate 4: Section 2, P29, Zone D, view 140°, 14.7.1988

Unit A of section 2 is the upper 5 cm, which contains sandy peat, and is separated from the underlying Unit B through a gradational contact over 1 cm. Unit B can be characterized as a silty sand diamicton with granules to small cobble clasts, which are predominately dolomite (making it a matrix supported diamicton too). Clasts are angular to well rounded. This unit overlies another layer; each of them are separated by a gradational contact over 1 cm. Unit C contains sand with a material of a peaty nature. It has the same matrix as Unit A, except that here it appears to pinch out laterally. Unit D is similar in texture to Unit B, but contains frost shattered boulders (5-20 cm thick). Unit E is a layer of coarse to very

coarse sand with abundant granules. Unit F can be interpreted as a silty sand diamicton and is similar to Unit B but seems to have a higher concentration of silt. Samples from this section were taken from Unit B and Unit F for comparison.

In summary, this section has two layers below the peat; Unit B is probably the result of a solifluction lobe which flowed over Unit C.

Plate 5: Section 3, P29, Zone D, view 140°, 14.7.89

Sections 1 and 3 from drumlin P29 show no grain-size, sedimentological or textural differences. Only Section 2, with its 'double arrangement of layers', with peat overlying the

till, is different but can be explained as being a surface unit covered by solifluction.

All three sections are from the same part of the drumlin; the first meter below the surface contains peat interbedded with 2-5 mm sand layers. The main part - the till body underneath this - is a silty sand diamicton with clasts ranging in size from gravel to small boulders, the coarser clasts being angular to well rounded. The clasts are predominately dolomite. Interestingly, the pebbles in the diamicton body seem to dip steeper than the slope, which has an angle of 6.5° . No evidence of stratified material within the diamicton body was found in the exposed parts of the section.

This section can be summarized as follows: The material can be considered as being lodgement till throughout the exposure. The till is homogeneous, except that the upper layers show the effects of solifluction (See Table 5).

P 3 4 - Z O N E D

Figure 18 and Plate 6 show the circumstances of the section cut in Drumlin P34.

Figure 18: Location of the trench on Drumlin P34.

Plate 6: Location of the trench on Drumlin P34, Zone D,
view west, 29.7.1988

This sequence of sediments in P34 consists of two major units exposed in a section perpendicular to the direction of the drumlin's main axis (77° - 257°).

Plate 7: Section in P34, Zone D, view NNW, 17.7.1988

The lower diamicton (Unit B) comprises sandy silt, gravel, pebbles, cobbles and boulders, all of which are subangular to rounded. Most of the pebbles have striations with different orientations. Many of the angular clasts seem to have been frost shattered. No preferred orientation of the clasts could

be recognized. All clasts are dolomite ($\geq 99\%$). The diamicton is overlain by Unit A, but separated from it by a sharp boundary. Unit A has a similar texture to Unit B; the only real difference is that organic material has already developed in the former.

Plate 8: Section in Drumlin P34. Degradation of trench work after 12 days, view NNW, 29.7.88

Unit B in Drumlin P34 shows only diamicton throughout its length and depth, and no stratified material could be

discerned down to a depth of 130 cm (permafrost table) (See Plate 7).

Figure 19 illustrates the exact locations (●) of samples taken from the section; the ones analyzed for grain-size distribution are marked with an (▲).

Figure 19: Samples taken from section in P34, Zone D

Sediment samples were taken to determine if there were variations with depth in the near surface material. According to Shaw (personal communication) sampling on a horizontal plane rather than at a constant depth is more likely to yield information relevant to the theory of drumlin formation. In those instances where samples were taken at the same depth their sedimentological characteristics were not sufficiently different to warrant changing the sampling procedures. However, if it had been possible to trench more deeply, that

would have been the preferred procedure.

The distance between samples (Figure 19) proved to be a good choice to investigate spatial differences in pebble orientation; they will be discussed in section 4.3.1 - Contour Diagrams.

In summary, P34 has the same sedimentological characteristics as P29 and therefore the material in the drumlins of Zone D can be interpreted as being lodgement till, the top part of which was reworked by the sea.

P 5 4 - Z o n e F

This drumlin was selected for a deep cross section as a natural cut had already been initiated by drainage down a steeper part of its slope (Figure 20).

Figure 20: The trench on Drumlin P54

The direction of the trench is 315°, almost perpendicular to

the crest of the drumlin (52-232°), and it has a slope of 8°. The trench's maximal depth was dictated by the permafrost table at 130 cm. Pebble orientation measurements were taken along the 15 m length.

Plate 9: Trench of drumlin P54, Zone F, view NW, 21.7.1988

Figure 21: Trench of P54 and location of samples

Photographs of material were taken on both sides and along the full length of the trench. Plate 10 shows a characteristic example of the matrix material of the trench where a section was measured and described at the deepest end (Figure 21).

Plate 10: Section of Drumlin P54, Zone F, view SW, 21.7.1988

An upper unit with organic material (Unit A) of 10-15 cm in depth overlies diamicton. The lower Unit B is a diamicton with a silty sand matrix containing clasts from gravel to cobble size with gravel and pebbles predominant. The clasts are subangular to well rounded, but the majority are sub- angular to subrounded². Many of the pebbles and cobbles show striae, and it should be noted that the plunge of the pebbles and cobbles inside the section is mostly up-dip (i.e., toward the slope of the drumlin).

Figure 22: Dipping of clasts in P54, Zone F, not to scale

Like the other drumlins described so far the trench in P54 exposes lodgement till with a top layer reworked by the sea.

²Roundness measurements are investigated statistically in Section 4.4.1.

P 5 5 - Z o n e A, "Burwash Point" Drumlin

Plate 11 illustrates the location and environment of drumlin P55 and P28 and shows the unique morphology of P28.

Plate 11: P28 (Fuller Point) and P55 (Burwash Point) in Zone A, view east, 16.7.1988

Figure 23: Cut into Drumlin P55

Both sections of P55 contain essentially the same information, a surface cover (15-26 cm) overlying a diamicton body (Unit C) composed of a silty sand matrix supporting subangular to rounded clasts from gravel to cobble in size. The exposed surface of Unit A has a dark brown colour, due to soil development, and it has a sandy matrix containing abundant gravel, pebbles and cobbles. In both cases Unit A and C are separated sharply by a band of medium to coarse grained sand containing granules of gravel and pebble size (Unit B).

Plate 12: Section 2 in P55, Zone A, view NE, 25.7.1988

It is striking that in both sections the diamicton body is not homogeneous throughout, but interrupted by layers or lenses of sand. In Section 2 these sand lenses are both only 2 cm thick and 24/40 cm across (See Plate 12). In section 1 this is a much longer sand lens or "intratill sand" (Ashley et al., 1985:43; Shaw) or "inter-till sand layer" (Dardis and McCabe, 1987) (Plate 13). The sand lens of Section 1, as the best one exposed, is chosen for a detailed description.

Plate 13: Section 1 of P55, Zone A, view North, 25.7.1988

In Section 1 at a depth of 112 cm there is a sharp contact with massive to weakly banded sand (Unit D). This is banded into layers of fine, medium and coarse sand, interrupted by a gravel band, Plate 14 and Figure 24.

Plate 14: Sand lens in Section 1 - Drumlin P55, 25.7.1988

Figure 24: Detail of intratill sand, Section 1, P55, Zone A

According to Dardis and McCabe (1987:230) who discuss three types of 'intertill sand layers', sediment facies arrangements of the type discussed here are commonly interpreted "as the end product of subglacial sheetwash or sheetflood sedimentation".

However, some authors explain drumlin sand-cores in terms of glacial overriding of proglacial water-laid deposits (De Jong et al., 1982; Whittecar and Mickelson, 1979). According to Ehlers and Stephen (1979)

...subglacial fluvial and lacustrine sedimentation must be invoked where there is the general absence of post-depositional deformation or dislocation structures, glacitectonic loading structures, glacial erosional flute casts or other erosion marks at the junction of sand-cores and overlying till facies.

(c.f. Dardis and McCabe, 1983:276)

Dardis and McCabe (1983:275) also provide a model for "Till lodgement & subglacial cavity sedimentation", which illustrates the development of sand lenses too.

Shaw and Freschauf (1973:31) discuss the "presence of layers, lenses, and blocks of water-sorted sediments" in flutings and provide three possible origins for such material.

First, several authors have assumed that the presence of stratified material illustrates the residual nature of fluting ridges and drumlins, the stratified material having been deposited before ice-moulding took place (Gravenor 1953; Lemke 1958). Lavrushin (1970) suggests that stratified material in till often takes the form of blocks of stratified material which became incorporated in the ice....Finally it is possible that stratified material is deposited during the melt-out of the fluting till. Subglacial accumulation of stratified sediments within tills has been invoked by several authors (Hoppe 1963; Johansson 1968; Shaw 1972). ... Although no definite conclusions can be drawn concerning the origin of the stratified material in the Athabasca flutes it is worth noting that the second and third alternatives above are compatible with the hypothesis of a secondary flow origin.

Shaw and Freschauf (1973:31)

Haldorsen and Shaw (1982:276) conclude that the "presence of sorted, undisturbed sediments interbedded with till (P_1) indicate that the sequences ... were formed in areas of stagnating ice." However, they go on to discuss the problem of distinguishing between melt-out facies and flow facies.

In addition to depositing the sand "en mass" it is suggested here that sand layers could also be a result of subglacial meltwater in the spring or summer. This could also explain the differences in the thickness of the sand lenses. Because Section 2 is located on a steep slope angle

(almost 20°), it is likely that less water was available, and so only small sand lenses could be developed, as compared to the conditions represented by Section 2 where more melt-water would have been present.

Despite this evidence the whole exposure (Sections 1 and/or 2) still can be described as a till body. However, if the observed sand lenses together with the till body in P55 are part of a stratified sequence this would be another example of stratified material within a drumlin as documented by various authors³. The work of Shaw (1983:473-475), who goes into great detail explains stratified material within drumlins, is particularly important and apropos to the evidence uncovered here in P55.

Like many sedimentological phenomena of glacial origin, however, no absolute proof of origin for the sand lenses in P55 can be given, and the origin of the 'intratill sand' still remains a matter of some speculation.

³These authors are identified in Table 1 in the appendix, and are marked with a x in the column for stratified material.

P 7 5 - Z o n e C , "Spindle Drumlin"

As the surface of this drumlin was covered with large angular shingle-beach sediments, the pump was not strong enough to remove the material, and the water caused the sides to collapse immediately. A second attempt was made to cut a small section manually. Plate 15 illustrates the trenches in P75 and their environment.

Plate 15: Trench in P75 after 5 hrs of work, view NW, 27.7.88

The section measured 3 m in length and 85 cm in depth (Plate 16), and exposed two major units which are covered by thick vegetation with short roots underlain by shattered

Plate 16: Section of Drumlin P75, Zone C, view NEE, 28.7.89

2

MICROCOPY RESOLUTION TEST CHART
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dolomite (shingles), Plate 16. The upper part (Unit A) shows frost shattered, angular bladed, dolomite clasts ranging in size from gravel to cobbles and supported by a matrix of medium to coarse grained washed sands. It is of interest to note the presence of marine shell fragments throughout the unit. Unit A is interpreted to be coarse littoral sediments, in which soil has been developing to give it a dark brown to black colour. Unlike the previous sections Unit A has an irregular contact with the underlying diamicton (Unit B). This lower unit is characterised by a silty sand matrix with angular to subrounded clasts of predominantly dolomite in sizes ranging from gravel to cobbles. This unit is interpreted to be till, in which most of the clasts are well striated.

4.1.1 The modified Drumlin (P 28, Zone A - Fuller Point⁴)

Drumlin P28 was close to the base camp and has the first section to be cut (Figure 13, and rear envelope). Plate 17 illustrates the original exposure with its five steps, which were studied in detail. The drumlin's setting is illustrated on Plate 11 (See also Figure 25).

⁴The name is taken from N.T.S. map 87A.

Plate 17: The original exposure of P28, view NNW, 11.7.1988

Figure 25: Trench in Drumlin P28, Zone A

It became apparent from the initial examination of this section that the evidence pointed in another direction than the expected diamicton (till), and so the whole section was cut deeper to obtain a more complete profile. The result was a two-stepped section having 360 cm of exposures (Plate 18).

Plate 18: Two-step section of P28, Zone A, view NNW, 20.7.88

The complete section is shown in Plate 19 (next page).

It can be divided into two major units; the layers in upper part (Unit A) alternate between pebbly sands with granules and layers of gravel with granules and cobbles. Sub-unit "a" contains medium and coarse grained sand supporting occasional subrounded gravel, while Sub-unit "b" has coarse grained sand with gravel.

Plate 19: Complete Section of
P28, Zone A

The lower 110 cm (Unit B) is not so well stratified as Unit A. Distinctive characteristics are the dark brown sand layers which appear to have been cryoturbated and the highly fossiliferous lower part. In Unit A there are a few locations with fossiliferous sand and one extraordinary pair of bivalves of Macoma Balthica in situ, Plate 20.

Plate 20: Shell in situ, P28, Zone A, 20.7.1988

Underneath this, in Unit B, shell fragments and other fossils are found throughout the exposure. Thereby indicating, that this drumlin (P28) shows evidence of extensive modification by the sea, which makes the area around the section younger than the original part of the drumlin.

Figure 26: Drumlin P28, Zone A. Sketch of Plate 11

Although the two drumlins P28 and P55 are close to each other, the material comprising them differs. This conclusion is supported as well by the till fabric analysis which is discussed in Section 4.3.

The remnants of drumlin P28 (Figure 27a) leave doubt about what its original form might have been (Figure 27b and c).

Figure 27: Speculation about original form of P28

In addition, the question "Where does the real drumlin (i.e., unmodified till) start?" is not clear, nor is it possible yet to tell how the drumlins and the marine sediments relate to each other (Figure 27d or e). These questions will be addressed later in this chapter.

4.1.2 Summary

In summary the exposures in drumlins of the Bernard Harbour area (excluding P28) are comprised primarily of diamictons. These diamictons are considered to be glacial till. They contain sandy silt or silty sand matrix with abundant clasts ranging in size from gravel to cobble. Clasts are mainly angular to subrounded with only minor rounding of edges and corners. Most clasts have striations. In one case a sand lens - "intratill sand" - could be recognized, but stratified material is almost totally lacking in the exposures. These findings of diamicton do not preclude the existence of stratified material in the interior of the drumlins⁵. Other

⁵The drumlins investigated in the Bernard Harbour area were only opened for 130 cm. However, as the drumlins were modified by the sea it is uncertain which part (depth) exactly of the drumlins was excavated.

workers have found till layers of 1-20 m⁶ over the stratified interior of the drumlins. The huge sections required for this have been mainly road cuts and could not be obtained with the resources available at Bernard Harbour.

It can be concluded that the material in all sections investigated indicate lodgement till with a top layer of till which was reworked by the sea (Table 5).

P	Zone	kind of till considered	till reworked /resedimented	by sea	by solifluction
29	D	lodgement	top reworked	X	X
34	D	lodgement	top reworked	X	7
54	F	lodgement	top reworked	X	7
55	A	lodgement	top reworked	X	7
75	C	lodgement	/sand lenses top strongly reworked (shingles)		

Table 5: Summary of sections cut in drumlins

4.2 Grain-size distribution

Because of the possibility that parts of the drumlins being studied may have been formed by different processes or been reworked by the sea, fifty-four sediment samples were collected in the field from different drumlins. Thirty-two

⁶For example like drumlins in Northern Ireland (Dardis, 1987:216), Hanvey (1987, 1989a:211) or Shaw (1982) where diamicton shows 3.5 m in thickness and other material follows.

⁷Not visible in section, but elsewhere on surface of drumlin.

of these were analyzed for grain-size distribution and the statistics were used to distinguish characteristics of the materials comprising their deposits.

The raw data for the grain-size distributions are provided in Table i of Appendix B. The cumulative curves of the grain-size distributions are in Appendix B (Figures i - vi).

While Figures i and vi show the size distribution of twelve of the samples from six different drumlins, Figures ii, iii, iv and v compare samples from different locations within one drumlin. Except for samples five and seven they all have essentially the same kind of curve with slightly different percentages. In the case of samples 5 (P18) and 7 (P27) the grain-size distributions are of a spit sitting on top of a drumlin (5) and an esker (7).

In Figure ii samples 9B-unit F and 9C⁸ show essentially the same distribution. The distribution of sample 9A has the same slope in the fines (clay and silt), but differs in the amount of sand. Therefore these three samples seem to be subject to the same process, but the original materials seem to have had slightly different compositions. Sample 9B-unit B has fewer fines and a peak in the coarse sand fraction. It can be interpreted as a layer of outwash in Unit F.

⁸All samples are from P29. For locations see Figure 17 and Plate 4.

In Figure iii, all curves (P34) have a similar slope, but sample 7A has approximately 20% less in each class than sample 10A. No differences of material in respect of grain-size distribution could be recognized with depth or location within one drumlin (P34). The samples seem to have had the same history, but the availability of different sizes differs slightly from sample to sample. As these nine samples show only slight differences the remaining seven, which were located between the others, were not analyzed.

The same pattern can be seen in Figure iv, where three samples were taken from different depths in one drumlin (P54). The first sample, taken at a depth of 35 cm, has a higher content of coarse silt and coarse gravel than the other two, which were taken at 70 cm and 105 cm depth. All three have a similar bimodal pattern and they are interpreted as having the same origin but different energy levels at the time of deposition.

Sample 16D from drumlin P55 has a different grain-size distribution from the other four samples from this drumlin (Figure v). The layer from which it was taken is a sand lens which may be interpreted to be an "intertill sand layer" (Dardis and McCabe, 1987:228) beneath the overlying till.

With the above exceptions the materials sampled in the

Bernard Harbour area are till⁹. Gravenor (1953:676/7) discusses in more detail the clay content of drumlins. The Bernard Harbour drumlins have an average of 6.26% clay (range 0% to 11.41 %) and follow Gravenor's conclusion that "clay is not necessary for drumlin formation".

The cumulative curves can be summarized as follows.

Figure 28: Cumulative curves of grain-size distribution, samples from the Bernard Harbour area.

Samples 6 and 2 depart most widely from the general trend of the curves. Sample 2 (P4) has almost no fines, and starts

⁹ According to Krumbein (1933), Johnson (1964) Beurlen (1975:28), Dreimanis (1976), Scott (1976), Haldorsen and Shaw (1982), Eyles (1983), Andrews (1985), Piotrowski and Smalley (1987), and Potschin (1987).

abruptly with the sand fraction; sample 6 (P18) has gravel and medium and coarse grained sand and the most clay, but much less silt. The reason for this is not clear since washing out of silt without causing a corresponding reduction of the clay is unlikely.

Grain-size distribution curves do not indicate the size composition limits of a particular depositional environment, nor how the great variation in range or sorting are related to sub-environments. These aspects can be considered, however, by comparing statistical parameters of the size composition of the sub-environment (Krumbein, 1933; Folk and Ward, 1957; Folk, 1965). The following size characteristics (Folk and Ward, 1957) were obtained:

- 1) mean diameter (M_z)
- 2) phi standard deviation measure (σ_1)
- 3) phi skewness measure (S_{K1})
- 4) phi kurtosis measure (K_G)

The value of these measurements for all analyzed samples are summarized in Table ii in the appendix B. The percentiles were taken directly from the curves and the values are provided in Table iii, appendix B. This allowed a regional comparison of grain-size distributions from the six different drumlin zones.

A triangular graph was prepared to show how the grain-size compositions are related¹⁰. Points representing the limits of the size compositions of a selected group of samples were joined by lines to form a polygon. In keeping with other studies¹¹ the triangular diagram, for summary purposes, was plotted without gravel.

Figure 29: Triangular diagram, samples from the st. area

¹⁰ Raw data for the triangular plot is provided in Table iv, appendix B.

¹¹ Dreimanis (1976), Scott (1976), Eyles (1983), Andrews (1985), Piotrowski and Smalley (1987).

Almost all samples are located in the silty sand and sandy silt portions of the diagram and only a few examples are in the sand component. These include 16D (sand lens), 5 (spit) and 7 (esker), the latter two, excluding their gravel component, falling in this section.

Drumlin samples within Zones A, D and F are very close together and form a concentration. They can be interpreted as being of the same material. Dreimanis (1976:26) differentiates between basal till and ablation till (melt-out till as a sub-group of it). In his triangular diagram all basal till samples are located within the clayey silt sector, and the melt-out tills are located within the silty sand, sandy silt and sand-silt-clay sector, see Figure 30.

Figure 30: Texture of basal and ablation tills
(Dreimanis, 1976:26)

Following Scott (1976:54) the tills in the Bernard Harbour area belong to two till provinces: the "Prairie-Mackenzie Province (IV)" and the "Canadian Shield Province (VII)", which agrees with the ice movement direction in the study area (See Figure 31)

Figure 31: Sand-silt-clay ratios for tills of various till provinces. Modified after Scott (1976:54)

Scott also describes "tills lying near 'S' corner of diagrams are commonly composed of reworked fluvial sediments", and this is where samples 2, 4, 5, 6, and 7 are located. According to Piotrowski and Smalley (1987) the character of the tills investigated in this study are more like the youngest till unit which can be interpreted as melt-out till.

4.2.1 Conclusion

The grain-size parameters for the drumlin-forming till in the Bernard Harbour area do not vary greatly; till in the study area tends to be silty/sandy. Fines (clay and silt) range from near absence to washed material with up to about 55% content of fines by weight.

The combination of grain-sizes in this area is similar to that of melt-out till in other studies. This observation is also supported by the fact that grain sizes tend toward a bimodal distribution. In contrast, the very poor sorting is indicative of lodgement till (Lawson, 1979; Inqua, 1981:6).

It can be concluded that the samples investigated in the Bernard Harbour drumlins show nothing unexpected. The statistical parameters are similar to those calculated for other tills in drumlins. "The median size of such deposits varies greatly; sediments are poorly sorted and phi skewness is more or less zero, ranging from slightly positive to slightly negative skewness" (Reineck and Singh, 1973:181).

4.3 Till fabric analysis

Till fabrics were obtained from five drumlins in the Bernard Harbour area. They were analyzed in two ways. First, the patterns of preferred orientation and orientation strength were considered collectively for the whole area (summary diagrams for all pebbles within one drumlin). Secondly, the individual results from one drumlin were examined and interpreted separately.

Site No.	Zone	DO	O_n	P_n	n
P28	A	87-267°	95.1°	21.0°	47
P29	D	75-255°	95.6°	26.6°	50
P34	D	77-257°	107.2°	32.5°	125
P54	F	52-232°	100.9°	19.4°	66
P55	A	85-265°	66.6°	16.9°	63
P75	C	30-210°	95.9°	18.2°	45

Table 6: Statistical parameters of till fabrics

4.3.1. Contoured Diagrams

To determine whether or not there is a difference within a drumlin or if the same fabric occurs throughout the drumlin fields, contoured diagrams were prepared of the distribution of clast long axis azimuth and plunge and the sample location within the five cross sections (Figure 32). Detailed information is provided in Figures vii - xii of Appendix B.

After the first interpretation of the sections it became obvious that in sample P29 no comparison between depth and length within one drumlin could be made, as the two fabric analyses represent the same depth and length but from two different sections. However, it is interesting that the previously described differences in the material (Section 4.1) also become obvious in the till fabrics. The upper Section B shows disturbance - no cluster of observations - while the pebbles in the lower Section C illustrate a preferred orientation (See Figure vii, Appendix B). Therefore, the upper section can be interpreted as remoulded material, i.e., solifluction or slumping.

In P34 three fabric samples show slightly increasing deviation from the orientation of the drumlin of pebble orientation with increasing depth (Figure viii, Appendix B). It can be postulated that pebbles from the upper layer of

Figure 32: Till fabrics (contoured diagrams) for the Bernard Harbour area

the section show downslope movement, while the pebbles at greater depth remained undisturbed. In the lower unit (101-150 cm) the average direction of pebbles is 107.2° and the mean plunge is 32.5° .

In sample P54 the mean orientation of the pebbles (99.10°) differs greatly from the orientation of the drumlin's crest (52° - 232°) and with distance down slope as well as increasing depth (See Figures ix and x, Appendix B). The mean plunge is 19.45° .

In P55 the preferred pebble orientation comes closer to the trench orientation with both increasing length and/or decreasing depth, which in both cases is a reflection of the fact that the pebbles are located closer to the surface (See Figures xi and xii, Appendix B). This condition can also be interpreted as downslope movement by solifluction activity. However, at a depth of 150 cm, pebble orientation is never parallel to the direction of the drumlin crest.

Analysis of till fabrics in the Bernard Harbour drumlins has provided some interesting results. These include:

1. All six fabrics show no significant preferred orientation. The preferred orientation of pebbles varies between 8° and 65° to the crest of the drumlins ridge.

2. All diagrams follow 'Type D' according to Mark (1974:102) and can be interpreted as pebbles which have preferred orientation transverse to ice movement¹² and a sub-horizontal preferred plan in contrast to parallel orientation and up-glacier dips.
3. The average plunge of all measured pebbles is 22.6° (range 16.9° - 32.04° (See Table 6). Over 33% (range 15.3 to 49%) of the long axes of pebbles plunge 10° or less.
4. The strength of the preferred orientation increases with increasing depth (exception is P34) which might be related to frost action (?).
5. All preferred orientations vary with drumlin orientation by 34.8° on average, and range from 9° to 69.38° (See Table 6).

In summary the contour diagrams from 5 sections show no uniform preferred orientation, although each has moderate orientation.

¹² "Landform orientation" should be used instead of ice movement. Both features are used synonymously in Mark (1974) but in respect of the "alternative hypothesis" might have different orientations.

4.3.2 Conclusion

The collective interpretation of the till fabrics from the five locations as well as the fabric analyses within each drumlin do not have similar orientations. It is suggested that the pebbles in the diamicton body 130 cm beneath the surface have orientations which do not correspond with the ice-movement direction¹³. This conclusion is in agreement with the observation made by Boulton (1968) and Shaw (1972); but it differs from those of Holmes (1941), Harrison (1957) and Donner and West (1957), cited from Shaw and Freschauf (1973:25). Latter also suggested that "stones in till have long-axis orientation approximately parallel to the flow direction of the depositing ice" (Shaw and Freschauf, 1973:25). However, it should be kept in mind, that pebble orientation measurements done in the Bernard Harbour area were only taken from one certain point of the drumlins; other investigations have measurements from various locations of the drumlins. Therefore, results of preferred orientation measurements of pebbles cannot always be compared.

¹³ As estimated on the basis of the orientation of landforms of the area, especially drumlins. For ice-movement direction in the Bernard Harbour area see Section 2.3.1.

Recommendations for future till fabric analyses

Interpretation of the fabric pattern is limited by an incomplete knowledge of the process by which stones become orientated in ice. One of the problems encountered had to do with the shape of the trenches which were cut into the drumlins. Because some of the trenches had horizontal floors, the wall sections were triangular in shape (See Figures 19 and 21). The initial plan called for 10 pebbles to be selected for orientation measurements in each vertical section of one certain width along the wall of the trench. Unfortunately, because it was not possible to excavate all the trenches so that their floors were parallel to the surface, the area of the vertical wall section decreased downslope and there were not always the desired number of pebbles exposed to make orientation measurements. It is recommended, therefore, that at least 25 pebbles be sampled from any future trenches. They may be sampled randomly along the length of the wall or taken from equal wall areas. Fabric analyses should be made below material subjected to solifluction or reworked by the sea. An ideal sampling plan would include different parts of a drumlin.

4.4 Clast analysis

This subject is dealt with separately from the till fabric analysis, because a random selection of clasts from the trench sides was made (See locations in the plates of Section 4.1 in this chapter). There was no preferred shape that could be related to lithology.

4.4.1 Roundness

The results of a study of roundness are presented in Figure 33.

Clast measurements from four drumlins ($n=100$ for each sample) have also been plotted as the ratio between short:intermediate and intermediate:long axes. The results are illustrated in Figure xiii, Appendix B. A general trend toward "equant" can be recognized in all 4 samples, whereas the trend toward a tabular/equant shape is apparent in P34.

The roundness ranges from 2.23 - 2.34 (Figure 33). The similarity of the roundness of the material in the till suggests that the whole drumlin field underwent similar abrasion processes and travel distances with little subsequent modification.

Figure 33: Roundness study of 4 till samples, study area

4.4.2 Lithology

Stone counts were carried out for clasts from 5 drumlin trenches¹⁴ and the results show an overwhelming abundance of locally derived dolomite (Figure 34).

¹⁴ P28 is still treated as an exception, because of its extraordinary character (modification by the sea).

Figure 34: Lithology of clasts in till, Bernard Harbour area

Gabbro comprises approximately 10 % of the till, P55 in Zone A being the only exception. There it makes up 28 % of the sample. Where it is found, the gabbro is highly weathered. There is very little Granite and Sandstone, 3-4% on average; it is difficult to suggest any regional differentiation on the basis of the limited amount of these minor constituents.

In contrast to the clasts of pebble and cobble size from the trenches, the lithology of the boulders sitting on top of the ridges is much more variable, the numbers of

boulders of dolomite being fewer (ca. 50 %). These boulders appear to have travelled englacially (?) and should be considered to be erratics.

Also the provenance of these materials remains to be established; there does not appear to be any extreme lithologic variation within the field area.

4.5 Summary and Conclusion

The following table (next page) describes the till types of the Bernard Harbour field and summarizes the important characteristics of lodgement and melt-out till.

The presence of striations on boulders and clasts suggests that they were transported glacially. The different directions of striae on them indicate melt-out till.

Boulders inside the till body usually indicate a lodgement origin (Shaw, 1982:1562). Not many boulders could be found beneath the surface, but the abundance of boulders on top of the 'modified drumlin surface' indicate that there may be many boulders inside, a fact reported by St-Onge and McMartin (1987) from the Bluenose Lake Region.

All five fabrics are weak to moderate and lie approx-

Chap.		Lodgement Till	Melt-out till	assumed origin for B.H. drumlins
4.1	Macroscopic characteristics Striae on boulder	diamicton parallel striae - small lenses of sorted material	stratification several directions intratill sand lenses or layers	lodgement till melt-out till m-o/lodgement
4.1	boulders in till body	yes	no	lodgement
4.2	grain-size distrib. grain-size sorting	multi-modal very poor	mean 1-6 1.8-3.5	melt-out lodgement
4.4.1	boulder shape	rounded	subr. to rounded	uncertain
4.4.1	roundness of clasts		angular clasts in frozen state carried stay angular	uncertain
4.4.2	Lithology		both lithological and textural, ablation tills are more variable than basal tills of the same stratif. unit	uncertain
4.3	Till fabric azimuth of principal eigenvector S_1	varying < 0.75	rel. unique > 0.75	lodgement lodgement

Table 7: The effect of lodgement or melt-out origin on drumlin materials in the Bernard Harbour area. Based on Draimanis (1976), Krüger (1979), Boulton (1978), Lawson (1979), Shaw (1982).

imately at a right angle to the crest of the drumlin. The azimuth of the principal eigenvector has no distinctive trend and varies greatly. This suggests a lodgement till. This conclusion is in harmony with the appearance of the till body, which has no visible stratification.

The similarity of the roundness (distribution and index) of materials in the till suggests that all six samples underwent similar processes and no zonal differentiation can be made. However, the slight roundness of corners and edges indicates a short distance of fluvial transport. It is suggested that the material in them was derived from the same source area, and formation occurred during one advance (Jones, 1982:65).

The collective properties described above and in Table 7 support an interpretation of deposition by lodgement rather than melt out, as illustrated in Figure 35.

Figure 35: Formation of lodgement and sub-glacial melt-out till (Catt, 1988:42)

Although this sedimentological analysis presents another example of 'the universality of the generally accepted assumption that drumlins are formed by lodgement under wet based glaciers" (Shaw, 1980:287), one cannot state exactly what the whole till body in the Bernard Harbour area was like shortly after its deposition. The upper layer eroded by the sea could have been melt-out or even another type of till.

C h a p t e r V

The morphology of drumlins in the Bernard Harbour area

The study of drumlin morphology is particularly pertinent since it supports much of the previous theoretical and sedimentological work, and it is a geographical framework within which to identify the origin of drumlins.

5.1 The morphometry of the Bernard Harbour drumlins

A total of 2145 drumlins have been studied in terms of location, density, orientation, length, and width. Although morphometric studies from topographic maps and air photographs have their limitation (Rose and Letzer 1975; as cited from Mills, 1987:131; Harry and Trenhaile, 1987:165; and discussed in Steinert, 1987:126), the great advantage of studying such a large number of drumlins from six zones is convincing. Length, width and height are terms which refer to the maximum boundaries of drumlins above an adjoining lake or interdrumlin trough. Plate 2 offers an example of measured and

real boundaries of the drumlin.

Considerable attention has been paid to determine the basal outlines of drumlins correctly, but a certain amount of subjectivity must be involved (Piotrowski and Smalley, 1987: 315). In addition the height and angle of slope of 87 drumlins were measured in the field.

All these properties will be related to local and especially bedrock topography.

Zone	n	Orientation (°)	Length, L (m)	Width, W (m)	L, W ratio :1	Height (m)	Slope (°)
A	247	262	950	233	4.07	9.0	6.4
		242-315	243-3406	104-556	1.3-16.8	3.4-27	1.5-23.5
B	464	238	575	210	2.74	3.6	1.3
		193-271	209-1703	104-487	1.0-12.3	1.7-5.0	1.0-1.5
C	174	216.5	1200	233	5.14	8.5	2.3
		200-241	350-3200	104-420	1.5-17.8	3.4-13.5	0.5-4.5
D	722	266	731	214	3.42	6.0	2.8
		212-310	243-1772	104-521	1.0-7.5	3.4-10.0	1.0-6.5
E	197	307	1200	325	3.68	12.2	4.9
		253-341	313-2641	70-835	1.3-16.3	4.8-17.8	2.0-9.0
F	341	227	751	213	3.52	12.0	4.3
		195-272	272-2502	104-382	1.4-14.4	5.0-20.0	2.5-6.5
* The first line represents mean values, the second line represents the range of measured values.							

Table 8: Summary of drumlin measurements in the Bernard Harbour area (after Potschin, 1989:114)

Table 8 lists the measurements and calculated length/width ratio related to the drumlins studied. Based on morphometric aspect, orientation, and degree of modification by the sea, drumlin fields of the Bernard Harbour area can be divided into six zones (Figure 36).

Figure 36: Drumlin fields of the Bernard Harbour area
Potschin (1989:114)

For a regional comparison the morphometric parameters: length, width, ratio length to width and the height are illustrated in Figure i, appendix C.

As illustrated in this figure, drumlins in the Bernard Harbour area vary greatly in length, but have similar widths throughout the zones. The ratio of these two parameters for the six

zones seems to be similar. However, Zone C, with a mean ratio of 5.14:1 stands out. These results are comparable to those reported from drumlin fields in northeastern and north-central USA (Mills, 1987).

Although many investigations have been made into drumlin form, only a few report data which can be quantitatively compared, and of these, the most useful ones are length and width (Mills, 1987), See Figure 37.

Figure 37: Drumlins - mean length and width
Mills (1987:132) and modified by the writer

Table 9 gives an overview of mean values of drumlin morphometry. Another table in Appendix C (Table i) provides drumlin measurements from the literature review except for those which fall within the limits of Table 9.

mean	data	extreme values by
length	236 m - 2660 m	Mills (1987) - Ebers (1926) Barnett and Finke (1971) - Ebers (1926) Miller (1972:420)
width	110 m - 755 m	
height ¹	3.6 m - 52 m	
ratio l:w	1.54 - 8.0:1	
angle of slope	25° - 40°	

Table 9: Mean values of drumlin measurements, summarized according to Mills (1987)

The shape of drumlins has been approximated by various mathematical models and according to Andrews (1975:166) the most interesting is Chorley's². Smalley and Unwin (1968:381-382) and Trenhaile (1971) discuss advantages and disadvantages of shape models by Chorley (1959) and Reed et al. (1962).

The drumlins of Zone A are "lenticular" drumlins (Kupsch, 1955); in Muller's (1963) system they are "long ovoid", while Shaw (1983) would call them "parabolic". The drumlins in this zone are concentrated in the vicinity of Bernard Harbour. They are 27 m high and have steep slopes of up to 23.5° and sharp crests. The ratio of length to width averages 4.07:1. Although

¹Height is the only parameter of the drumlins in the Bernard Harbour area which is not covered in this literature review. However it has to be kept in mind that these drumlins illustrate a modified surface and not the original form. The lowest value of 4.4. m otherwise is reported from Jauhainen (1975, c.f. Mills, 1987).

²Formulae by Chorley and Reed et al. are discussed in more detail in Section 1.1.1.

the orientation of the drumlins in Zone A varies by 72° , the majority are concentrated between 235° - 265° and have a mean trend of 262° (Figure 36). The largest concentration of drumlins in Zone A lies below 70 m a.s.l., well below the marine limit of 160 m (McMartin and St-Onge, in press); consequently these drumlins have been extensively modified by wave action.

Contrary to the pronounced grouping of drumlins in Zone A, the drumlins of Zone B are widely dispersed. With a mean trend of 238° they have the same general orientation as those in Zone A. measurements of 464 drumlins give an average length of 575 m, mean width 210 m, and a crest height 3.6 m (Plate 21).

Plate 21: Drumlins typical of Zone B illustrate the flatness of the majority of drumlins in the study area.
View west (Photo taken by I.McMartin, June 1989).

The drumlins in Zone B are the smallest in the Bernard Harbour drumlin field. Furthermore, the average ratio between length and width is 2.75:1, which makes them "broad ovoid" (Muller, 1963) or "oval" (Embleton and King, 1975).

Drumlins in Zone C are concentrated in a belt southwest of Cape Krusenstern (Figure 36). The main trend of this field is towards 216° with variations from 200° - 241° . The dominant characteristic of the drumlins in Zone C is their obvious "spindle form" (Shaw, 1983) (Plate 22).

Plate 22: Drumlins typical of Zone C, "spindle form".

The ratio of length to width of 174 drumlins in this field varies from 1.5:1 to 17.8:1, with a mean value of 5.14:1;

both the mean and the absolute values are the highest in the Bernard Harbour drumlin field. Kupsch (1955) would classify them as "ridges". The average length is around 1200 m, but individual drumlins can be more than 3200 m long. These drumlins occur below the upper marine limit and show extensive modification by wave action, in part in the form of large ridges of beach shingles. The average height of 8.5 m reflects a severely subdued and altered set of landforms (Compare Figure 27).

The drumlins north of Basil Bay in Zone D are grouped in a spectacular swarm which trends east to west with a pronounced swing toward the south (Plate 23).

Plate 23: Basil Bay drumlin swarm, Zone D, view west, 7.7.88

Measurements of 722 drumlins in this zone yield an average length to width ratio of 3.42:1 which would classify them as "ovoid" or "lenticular". There is no doubt, however, that the general appearance of these drumlins on air photographs is best described as "parabolic" (Shaw, 1983). They are smaller and more streamlined than those in zone B to the north.

The southwest corner of the map area is part of the Inman River drumlin field, Zone E in this study, a belt 5-45 km wide which extends northwest ward to the shores of Amundsen Gulf, (Figures 36 and 38) north of Bluenose Lake (Craig, 1960-map; St-Onge and McMartin, 1987).

The 198 drumlins in Zone E³ show a mean trend of 307° (Figure 36). The average drumlin length is 1200 m; the average width is 325 m, and the average length to width ratio is 3.68:1. The average height is 12.2 m, and the maximum slope average is 4.9°.

Drumlins in Zone F are slightly higher at the stoss end and have a symmetrical transverse profile. The longest of this set is 2500 m long; it is 12 m high at the northeast stoss end, slopes decrease in elevation down to 8 m in height along most of its length and tapers down to only 5 m at the south-

³Only the drumlins of the Inman River drumlin field located on the Cape Krusenstern map area (87A) were analyzed for morphometric studies of this zone. The ones belonging to the Bluenose Lake Region (Figure 38) west of 116°N are not included.

Figure 38: Morphosedimentary zones of the Bluenose Lake region, "Zone C" here indicates the Inman River drumlin field to which Zone E of the present study belongs to.

west or lee end. This particular feature has a length to width ratio of 14.4:1. Generally, however, drumlins in this zone are 750 m long and 210 m wide and have an average length to width ratio of 3.5:1, which characterizes these drumlins as "lenticular" (Kupsch, 1955), "long-ovoid" (Muller, 1963), or "parabolic" (Shaw, 1983).

Plate 24: Drumlins typical of the eastern part of Zone F.
View NW, 29.7.1988.

The distribution, orientation, shape, and size of drumlins demonstrate that there is a systematic variation in morphology across the Bernard Harbour drumlin fields. These preliminary results make it possible to formulate questions which will be addressed and discussed in the following chapters.

1. "Why do drumlins only appear in certain locations?"
(Section 5.2).
2. "What is the fundamental reason(s) for the pronounced morphological differences between the drumlins studied?"
Is it because of properties of the ice mass or the till, or other factors? (Section 5.3).

3. Why are a few drumlins greatly modified by the sea, while others nearby show only surface washing?" (Section 5.3).
4. "How can the variation in drumlin orientation be explained?" "Do the ice flow patterns represent separate events or do they result from a different flow pattern within the same ice mass (Section 6.1) or were other factors involved (Section 5.3).

5.2 The Quaternary setting of the drumlins

The population density of drumlins in the Bernard Harbour area was calculated by counting the number of drumlins contained within a specific area ; three class intervals are identified (Figure 39). Figure 39 illustrates that drumlins in the Bernard Harbour area as elsewhere are not distributed randomly within the field; their occurrence is often very localized in any one zone. This phenomenon raises the question: "Why do drumlins only appear in certain locations?". Many investigators have offered suggestions; the major ideas are listed below.

Figure 39: Relative density of drumlins in the study area

It has long been known that drumlins are widely distributed in those areas that were glaciated during the last two major ice advances (Wisconsin, Würm, Weichsel), but only a few drumlins are left over from earlier ice ages (Woldstedt, 1954; Embleton and King, 1975:416). However, as Gravenor (1953) has pointed out "many glaciated areas do not have drumlins" which searches for further explanations of the occurrence of drumlins. This requires, as Aronow (1959:202, c.f. Menzies, 1979:329) suggests, that a certain "something" was necessary, before drumlins could form.

It is generally accepted that drumlins are mostly formed at the ice margins (Smalley and Unwin, 1968; Sharpe 1988, McMartin and St-Onge, in press). However, maps of drumlin fields associated with the Laurentide and Fennoscandian ice sheets show that drumlins extended almost to the ice sheet centres (Prest et al., 1970 and Punkari, 1982 as c.f. Shaw et al. 1989).

The availability of till and variations in till strength may favour drumlin formation within a limited zone (Miller, 1972; Hill, 1973; Embleton and King, 1975; Boulton, 1979). While Embleton and King (1975:427) still believe that the 'dilatancy of drumlin forming material is an important prerequisite', a model developed by Smalley (1966) and Smalley and Unwin (1968), Smalley and Piotrowski (1987:81) propose "that the actual dilatant nature of the ground material is not strictly required any more".

It is also recognized that the transition from drumlinized to non-drumlinized terrain is gradational and seems to be related to reduced availability of sediment because the neighbouring landforms are flutings with very little drift (Sharpe, 1988:272). Field evidence supports this interpretation in the Bluenose Lake and Bernard Harbour area (McMartin and St-Onge, in press).

Numerous studies of drumlin fields in their Quaternary setting have shown that drumlins are located in a transition

zone between undrumlinized areas and moraine complexes (Gravenor, 1953:678; Smalley and Unwin, 1968:381; Shaw and Kvill, 1984:1442; Smalley and Piotrowski, 1987:82; Sharpe 1988; Bouchard, 1989:293).

Figure 40: Drumlins in a transition zone, modified according to Smalley and Unwin (1968:380)

Like Smalley and Piotrowski (1987) in Figure 40, Glückert (1987) also found a pattern of morphological transition from the proximal to the distal part of a large drumlin field in Central Finland (c.f., Menzies and Rose, 1987:4); this is also supported by investigations by Boulton (1987), Aario (1987), and Menzies and Rose (1987).

Lundqvist (1970, 1989:281) recognized a transition form between Rogen Moraines⁴ and drumlins, while Habbe (1989:357)

⁴The term 'Rogen Moraine' is discussed in detail and defined by Lundqvist (1989).

studied "drumlins between the glacially incised basin, and behind the terminal moraines". Rôuk and Rankes (1989:371), in Scandinavia, found that "drumlins serve as a transitional landscape type between predominately erosional ... and depositional zones".

It is recognized that the occurrence of drumlins is not related to different bedrock lithology (Shaw and Kvill, 1984; Mills, 1987) as was suggested by several authors in earlier studies (Heidenreich, 1964:106; Savage, 1968:5053; Trenhaile, 1975; c.f. Menzies, 1979).

Other terrain factors such as the preglacial topography (Aronow, 1959:200) were suggested to be responsible for the occurrence of drumlins. An overlay of drumlin distribution and density in relation to elevation illustrates that there is no relation between these parameters in the Bernard Harbour area (See Figures 6 and 39).

Reed et al. (1962:209) suggest that the location of drumlin fields and spacing of drumlins within the fields are controlled by characteristics of moving ice⁵.

A new idea developed by Shaw (1983) and Shaw and Kvill (1984) suggests that drumlins only occur where meltwater was running. This theory should be tested on several drumlin fields.

⁵C.f. Menzies (1979:337) provides list of supporters of this idea.

Most of the above points apply to the Bernard Harbour drumlins. The Late Wisconsinan Ice lobe had its western limit in this area on the eastern slopes of the Melville Hills just west of the Bluenose Lake. The ice, which retreated toward Coronation Gulf, can be divided into four phases of retreat (McMartin and St-Onge, in press). The drumlins in the study area lie in the Phase IV - Stapyhton Bay Phase, Figure 11. In the Bernard Harbour area the drumlins are located in a transition zone between moraine belts and undrumlinized areas (Figure 11, and Landsat photograph in the rear envelope), this is supported by field evidence and mapping of glacial features from air photos.

Field evidence⁶ suggests that drumlins in the Bernard Harbour area are a result of the same ice mass responsible for the set of late glacial landforms on Wollaston Peninsula, Victoria Island (Sharpe, 1985, 1988).

Smalley and Piotrowski (1987:85) suggest that "drumlins should be clustered in the downstream part of the field. Any obvious erosional forms should be in the upstream part of the field". This model is derived from Smalley and Unwin (1968) and had already been used by Fairchild (1929), Hollingworth (1931), Charlesworth (1957), Wright (1957) and Vernon (1966),

⁶In addition, personal communication with David Sharpe, GSC, Ottawa and also supported by McMartin and St-Onge (in press).

as cited in Menzies (1979:339)⁷ (Figure 41).

Figure 41: General conditions for drumlin formation; drumlins are concentrated in the downstream part of the field. Modified after Smalley and Piotrowski (1987:82)

At present, drumlin density studies give no unique explanation for their widespread variability (Jauhiainen, 1975; c.f. Mills, 1987). Comparing the density map of drumlins in the Bernard Harbour area (Figure 39) to the location of moraines (Figure 11) suggests a vague relationship between density and moraines and flutings. In addition there is a relationship between location and the ice margin or centre (Smalley and Piotrowski, 1987). However, flutings in the Bernard Harbour drumlin fields are restricted to a thin drift cover (Sharpe, 1988; McMartin and St-Onge, in press), and the

⁷Hill (1973) states an opposite view that drumlin density frequently declines from the centre to the margins of the field.

transition is gradual. This agrees with investigations on Victoria Island, where Sharpe (1988) reports that flutings are in a transition zone between drumlins and the morainic belt. Further studies are required of the entire area covered by the ice lobe, including Victoria Island and the area southeast of the study area.

5.3 Landscape and features associated with the drumlins

Modification of drumlins by the sea

Almost all drumlins in the Bernard Harbour area are modified by the sea. This fact is not very surprising, as almost all drumlins in the study area are well below the marine limit of 160 m (McMartin and St-Onge, in press) Figure 11. The majority of drumlins show only a modification on the surface. Field evidence demonstrates shell fragments in sections down to 15-20 cm, very occasionally down to 30 cm depth.

Major surface modifications in the Bernard Harbour area have different appearances. One such feature is a huge boulder up to 2.5 m in diameter on top of a drumlin, see Plate 25.

Plate 25: Typical appearance in Zone A, a boulder on top of a drumlin, for example P8, view west, 6.7.88

This phenomena will be called 'modification degree one' here, and was found on numerous occasions during a traverse west of the major drumlin field in Zone A (See Plate 26; on drumlin P8 the boulder can be recognized as a black dot).

Plate 26: Single boulders on top of drumlins, modification degree one, Zone A, Air photo (GSC, A 21509-23)

Taking into consideration that almost no boulders were found in the cross sections (Section 4.1) the easiest explanation for these boulders is that they are dropstones. This would also explain their different lithology⁸. Boulders usually travel much longer distances because they tend to be higher in the ice body. The granitic and gabbroic rock, can only have been derived from the south and southeast of the study area (McMartin and St-Onge, in press). However, it is striking that the boulders on top of the drumlins in Zone A are always located at a certain point (Figure 42).

Figure 42: Location of boulders on drumlins in Zone A

⁸Few of the boulders are dolomite even though the clasts inside the sections are (approximately 95 %). Boulders are mainly Gabbro, Granite or Red Sandstone.

The material behind the boulder stands almost 1 m above the surface of the drumlin. This model demonstrates the same features as an obstacle causing the secondary flow in bedrock (Shaw and Sharpe, 1987), See Figures 4 and 43. Shaw (1980:288) discusses in detail, why these obstacles are pre-existing rather than lodgement till depositing around them.

Figure 43: Erosion marks, Cantley, southern Québec. Flow from right to left. Note the small, remnant medial ridge in the largest erosional mark. (Shaw and Sharpe, 1987:2319)

In Zone A, there is a higher density of boulders, Plates 27 and 28 illustrate an example; See Plate 30 for locations. In this study this feature is called 'modification degree two'.

Plate 27: Bouldery ridge on top of drumlin P56, Zone A,
view west, 26.7.88

Plate 28: Bouldery ridge of drumlin from the air, Zone A

However, studying the air photos of drumlins like P8 and P56 shows beach ridges, and it can be concluded that these abundant boulders are laid free by the sea activity. Another suggestion could be that the distribution could also be a combination of ice shove and mass movement. They might even have been initially boulder barricades on the ridge.

Taking these facts into account, questions like 'are both features the result of the same activity or are they from two different events?' arise. However, at this stage of research it is not possible to provide a definitive answer to this question.

Another, far more spectacular form of modification - beach lines, is found on only a few isolated drumlins, for example drumlin M1 in Plate 29 (See Plate 30 for location). This modification will be called 'degree three' in the following section.

Plate 29: Modification degree three, drumlin M1, Zone A

These beach lines show a strong similarity to lines in undrumlinized features, for example the coastline of Cape Hearne near Basil Bay.

Once the area was completely ice free, sedimentation had all but ceased and marine action was confined to wave washing of emerging landforms much as occurs along the present-day coastline.

(McMartin and St-Onge, in press)

Plate 30: Modification of drumlins, 'degree two' - bouldery ridge (P56) and 'degree three' (M1)
(Air photo, GSC, A 19211-43)

Plate 31: Beach lines on coast of Cape Hearne, Basil Bay

It is striking that this form of marine modification which leaves many beach lines behind, only appears in very specific locations. First, only in Zones A, B and C and secondly, only in the coastal area, Figure 44, and Plate 30.

Figure 44: Modification of drumlins in the Bernard Harbour area. If not indicated otherwise, drumlins show 'normal' surface modification by the sea.

It can be speculated that time is a major factor. These areas were covered by the sea for most of the period of emergence. It is important to note that even along the shore, drumlins of this kind of modification (degree three) alternate with drumlins little affected by the sea. For example P56, a

drumlin with modification 'degree two' - bouldery ridge - is located between two strongly modified drumlins M1 and M2 (Plate 30). This fact raises the question why only these two and not the surrounding drumlins are strongly modified.

Another form of modification was observed: shingle beach composed of abundant clasts. This phenomenon is limited to Zone C, and D, and was not observed anywhere else in the Bernard Harbour area, Plate 32.

Plate 32: Modification of drumlins, shingle beaches P74, Zone C, view NE, 28.7.88

This form of modification is very often associated with spits on top of drumlins, which suggests strong influence by the sea.

Throughout the traverse through Zone A (Plate 26) some striae on dolomite outcrops were observed where the surface was not frost-shattered.

P2	P5	P6	P7
2x 262° 2x 263° 2x 265° 275°	252° 338°	265° 290°	246° 264° 273°

Table 10: Striae on dolomite bedrock, Zone A, location for points see Plate 26; mean orientation of drumlins in Zone A is 262°.

Plate 33: Striae on bedrock, P6, Zone A, view west, 6.7.88

The mean trend of drumlins in Zone A is 262° (Figure 36), and striae on dolomite outcrops show the same mean trend, which is true also for the whole Bernard Harbour area (McMartin and St-Onge, in press).

The air photos of the Bernard Harbour area contain some interesting features and patterns "if you ask the right questions". The whole area, especially in Zone D - the spectacular drumlin swarm - shows abundant truncated drumlins, Plate 34, Overlay No. 1.

Plate 34: Drumlins of Zone D (Air photo, GSC, A 21510-230)
Overlay No.1 demonstrates example for truncated
drumlins, Overlay No.2 shows herringbone pattern.

One possible explanation for these features could lie in secondary flow (Figure 4) induced by meltwater (i.e., the alternative hypothesis by Shaw, 1983). A spiral or helicoidal flow would work backward into an already formed drumlin. This hypothesis is supported by the numerous lakes 'in front' of the drumlins (See Plate 34 - Overlay No.1), and Shaw and Sharpe (1987:2320). Other possibilities are backward cutting by wind or slumping after the melting of the ice body.

Clearly this is a matter about which further investigations are necessary.

Plate 34 of Zone D shows drumlins with interspersed dolomite platforms without any sediments (till) on them. The formation of drumlins stops right in front of these eroded outcrops (Plate 35 and 36)⁹.

It could be suggested, following Shaw's alternative hypothesis, that the meltwater was under much higher pressure as the bedrock is at a higher elevation¹⁰ which made it possible for it to erode all the sediments.

⁹ Also see GSC air photos C'-A 21510-185, D"-A 18910-162, E'-A 21510-229,230, F"-A 18910-28,29,32, I'-A 21509-31.

¹⁰ Determined by overlaying of two maps, the geological one and one of glacial features on the elevation map of the Bernard Harbour area. The outcrops coincide exactly with the contour line of the next higher elevation (100 ft $\approx$ 33 m).

Plate 35: Eroded outcrops, Zone D, air photo (GSC A18910-34)

Till, one of the major requirement of the formation of drumlins, as mentioned in Section 5.2, is no longer available¹¹, Figure 45.

¹¹ D.Sharpe investigated the same phenomena on Victoria Island, east of Wollaston Peninsula (personal communication, 3.8.89, and Sharp, in press).

Figure 45: Model for explaining the eroded platforms of dolomite and the lack of drumlins, not to scale

At present, the drumlins in this area average 5.4 m in height¹² and range from 3.35 to 10 m. The outcrops are at least three times higher than the neighbouring drumlins. Erosion marks in bedrock, which would support the model of meltwater erosion were not observed in the Bernard Harbour area. However, they are reported from different places: p-forms in bedrock in between drumlins from Victoria Island (Sharpe, 1988) and in bedrock from Georgian Bay (Sharpe personal communication, and in press). An alternative explanation would be erosion by the ice sheet itself. Another phenomenon, which can be studied on the air photos is the so called "herringbone pattern" (Sharpe, 1988)¹³. In Zone D, abundant short, oval drumlins occur beside

¹² As mentioned before, values for the original height, before the modification by the sea, cannot be given.

¹³ Shaw, Personal communication, June 1989.

a field of elongated drumlins or within a cluster (Overlay No.2 Plates 35 and 36. These short drumlins occur as individual parabolic forms, which appear to fan out, rather than parallel the elongate drumlins (Overlay No. 2, Plate 36). An en échelon pattern¹⁴ occurs in Zone D, where its principal trend lies between NNW and W (Plate 36).

Plate 36: An en échelon pattern in Zone D
(Air photo, A-21510-233)

¹⁴ En échelon pattern in association with drumlins has "the tail of one [drumlin] rising from the flank of the other as an inclined terrace or shelf" (Flint, 1971:102); or "in steplike arrangement" (Bates and Jackson, 1980:204).

Plate 37 illustrates an oblique view of the en échelon patterns in Zone D.

Plate 37: En échelon patterns in Zone D, view W, 7.7.88

These patterns illustrate another example of the relationship between drumlins and erosional marks. Clustering of erosional marks in conjugate patterns is common (Shaw et al., 1989:fig.8A and 11B; Rose and Letzer, 1977; Shaw and Kvill, 1984; c.f. Shaw et al. 1989). These offset, configuration or échelon patterns of drumlins have a similar locational pattern to erosional marks (Allen, 1982:fig. 7.2). Consult Shaw et al. (1989) for more form similarities. All the drumlins within this study support Shaw's et al. (1989)

observation and description of form similarities between erosional marks and drumlins, all of which point to water rather than ice as the agent responsible for their form.

Another phenomenon associated with drumlins which is described more frequently, is the locational relationship between eskers and drumlins. Plate 38, an air photo from the west corner of Zone B illustrates an example. Figure 11 shows the eskers of the Bernard Harbour area.

Plate 38: Relation of eskers and drumlins in Zone B
(GSC, Air Photo A 21509-81)

Esker ridges, some as long as 10 kilometres, wind between the drumlins and through the fluted terrain, a phenomenon widely described by Prest et al. (1968), Shaw (1983:473), St-Onge (1984:272), Boulton (1987:59), Sharpe (1988:237), and Aylsworth and Shilts (1989:407). Kames and kame terraces sometimes occur but mostly at the downstream end of an esker ridge. Eskers and drumlins in the Bernard Harbour area are oriented in roughly the same direction.

Sharpe (1985) comments that fluted landscapes are spatially gradational to drumlin features, which in turn are transitional to large eskers. He also suggests that drumlinoid and fluted forms could result from meltwater. Shaw (1983) suggests that the drumlins are a result of "large-scale subglacial melt-water channels" and that eskers are the subsequent formation when less melt-water is present.

A striking feature of the Bernard Harbour area is the curving drumlin swarm in Zone D, Figure 36 and Plate 23. The swarm comes from the east, flows parallel to Basil Bay and ends abruptly northwest of the bay. Its westerly end can perhaps be explained by the position of the ice lobe covering this area during its fourth retreating phase. The ice lay between Stapyilton Bay and Klengenberg Bay (McMartin and St-Onge, in press). Explanations for this are offered by Hanvey (1989b) who suggests that

The arcuate nature of the drumlins has been largely attributed to curvature of ice flow paths conditioned by one or more of three factors;

1. deflection of ice due to the convergence of two ice streams.
2. differential ice flow velocity with concomitant curvature of faster moving ice around retarded ice caused by the confined topographical nature ..., with retardation of flow along the bay margins relative to enhanced flow rates towards the central bay axis.
3. differential ice flow velocity with concomitant curvature of faster moving ice around relatively slower moving ice due to differential ice-basal lubrication caused by a variation in basal topography.

Hanvey (1989b)

While the last two points do not appear to apply to the Bernard Harbour area, the first point, the convergence of two ice streams, could have occurred as drumlins in Zone D and E are the result of two different ice lobes (McMartin and St-Onge, in press).

According to Mills (1987:147), the curving flow lines, near the margins are subject to "more variation in direction as the glacier front fluctuates, and locations near the junction of two lobes should be subject to still more variation".

An alternative explanation could be that the melt-water responsible for the formation of these drumlins, was deflected by a stagnating ice lobe coming from the east and flowing westward along Basil Bay forcing the water to move more northwesterly.

Related to the location of drumlins is the variation in drumlin form and size, particularly as all drumlins in the Bernard Harbour area are composed of the same material and are a result of the same ice lobe¹⁵. Such questions as "what causes differences in drumlin form within one field?" need to be answered, because variations in size, crest elevation, length, ratio of length to width, the form in general, and streamlining of the form can occur within the same field. As described in Section 5.1, there are longer drumlins near the parabolic-shaped ones in Zone D (Plate 36), than elsewhere in the study area. It is also important to note that the distribution of the transverse-shaped drumlins have a herringbone pattern, in which the longer drumlins are concentrated in the trough of the wave¹⁶. If drumlin formation is a result of melt-water erosion, these form changes could be explained in terms of the dynamics of water, especially by the velocity of water. In the example illustrated on Plate 35, water flow was from left to right on the photo. One could suggest that the drumlins at the left hand side (A) are the result of faster moving water than the drumlins located on the same 'wave' but beyond B. This would also help to explain the

¹⁵But two different events (McMartin and St-Onge, in press).

¹⁶The concept of a wave pattern in this distribution of drumlins in the Bernard Harbour area was jointly determined by John Shaw and myself during a discussion about this field.

herringbone pattern and the transverse form of drumlins throughout the area. The difference in water velocity in different parts of the field could be the result of pressure increase associated with the dolomite outcrop which can be seen rising above the remaining landscape in the upper half of the photo. Shaw (1983) and Shaw and Kvill (1984) have suggested that morphological variation within a drumlin field formed by subglacial meltwater discharge may be interpreted in terms of regional patterns of melt-water flow (c.f., Harry and Trenhaile, 1987:197).

Explanations for the variability in drumlin form have been suggested also in terms of the classical hypothesis of drumlin formation. Menzies (1987:10) illustrates models to explain the variability in drumlin form¹⁷.

Figure 46: "Bedform transition series beneath active ice"

¹⁷ See also Menzies (1979:339) and Embleton and King (1975:419ff).

Figure 46 cont.: "Bedform transition series beneath active (Menzies, 1987:10)

Mills (1987:143-146) provides a review of the influence of glaciological factors on variation in drumlin forms and gives evidence as to why "constancy of ice flow direction may be the major factor". He also investigated drumlin elongation in relation to geological factors and illustrates that there is no influence related to drift texture, drift thickness and regional slope. However, relief and lithology do have some bearing on degree of elongation. Miller's (1972) study of drumlins in New York state concludes that variations in form "result from variations in glacier bed load and consequent variation in the viscosity of glacier sole". Harry and Trenhaile (1987:169) suggest that in response to progressive decrease in ice thickness and velocity drumlins become smaller and less elongated toward the down-glacier margin of the field.

As reported in Mills (1987), Charlesworth (1957) noted that in SE Wisconsin, drumlin length increases toward the axis of the lobe; Trenhaile (1975) reported a similar finding for southern Ontario; Doornkamp and King (1971) measured length-width ratios in the Eden Valley Fields of NW England and concluded that elongation of drumlins was greatest where the ice was thickest and moving fastest. However, the Bernard Harbour study is based on a small scale example. Up to present it has not been demonstrated that these ideas can be applied to a large scale regional setting. In this respect, further work is required in the Bernard Harbour drumlin field as it is just a small part of a larger field.

From the field study and review of the literature it may be concluded that there is no single explanation as to why drumlins should be formed in certain locations and not in others. Similarly, the variability in form and size cannot be explained through one simple hypothesis. It is possible that all drumlins are different. However,

Some drumlins ... depart dramatically from the classical description. This raises a question of definition as some might argue that features differing from the classical form should not be called drumlins at all. From what follows, the various forms, including classical drumlins, appear to be closely related. So I prefer to follow the practice of earlier researchers of these features and call them all drumlins (Sproule, 1939; Acton et al, 1960; and Bayrock, 1972).

Shaw (1983:462)

5.4 Summary and Conclusion

Orientation, drumlin shape, size and distribution demonstrate that there is a systematic variation in morphology across the Bernard Harbour drumlin field. In general, it can be stated that the observed patterns are in accordance with models which relate drumlin morphology to theoretical variations in ice velocity and pressure in the marginal zones of a glacier lobe (Harry and Trenhaile, 1987). At the same time, however, patterns investigated could be better related to alternative explanations.

The Bernard Harbour drumlins, like the drumlins on Wollaston Peninsula, (Sharpe, 1988:275) have many form elements that are analogous to those of glaciofluvial drumlins and to erosion marks produced by vortices within turbulent water flow (Shaw, 1983).

Some of the speculations, of course, require further examination and investigation. What does seem certain, however, is that some regularities in form patterns are present which were never studied within the 'classical hypothesis', and their relation to subglacial meltwater should be considered.

Chapter VI

Summary and Conclusions

The morphological zones described in the Bernard Harbour study area result from the activity of the last ice sheet during the Late Wisconsinan. The two major trends of drumlins, NE-SW and NW-SE, strongly suggest that they were constructed by two different ice flows which may have originated from the same ice mass to the east.

The sedimentary sequence from the Bernard Harbour area suggests lodgement rather than melt-out till. The sediments largely indicate that although drumlins were formed from lodgement till, they do not appear to have been overridden by deforming ice flow. As most drumlins occur below the marine limit, they display an increasing degree of modification by wave action with decreasing elevation. A 6 m high section in a drumlin in the Bernard Harbour (Zone A) shows a coarsening upward gravelly sequence overlying till (Plate 19). The marine influence is commonly indicated by marine shells and by marine silty clay sediments covering the surface of the drumlins. In some cases raised beaches cover parts or all of the drumlin

(Plate 28 and 30). All drumlins are overlain by a layer of marine reworked sediments 25-30 cm thick, and the drumlins overlie dolomite bedrock.

The field evidence of the till fabric also indicates lodgement rather than melt-out till, and the preferred orientation of clasts has a slightly different orientation from the mean trend of the drumlins. It seems likely that the direction of ice movement which deposited the lodgement till was different from the direction of movement which formed the drumlins by flowing melt-water.

Figure 47: Drumlins formed by melt-water erosion into lodgement till

The till fabric, therefore, suggests an erosional origin rather than a depositional one for the formation of drumlins as proposed by Piotrowski and Smalley (1987).

This concurrence between pebble orientation and orientation of landform suggests a formational relationship, supporting the primary depositional character of the drumlins concerned. Should formation be primarily erosional, preferred orientation of the clasts may be expected to deviate considerably from the drumlin axis, being inherited from the original, pre-drumlin sediments.

Piotrowski and Smalley, 1987:313

However, if the melt-water erosional theory gains more support, the lack of coincidence of the long axes of drumlins with the direction of ice movement need not be a problem, because some studies show a strong preferred orientation of clasts parallel to drumlin orientation. In these cases the ice movement direction and melt-water direction could have been the same, perhaps due to topographic reasons.

The roundness of the clasts in the Bernard Harbour lodgement till is similar throughout the area and suggests glacial transportation rather than a fluvial influence. The lithology of the clasts is dominated by the local dolomite bedrock and the lithology of other boulders indicates their transport from southeast of the study area. Both facts illustrate nothing unexpected. They neither support nor disprove one or the other theory. As for the classical and alternative hypotheses (melt-water erosion rather than

cavity filling) - a variety of evidence is available. The detailed sedimentology of drumlins caused by scouring has little to contribute about their genesis, since any sediment within them predates drumlin formation (Shaw et al., 1989).

This melt-water hypothesis is used to explain the formation of drumlins in the Bernard Harbour area; it is strengthened by the morphology of the drumlins, the herringbone pattern of their distribution, truncation of the drumlins and the 'negative forms between the drumlins'. These features have forms similar to erosional marks (Shaw, 1983; Shaw and Sharpe, 1987).

The erosional mark hypothesis, which is based on air-photo interpretation and field study, appears to give more complete explanation of the individual drumlin shape, the drumlin patterns, the sedimentology of the drumlins, than does the subglacial deformation hypothesis.

Shaw et al. (1989:191)

Sichelwannen, as an example of erosional marks, were most probably formed "as some kind of negative drumlin" (Dahl, 1967; c.f. Shaw, 1983:473). Tarr (1894) had already found that rock drumlins and till drumlins have the same shape and concluded that the same erosive process produced both types (c.f. Gravenor, 1953:676). While Tarr and Dahl identify ice as the agent causing these features, erosional water, as suggested by Lundqvist (1970), rather than ice, is the preferred agent in this study. This is supported by Sharpe (1987:73) who points out why the agent creating erosional

marks must be melt-water rather than ice. Furthermore all restrictions to the erosional theory, given in Gravenor (1953:680)¹ could be explained through the melt-water theory.

A simplified model is presented below (next page) to account for the process of formation of drumlins in the Bernard Harbour area.

To date it is not clear, how or why the huge amount of water accumulated that caused the catastrophic glaciofluvial melt-water event portrayed in Figure 48, step 3.² McMartin and St-Onge (in press) report numerous ice-marginal lakes in the Bernard Harbour area, southwest of the Inman River drumlin field. Kerr (1987a) also reports many glaciolacustrine deposits in the Richardson and Rae River basins. According to Shaw et al. (1989) ice-marginal lakes accumulate enough water to cause the catastrophic meltwater event to form drumlins. The difficulty with the ice-marginal lakes that they are west of the study area, and Kerr (1987a) identified water outlets

¹According to Gravenor (1953:680) "The erosional theory is not acceptable in its present form because of the following objections:

- (1) In many areas where there are till drumlins there is no evidence of readvance of the ice.
- (2) Morainic belts usually are not as wide as drumlin fields.
- (3) The stratified materials found in drumlins is unlike that found in kames."

²Shaw et al. (1989) review the literature on catastrophic melt-water events and discuss the details of how it could be applied to drumlin formation.

Fig.48: simplified model of Quaternary events and the possible formation of drumlins in the Bernard Harbour area with special reference to Zone D

west of Klengenberg Bay, which indicates that the melt-water from these lakes drained eastward into Coronation Gulf. McMartin and St-Onge (in press) also show a drainage system to the north of the Bernard Harbour area into Stapylton Bay. If this is the water outlet for the reported ice-marginal lakes, the water could have drained northward toward the main trend of the Inman River drumlins (Zone E). However, this still does not explain where the melt-water for the formation of drumlins of the remaining zones came from, and further detailed research is necessary. The existence of lakes suggests negative mass balance and possibly warm ice. If so, perhaps the lakes were linked via englacial/subglacial (?) drainage systems, and, depending on their elevation, and the head of pressure generated, even responsible for the direction of flow of subglacial water.

Sharpe (1988:266) reports that melt-waters on Wollaston Peninsula were able to drain freely to the west but it remains to be seen if these melt-waters also could have reached the neighbouring Bernard Harbour area.

The argument for the fluvioglacial erosion of drumlins is not reduced by facts which also support the classical hypothesis. Striae in Zone A have the same direction as the mean trend of drumlins. The presence of homogeneous material (diamicton) does not disprove the alternative hypothesis, according to which drumlins are formed in pre-existing till.

Stratification is not a condition for the fluvioglacial erosion theory, although it is for the cavity-filling hypothesis.

6.1 Conclusions

This thesis is a regional study of a drumlin field and combines sedimentological, morphological and theoretical approaches. It provides information about regional patterns of ice movement and contributes to new or revised concepts of drumlin formation.

The investigation of drumlins in the Bernard Harbour area has produced several interesting facts:

First, the sedimentary composition of drumlins can be attributed to lodgement deposition processes operating prior to drumlin forming events.

Second, the preferred orientation of pebbles indicates lodgement till rather than melt-out till. However, it deviates slightly from the direction of the investigated drumlin's crest, and may be the result of a different direction of movement for the drumlin forming agent.

Third, a large moraine belt west of the drumlins forms a transition zone to undrumlinized terrain (Figure 11).

Fourth, the relationship of drumlins and eskers suggests formation of drumlins through stagnation of ice rather than actively flowing ice.

Fifth, the Bernard Harbour drumlins have many form elements that are similar to those of fluvioglacial drumlins (Shaw, 1983) as well as to erosional features.

Sixth, the absence of moraines related to ice retreat over the Bernard Harbour drumlins indicates regional stagnation followed by drumlin formation and ice thinning.

The accumulation of subglacial water is considered to have triggered the ice calving, but it is likely that this was preceded by a mass of thick ice which had to melt free from the ground in the reservoir area. Catastrophic drainage was the result (Shaw et al., 1989). Mass wasting of the resulting thinner ice mass in situ produced no ice-marginal or outwash sediments in between drumlins other than small interdrumlin eskers and kames.

Z O N E					
	A	B	C	D	E	F
<i>mean drumlin orientation</i>
<i>till fabrics</i>
<i>bedrock striae</i>
<i>herringbone pattern</i>			NO	YES		partly
<i>truncated drumlins</i>			YES	YES		YES

Table 11: A comparison of structural, textural and orientation elements of the Bernard Harbour drumlin field to morphology

A major conclusion of this study is that the formation of drumlins can be the result of different processes. None of the prevailing theories are entirely satisfactory as a means to explain findings in the Bernard Harbour area. The drumlins themselves are so different that it has to be accepted that no single explanation can satisfy all of them.

However, evidence from the field and laboratory work on the Bernard Harbour drumlins can be more completely explained by the fluvioglacial melt-water erosion theory than any of the others. The classical theory and the 'cavity hypothesis' fail to explain fully the morphological patterns described in this study.

6.2 Recommendation for Further Research

Rarely is it possible in a single field season to collect as much information as one would like for a subject as complex and controversial as drumlins. Certainly, in the context of this study, time and the difficulty of working in a permafrost environment limited what could be done. Nevertheless much was learned about the morphology of the Bernard Harbour drumlin field and a good start was made on the near surface character of the drumlin materials. On the basis of the experience gained recommendations are made for future drumlin research. Thus, (1) A variety of explanations for drumlin morphology is introduced keeping in mind Menzies's point that, "if this multiform origin is the case, then a process of categorization of drumlin forms must occur first before further speculative processes of formation can be ascribed" (Menzies, 1987:22).

(2) Further Research on till fabric, as described in Section 4.3.2.

(3) If the glaciofluvial erosion theory is correct, there has to be a huge amount of outwashed sediments some where. The Bernard Harbour area was covered by an ice lobe which extended northward into the Dolphin and Union Strait, so the outwash is likely to be there. However, this applies also to all drumlin fields, which might be formed by melt-water erosion, and further research is desired on this point as one of the major kinds of evidence which will support this theory.

(4) Previously investigated drumlin fields should be reexamined (for point 3) to determine the relationship of melt-water channels to drumlins. This could be done with the help of a Geographical Information System. Because drumlins are frequently associated with huge melt-water channels, or where there was much melt-water, further study of this matter could provide greater support for or against the melt-water erosion theory. Additional research on and modelling of ice-marginal lakes and their drainage patterns ought to be an integral part of such studies.

(5) Shaw et al. (1989) suggest how a catastrophic melt-water event could have happened. The limitations and uncertain implications of some of the evidence collected in the Bernard Harbour area suggests that further research should be done on the work initiated by Wright (1973) and Boyd et al.

(1988) (c.f. Shaw et al., 1989).

(6) Effort should also be made to provide better answers to the question "are drumlins more similar to moraines or eskers?". This is especially true in light of the presence of subglacial glaciofluvial material associated with the Bernard Harbour drumlins and their possible locations near the edge of an ice sheet.

(7) Some questions remain unanswered about the modification of drumlins by the sea, and it is hoped that this study will stimulate further research in this field.

(8) Finally, further comparison with other research projects, especially in other countries, should provide new insights or alternative interpretations.

A p p e n d i x A

I n t r o d u c t i o n

Table 1: Main contributions to the origin of drumlins (in alphabetical order)						The contribution is used by the following author's to support their own theory. The writers comments are in brackets.
Name ¹	Year ²	Study Area ³	T ⁴	Sub ⁵	S ⁶	L ⁷
Aario	1977	Finland	(A)	3		
Alden ⁸	1918	SE Wisconsin		3	x	
Allen	1982		A			
Baranowski	1970	Svalbard		1		

¹The complete reference is listed in the bibliography.

²Only the major contributions are listed, the whole period of work is mentioned in the column 'comments'.

³If a publication is theoretical only (no field work reported), this column is blank.

⁴"A" stands for alternative hypothesis; brackets mean "precursor", or the facts support this theory, but the author did not write directly "I agree with...". "C" stands for conventional hypothesis.

⁵Suborder 1-4 according to Menzies (1984) 5 and 6 according to Sharpe (1988).

⁶This column indicated if the author(s) report stratified material. The presence of stratified material is indicated by an "X"; a blank indicates no information.

⁷This column shows if the publication can be classified as a 'landmark in Drumlin Research'.

⁸Cited from the references in the last column.

⁹In the following Embleton and King (1975) will be only cited as E & B; Dardis and McCabe (1983, 1987) as D & M; Harry and Trenhaile (1987) as H & T; Shaw and Kvill (1984) as S & K; Shaw and Freschauf (1973) as S & F; Shaw and Sharpe (1987) as S & S; Shaw et al (1989) as Shaw et al.; Smalley and Unwin (1968) as S & U;

Name	Year	Study Area	T	Sub	S	L	
Boulton	1979/82	Spitzbergen	C	4			Andrews (1975), DEM (1983, 1987), De Jong et al. (1982), Drenth (1986), Haldoren and Shaw (1982), Menzies (1982, 1987), Muller (1974), Rose (1987), Sharpe (1985, 1988), Shaw (1980, 1982, 1983, 1987), S&F, S&K, Shaw et al., Smalley and Piotrowski (1987) [Boulton has been testing a variety of hypotheses in the field since 1968]
Charlesworth	1957	Theory		3			Aronow (1959), Chorley (1959), Menzies (1987), Miller (1972), Mills (1987), Muller (1974), S&K, S&U, Trenhaile (1971). [Besides his more theoretical paper in 1957, Charlesworth made other contributions between 1924-1967]
Chorley	1959		C	5		X	Aario (1987), Andrews (1975), E&K, Evans (1987), Flint (1971), H&T, Krüger (1987), Mills (1987), Muller (1974), Reed et al. (1962), S&F, Shaw et al., S&U, Steinert (1987), Trenhaile (1971). [Chorley's only paper but a major one on drumlin morphology]
Dahl	1965	Finland	(A)				Boulton (1974), Sharpe (1987), Shaw (1983), S&K, S&S. [Dahl developed the terminology of 'Sichelwannen' in Finland]
Dardie & McCabe	1983	Ireland	(A)		X		Boulton (1987), Menzies (1987), Sharpe (1987, 1988), Shaw (1983), Shaw et al. [Dardie and McCabe are still working on drumlins, together or in separated contributions. However, both specialized on the explanation of stratified material in drumlins in Northern Ireland, contribution also in 1987, 1989]
Ebers	1926	Germany			X	X	DEM (1983), Habbe (1988), Kupsch (1955), Menzies (1987), Muller (1974), Shaw (1983), S&F, S&U, Steinert (1987). [Ebers made other contributions between 1926-1977]
Fairchild	1929	New York State	C	3		X	Aario (1987), DEM (1987), Gravenor (1953), Miller (1972), Muller (1974). [Contributions are between 1900-1932]
Flint	1971		C	1	X		Boulton (1975, 1976), DEM (1983), Dionne (1987), E&K, Jones (1982), Muller (1974), Rabassa (1987), Rose (1987), S&F, S&U, Steinert (1987). [Flint changes from his idea of drumlins being the result of erosion (1947) to deposition (1971)]
Gillberg	1976	Sweden	(A)	1	X		Aario (1987), Sharpe (1985), Shaw (1980, 1983), S&K.
Goldthwait	1974	E-coast NA	C	1			DEM (1983, 1987), Menzies (1979), Sharpe (1985, 1987), Steinert (1987).
Gravenor	1953	Ontario	C	1	X	X	Aario (1987), Aronow (1959), DEM (1983, 1987), Dionne (1987), E&K, H&T, Jones (1982), Kupsch (1955), Menzies (1982, 1987), Miller (1972), Muller (1974), Rabassa (1987), Sharpe (1985, 1987, 1988), Shaw (1980, 1983), S&K, S&U.
Gravenor & Meneley	1958	N-Alberta		1			Aario (1987), Jones (1982), Reed et al. (1962), Sharpe (1987), Shaw (1980, 1983), S&F, S&K. [The theory that drumlins are a result of 'englacial agglomeration' was developed by Gravenor and Meneley]

Name	Year	Study Area	T	Sub	S	L	
Hoppe & Schytt	1953	Sweden		3			Aario (1987), Boulton (1976, 1982), E&K, Jones (1982), Sharpe (1985), Shaw (1980), S&F. [Hoppe contributed between 1951-1968]
Jones	1982	Alberta	A	3			Menzies (1987), Sharpe (1985), Shaw (1983), S&K.
Kupsch	1955	Saskatchewan		1	x	x	D&M (1983), E&K, Muller (1974), S&K, S&S.
Lenke	1958	North Dakota	C	1	x	x	Aronow (1959), D&M (1983), E&K, Gravenor and Meneley (1958), H&T, Sharpe (1985, 1987), Shaw (1983), S&K. [Lenke "considered the possibility of deposition in a cavity but rejected it because of the difficulty of explaining the origin of the cavity" Shaw (1983:474)]
Lundqvist, J	1970	Sweden	(A)	1			De Jong et al. (1982), E&K, Menzies (1982, 1987), Rabassa (1987), Shaw (1983), S&K. [Lundqvist is working on glacial deposits in general since 1958, but concentrates recently more on moraine and developed the term 'Rogen Moraine' (1969), another major contribution in (1989)]
Menzies	1979	Literature Review	C				Aario (1987), Dardis (1987), D&M (1983, 1987), De Jong et al. (1982), Dionne (1987), Habbe (1988), Hanvey (1987), H&T, Jones (1982), Krüger (1987), Rose (1987), Sharpe (1985, 1987), Shaw (1980, 1983), Shaw et al., Smalley and Piotrowski (1987), Steinert (1987) [Theoretical review on the literature, Menzies published a bibliography on drumlins in 1984, and edited two major contributions on drumlin research together with Rose, the Drumlin Symposium in 1987 and a special edition of Sedimentary Geology on drumlins in 1982]
Moran et al.	1980	Prairies NA		3			Boulton (1987), Haldorsen and Shaw (1982), Jones (1982), Menzies (1987), Sharpe (1985), Shaw (1983), S&K.
Muller	1974	Theory	C	3		x	D&M (1987), De Jong et al. (1982), Dionne (1987), Hanvey (1987), H&T, Menzies (1979, 1987), Rabassa (1987), Sharpe (1987), Shaw (1980, 1983), S&K.
Paul & Evens	1974	Spitzbergen	(A)	1			Boulton (1976, 1982), Sharpe (1988), Shaw (1980).
Reed et al.	1962	Aerial Photos		1+3		x	Aario (1987), E&K, Evans (1987), Flint (1971), Krüger (1987), Mills (1987), Muller (1974), Shaw et al., S&U, Trenhaile (1971). [Reed et al.'s only paper on drumlin morphology]
Rose & Letzer	1977	Scotland					H&T, Krüger (1987), Sharpe (1987), Shaw (1980, 1983), S&K, Shaw et al., Steinert (1987). [Rose as editor see Menzies (comment)]
Sharpe	1985	Victoria Island	A	5	x		Dionne (1987), H&T.
	1988	Victoria Island	A	6	x		McMartin and St-Onge (in press), Shaw et al.
Shaw	1983	Saskatchewan	A	5	x	x	Boulton (1987), Dardis (1987), D&M (1987), Hanvey (1987), H&T, Jones (1982), Menzies (1983, 1987), Sharpe (1987). [Development of alternative hypothesis]
Shaw & Freschauf	1973		A	(5+6)			Boulton (1976, 1987), Menzies (1979, 1987), Muller (1974), Sharpe (1987).

Name	Year	Study Area	T	Sub	S	L	
Shaw & Kvill	1984	Saskatchewan	A	5			Boulton (1987), Dardis (1987), DeM (1987), H&T, Menzies (1987), Sharpe (1987).
Shaw et al.	1989		A	5+6			[Idea of 'catastrophic meltwater event']
Shaw & Sharpe	1987		A	6			
Slater	1929	Lake Ontario		3	x		DeM (1983, 1987), Plint (1971), Gravenor (1953), Kupsch (1955), Muller (1974), Sharpe (1987, 1988), Shaw (1983), Steinert (1987).
Smalley & Unwin	1968		C	4		x	Aario (1987), Boulton (1987), De Jong et al. (1982), Dionne (1987), E&K, Eyles (1982), Habbe (1988), Haldorsen and Shaw (1982), H&T, Menzies (1979, 1982), Muller (1974), Rabassa (1987), Rose (1987), Sharpe (1985, 1987, 1988), Shaw (1980, 1983), S&F, S&K. [This contribution is always cited as 'the example' for the conventional hypothesis]
Upham	1892	Boston		3	x		Aronow (1959), Gravenor (1953), Muller (1974), S&K. [Upham found stratified material inside drumlins in 1892, but without being able to give it an explanation]
Whittecarr & Mickel	1979	Wisconsin	C	1	x		Aario (1987), Dardis (1987), DeM (1983), De Jong et al. (1982), H&T, Sharpe (1985, 1987, 1988), Shaw (1980, 1983), S&K. [major contributions since 1976]
Wright	1957	Minnesota	(A)C				Andreva (1975), De Jong et al. (1982), E&K, Gravenor and Menzies (1958), Mille (1987), Menzies (1979), Muller (1974), Sharpe (1987), S&F. [Major contribution on till fabrics in drumlins]

Flora

Family	-	Suborder	-	engl.term.
Asteraceae	-	Antennaria compacta	(1)	
Beculaceae	-	Alnus spp.	(1)	
Brassicaceae	-	Cardine pratesis	(1)	
Caryophyllaceae	-	Stelleria monthana	(1)	
Cruciterae	-	Draba cinerea	(2)	
	-	Lesquerella arctica	(2)	
Cyperaceae	-	Eriphorum triste	(1)	
	-	Carex rupestris	(2)	Sedge
Compositae	-	Artemisja richardsoniana	(2)	
Ericaceae	-	Ledum groenlandicum	(1)	
Fabaceae (1)	-	Oxitropis spp.	(1)	Oxitrope
Leguminosae (2)	-	Oxitropis arctica	(2)	
	-	Oxitropis arctobia	(2)	
	-	Oxitropis hyperborea	(2)	
	-	Lupinus arcticus	(2)	
Poaceae	-	Poa arctica	(1)	Bluegrass
Primulaceae	-	Androsace chamaejasme	(2)	
Ranunculaceae	-	Ranunculus pygmaeus	(1)	
Rosaceae	-	Dryas integrifolia	(1,2)	
	-	Potentilla rubriculis	(2)	Cinquefoil
Scrophulariaceae	-	Pedicularis capitata	(1,2)	Lousewort
Saliaceae	-	Salix arctica	(1)	Willow ar.
Saxifragaceae	-	Saxifraga oppositifolia	(1,2)	Saxifrage
	-	Betula nana	(1)	Arctic Dwarf Birch

Table ii: Flora observed in Bernard Harbour area

FaunaMammals

Bear	- brown or grizzly	Ursus arctos
Caribou	- Canadian barren gr.	Rangifer tarandus
Fox	- arctic	Alopex lagopus
Hare	- arctic	Lepus arcticus
	- tundra	Lepus othus
Lemming	- brown	Lemmus sibiricus
Marmot	- hoary	Marmota caligata
Muskox	- ?	Ovibos moschatus ?
Seal	- ?	?
Squirrel	- arctic ground	Spermophilus undulatus
Wolf		Canis lupus

Birds

Duck	- Labrador	Camptorhynchus labradorius
Falcon	- peregrine	Falco peregrinus
Goose	- Canada	Branta canadensis
Gull	- ?	?
Hawk	- ?	Buteo ?
Jaeger	- long-tailed	Stercorarius longicaudus
Loon	- arctic	Gavia arctica
	- red-troughted	Gavia stellata
Owl	- snowy	Nyctea scandiaca
Ptarmigan	- ?	Lagopus ?

Fish

Char	- Arctic	Salvelinus alpinus
Trout	- Lake	Salvelinus namay cush

Table iii: Fauna observed in Bernard Harbour Area

A p p e n d i x B

S e d i m e n t o l o g y

Sample No. W(PS) 32	Site No.	Alt. Elev. ft.	Loc. H. S. A.	Elevation m	Elevation ft.	Depth m
1	P1	A21509-27	14	18°45'40"	114°59'50"	6' m
2	P2	A21504-28	13	68°41'40"	115°02'10"	6' m
4	P11	A21507-29	11	68°43'50"	114°59'50"	6' m
5	P18	A21510-230	1	68°15'40"	114°44'50"	6' m
6	P15	A21510-230	6	68°17'40"	114°52'10"	6' m
7	P27	A21510-234	5	68°16'24"	114°08'55"	105 m
8 (400)	P29	A18910-36	6	68°21'28"	114°30'35"	40 m
11 (200)	P34	A18910-34	1	68°00'30"	114°24'20"	41 m
13	P46	A21507-31	10	68°39'02"	114°05'30"	92 m
15 (200)	P54	A21509-31	12	68°39'08"	115°35'20"	50 m
16 (500)	P55	A19211-42	14	68°46'01"	114°46'51"	15 m
17	P75	A18910-29	6	68°23'10"	114°13'55"	15 m
18	P78	A21509-71	12	68°25'24"	115°17'25"	105 m
19	HD1	A19211-42	14	68°47'00"	114°50'23"	20 m
20	HD2	A19211-42	14	68°47'00"	114°50'23"	20 m

Table 19: Location of samples in the Beaufort Harbor area

CLAY	SIF	SIM	SIC	SVF	SP	SM	SC	SVC	VFGR	FGR	MGR	CGR
2	2-5	5-20	20-50	>0.05	>.1	>.25	>.5	>.1	>.2	>.4	>.8	>.16
1	2.27	3.97	8.51	18.51	25.57	35.08	44.92	55.51	65.19	76.3	86.71	100
2	0	1.12	7.92	8.91	11.32	16.65	26.53	39.24	55.97	70.64	96.71	100
4	0.31	0.52	3.52	4.38	9.29	17.21	26.69	36.48	51.19	65.63	86.46	100
6	0.12	0.47	3.17	8.87	11.62	15.27	25.12	37.63	50.03	60.84	78.75	100
7	0.3	0.91	4.24	11.34	13.26	14.9	20.31	33.15	46.39	64.19	81.34	100
91	5.54	9.23	19.38	38.01	44.91	51.8	57.5	63.07	68.56	74.32	80.86	100
92	2.5	13.3	25.52	32.16	41.11	50.75	62.1	73.97	84.64	91.44	98.81	100
93	9.38	14.74	26.8	44.06	51.66	59.51	66.27	72.99	79.9	86.67	92.15	100
94	9.32	14.34	27.25	42.78	50.31	58.05	64.69	71.51	78	85.36	91.72	100
110	5.4	10.12	20.92	36.92	42.76	46.61	50.75	57.13	64.2	76.87	85.32	100
117	8.02	12.96	24.68	42.69	49.67	54.55	59.46	65.52	72.02	78.98	85.32	100
1170	6.94	11.21	21.35	35.86	42.11	46.45	50.91	56.39	62.19	68.34	74.95	100
1110	8.12	11.08	26.59	43.21	50.63	55.99	61.2	67.41	73.95	81.14	89.23	100
11100	9.04	15.37	29.83	47.17	55.3	61.34	67.18	74.11	80.99	88.69	94.92	100
11101	9.08	14.53	27.83	44.13	51.41	56.96	62.06	68.22	74.32	80.71	86.1	100
1111	5.38	11.53	23.83	44.85	51.58	56.56	61.76	68.06	74.58	81.46	87.99	100
11110	5.25	9.45	20.47	35.61	41.41	45.72	49.96	54.86	59.81	65.13	70.53	100
11111	8.44	12.66	25.92	42.32	54.52	60.99	67.53	73.64	80.28	86.28	91.27	100
13	9.28	13.92	25.52	43.02	57.06	68.94	75	83.79	89.59	94.93	99.9	100
15	7.76	12.53	22.08	43.02	57.06	68.94	75	83.79	89.59	94.93	99.9	100
150	6	11.53	19.83	33.15	44.25	53.44	58.26	61.69	65.05	69.25	75.04	100
151	10.93	15.3	24.48	35.97	47.34	54.81	59.6	63.27	67.15	71.62	76.62	100
16	9.72	12.96	20.36	30.5	41.4	56.3	64.92	71.13	77.8	81.79	88.45	100
160	10.43	14.08	22.42	35.03	46.52	56.3	64.92	71.13	77.8	81.79	88.45	100
161	6.23	8.65	14.53	25.93	38.81	59.09	69.94	77.13	82.06	85.29	92.79	100
162	1.6	1.78	3.02	5.93	11.45	39.86	79.12	95.89	98.35	99.6	100	100
163	9.12	15.81	28.58	44.96	54.45	64.39	70.77	75.79	80.82	85.47	90.69	100
17	7.54	10.64	19.07	31.09	41.37	50.37	54.87	59.25	61.71	66.34	72.21	100
18	7.3	10.34	18.85	27.32	39.37	56.75	66.38	72.75	76.32	80.69	88.14	100
19	11.41	15.21	25.36	39.66	55.04	73.31	82.16	84.89	86.86	89.34	92.47	100
20	0.12	0.49	3.78	6.68	7.07	9.68	26.58	63.89	73.58	83.71	95.2	100

Table I: Raw data of grain-size distribution (cumulative curves) additive

3

of/de

3

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

CUMULATIVE GRAIN SIZE DISTRIBUTION

SAMPLES 1,2,4,6,7,9A

Figure i

CUMULATIVE GRAIN SIZE DISTRIBUTION

SAMPLES 9A,9B-B,9B-F,9C (P29)

Figure ii

CUMULATIVE GRAIN SIZE DISTRIBUTION

SAMPLES 11-0,-7,-7A,-10,-10A,-10B (P34)

Figure 1

CUMULATIVE GRAIN SIZE DISTRIBUTION

SAMPLES 15,-A,-B (P54)

Figure 2

Figure v

Figure vi

sample	point no	Mean	Stand.Devi.	Skewness	Kurtosis
		2.910333	-2.76075	-0.29115	1.607507
2	P 4	-0.47333	-2.77737	-0.29053	1.155510
4	P 11	-0.67766	-2.60162	-0.23336	0.819672
5	P				
6	P 19	-1.44466	-2.58212	-0.05825	1.124056
7	P 27	0.125	-2.92965	-0.36812	1.461740
91	P 51	3.204166	-4.44845	0.080478	0.404803
92	P 29 B-B	2.951333	-3.92078	-0.25983	0.838413
93	P 29 B-F	4.32	-4.21591	0.138506	0.646259
94	P 29	4.116	-4.35812	0.088824	0.458862
110	P 34-0	2.946333	-4.54951	-0.18873	0.603083
117	P 34-7	3.503666	-4.46245	-0.05235	0.591131
1110	P 34-10	3.880333	-4.48328	0.135425	0.614489
11100	P 34-10A	4.362	-4.04415	0.073897	0.598766
1111	P 34-11	3.625333	-4.46693	0.023946	0.638761
11110	P 34-11A	2.427	-5.01532	-0.11610	0.520844
		3.856666	-4.55131	0.177292	0.620956
13	P 48	4.583333	-4.00784	0.638773	0.787233
15	P 54	4.527666	-4.00996	0.144591	0.837817
151	P 54 B	3.049	-4.64377	0.144439	0.611598
16	P 55	3.889	-4.62870	0.059298	0.758747
161	P 55 B	3.851	-4.55262	0.057363	0.859020
162	P 55 C	3.479333	-4.28082	0.093087	0.991536
17	P 75	4.346333	-4.31161	0.073662	0.697018
18	P 78	2.975666	-5.02082	0.104026	0.591023
20	HD2	4.967333	-3.99438	0.013964	0.944423

Table II: Statistical parameter for grain-size analysis

Number of Percentiles	Percentiles							
	5	16	25	50	75	84	95	
3								
4	6.75	2.104	1.25	-0.67	-2.35	-2.854	-3.4	
5	4.25	2.25	1.25	-0.975	-2.75	-3.308	-3.75	
6								
7	7.437	0.083	0.958	-1	-3.15	-3.417	-3.83	
8	8.25	2.75	1.583	-0.25	-1.583	-2.125	-3.042	
9								
10	9	7.75	5.625	2.042	-0.017	-0.934	-2.542	
11	9.912	8.834	8.563	4.709	0.771	-0.583	-2.375	
12								
13	9.208	8.664	7.751	2.083	-0.8	-1.908	-3.375	
14	9.708	8.805	8.14	3.289	-0.396	-1.583	-2.604	
15								
16	9.708	8.769	8.531	4.284	0	-1.412	-3.083	
17	9.334	9	8.625	4.419	0.896	-0.333	-1.958	
18								
19	9.582	8.734	8.126	3.6	0	-1.458	-3.083	
20	9.458	8.656	7.437	2	-2.989	-3.375	-3.792	
21								
22	9.834	9	8.5	4.589	2.333	0.167	-2.042	
23	9.834	8.75	7.996	4.875	2.146	-0.042	-2.125	
24								
25	9.458	8.063	7.35	3.667	-1.417	-2.583	-3.625	
26	10.167	9	8.313	4	1.021	-1.333	-3.333	
27								
28	10.125	8.886	7.751	4	1.46	-1.333	-3.061	
29	9.604	8	6.15	3.771	0.837	-1.333	-3.25	
30								
31	9.75	9.188	8.593	4.384	1.292	-0.533	-2.667	
32	9.5	8.761	6.938	3.458	-2.25	-3.292	-3.75	
33								
34	10.017	9.188	8.5	4.589	2.833	1.125	-3.042	

Table III : Percentiles from grain size distribution curves

Sample no	clay	silt	sand
1	3.48	24.92	71.60
2	0	20.18	79.82
4	0.86	8.98	90.16
6	0.31	23.25	76.44
7	0.65	23.80	75.55
91	8.08	47.37	44.55
92	3.37	31.13	65.50
93	11.70	43.25	45.05
94	11.88	42.67	45.45
110	8.15	47.61	44.24
117	11.14	48.14	40.72
1170	11.15	46.46	42.39
1110	10.98	47.45	41.13
11100	11.16	47.08	41.76
11101	12.20	47.16	40.64
1111	7.22	52.92	39.86
11110	8.77	50.75	40.48
11111	11.46	48.50	40.04
13	11.27	40.13	48.60
15	9.26	42.08	48.66
150	11.34	39.61	49.05
151	8.93	41.85	49.22
16	14.05	32.19	53.76
160	13.76	30.10	56.15
161	13.29	31.35	55.36
162	6.10	26.08	67.82
163	1.62	4.40	93.98
17	11.29	44.34	44.37
18	12.22	38.18	49.60
19	10.03	27.52	62.45
20	16.93	31.11	51.96
5	0.19	10.26	89.55

Table iv: Raw data for triangle plot

Figure vii: Till fabrics with increasing depth
for P29 - Zone D

Figure viii: Till fabrics with increasing depth
for P34 - Zone D

Figure: ix: Till fabrics with increasing depth
for P54 - Zone F

P54-1
Zone F
0-1 m length
DO=52-232.
Om=93.93.
Pm=25.93.
n=14

P54-3
Zone F
4-7 m length
DO=52-232.
Om=87.62.
Pm=15.58.
n=24

P54-4
Zone F
7-10 m length
DO=52-232.
Om=92.2.
Pm=37.5.
n=10

P54-5
Zone F
10-15 m length
DO=52-232.
Om=103.25.
Pm=12.9.
n=20

Figure x: Till fabrics with increasing length for P54 - Zone F

Figure xi : Till fabrics with increasing depth
for P55 - Zone A

P55-4
Zone A
3-4 m length
DO=85-265.
Om=79.5.
Pm=20.17.
n=6

P55-3
Zone A
2-3 m length
DO=85-265.
Om=71.25.
Pm=12.94.
n=16

P55-2
Zone A
1-2 m length
DO=85-265.
Om=65.4.
Pm=19.3.
n=20

P55-1
Zone A
0-1 m length
DO=85-265.
Om=49.07.
Pm=13.29.
n=14

Figure xii : Till fabrics with increasing length for P55 - Zone A

Table xlii: Roundness of clasts

A p p e n d i x C

M o r p h o l o g y

			mean (in m)		
Author	year	area	length	width	height
Alden	1905	S.E. Wisconsin	804-1206	304	9.14-18.24
Armstrong ¹	1949	B.C.	804-2413	<402	---
Aronow	1959	Warwick-Tokio, N.D.	---	---	< 15.24
Bennett & Finke ²	1971	S-FRG (3 fields)	549-745	236-279	16-29
Deane ¹	1950	Orillia, Ont. Sunderland, Ont.	6438 914	182 365	< 15.24 < 45.72
Flint	1971	"ideal drumlin"	1000-2000	400-500	5-50
Goldthwaite ¹	1924	Nova Scotia	804-1206	304	14.63-30.48
Hanvey	1989a	W-Ireland	2000-4000	---	50
Heidenreich ¹	1964	Peterborough, Ont. Warton, Ont.	1206 997	193-274 386	--- ---
Kupsch	1955	Dollard, Sask.	228	106	< 45.72
Lemke	1958	Velva, N.D.	3219	46-61	4.57
Sharpe	1985	Victoria Ireland N of Cambridge B.	500-2000	---	10-25
	1988	Wollaston Penin.	2000	200-300	10-30
Stea & Brown	1989	Nova Scotia	800-1600	30-60	12-46
Steinert	1987	N-FRG (SH)	407.5 $\pm$ 230	210 $\pm$ 102.5	8.3 $\pm$ 4.7
St-Onge	1984	Rock lake area	1500-2000	500-600	30-50
Vernon	1966	Ireland	309	155	---
Footnote ¹ Cited from Grant (1974)					
Footnote ² Cited from Embleton and King (1975; 408)					

Table i: Drumlin measurements from literature review

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THE MORPHOLOGICAL ZONES OF THE BERNARD HARBOUR DRUMLINFIELD

SAMPLES

Figure 13: Distribution of samples in the Bernard Harbour area

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