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Glacigenic Streamlined Landforms in the Hinton/Edson area, Alberta.

by

Andrew Morley Gambier

A THESIS

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Date December 6, 1983

Dedication

This thesis is dedicated to my family and to Jan, with many thanks for their support.

Abstract

Drumlins and flutings are widespread in the Hinton/Edson area. The orientation of these streamlined forms is approximately 40°–220°. This trend follows the Athabasca River valley and presumably parallels the former flow direction of ice close to the valley centre. Ice moulded landforms to the east illustrate deflection of former ice flow, first eastwards and then southwards. This deflection is attributed to confluence of the Laurentide Ice Sheet and Cordilleran piedmont ice when the landforms were formed.

Forestry road cuts have exposed sections through three streamlined landforms in the vicinity of Canyon Creek, ten kilometres northeast of Hinton and these forms have been investigated intensively. Diamicton is the dominant material exposed but numerous stratified layers reveal a complex internal structure. Thrust blocks and overturned folds are well displayed in one fluting, indicating that the sediments of the proximal part of this form have undergone stacking by shearing and overfolding. It is proposed that a transverse feature similar in origin to a Ribbed or Rogen moraine, acted as a nucleus for fluting formation and that the fluting resulted from subsequent lee-side agglomeration of debris-rich ice behind this obstacle. Final till deposition occurred by melt out. The importance of melt out processes to the final preservation of drumlins and flutings in the Hinton/Edson area is evident from observations of two other streamlined forms.

Two-dimensional and three-dimensional fabric patterns illustrate the complexity of fabric orientations within each form and raise questions concerning the role of fabric analyses in the evaluation of genetic processes.

Acknowledgments

There are many people who have contributed to this thesis over the years. In particular, I would like to extend thanks to Dr.John Shaw, now at Queen's University, for acting as the first Supervisor for this project. His help, criticism and guidance will always be appreciated. Special thanks also go to Dr.John England, who subsequently became the thesis Supervisor. His meticulous editing, enthusiasm and energy added immensely to the quality of this work. Dr.Bruce Rains, Department of Geography, also provided considerable help. Dr.R.B.Rains and Dr.N.W.Rutter, Department of Geology, served on the examining committee. Their contributions are gratefully acknowledged. In addition, conversations with Dr.Alexis Dreimanis, Department of Geology, University of Western Ontario, assisted in the understanding of some aspects of till.

Field support was provided by the late Dr.Don Gill, Department of Geography, at "The Drystone Ranch" and additional logistical support was given by Steve Gill. Fellow graduate student, Rod Olson and his sister, Jo Anne, also contributed to a successful field season in Hinton.

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1. INTRODUCTION

1.1 Introduction to Aims and Objectives of the Study

In the Hinton/Edson area (Figure 1.1), glacial landforms are diverse, widespread and well preserved. Although the stratigraphy of the surficial deposits has been interpreted by Roed (1968, 1975), detailed analyses and process interpretations of the glacial landforms have not been undertaken. It is for this reason that a selection of drumlins and flutings were chosen for investigation. The primary objective of this study is to explain these selected landform assemblages and their sedimentological characteristics in terms of glacigenic processes. These findings may also provide some general conclusions concerning the nature of glaciation and deglaciation in a restricted zone of a piedmont glacier which Roed (1975) suggests was confluent with a continental ice sheet in the Hinton/Edson area during the Early Wisconsin glaciation. It is noteworthy, however, that the chronology of glacial events in the Hinton/Edson area is still unclear.

1.2 Location of the Study Area

The area around Hinton (NTS 83F) was examined during the course of this study (Figure 1.2). It is situated in west central Alberta and is bounded to the west by the Jarvis Lake Valley at 117° 47′ W and to the east at 117° 00′ W. The northern boundary is defined by the latitude 53° 40′ N and the southern margin by 53° 20′ N.

Priority was given to an investigation of the streamlined landforms within the Athabasca Valley between Hinton and the Emerson Lakes (Figure 1.2). This constitutes a linear distance of approximately 45 kilometres. In this area a logging road on the north side of the Athabasca River has exposed road cuts through many glacigenic streamlined landforms and data from three streamlined landforms will be presented here.

1.3 Thesis Organisation

In this chapter, drumlin and fluting genesis is reviewed briefly and the physical setting of the Hinton/Edson area is presented. This includes a summary of the glacial history and stratigraphy proposed by Roed (1968, 1975). At the end of Chapter 1 detailed objectives of this study are elaborated. Chapter 2 clarifies certain terminology

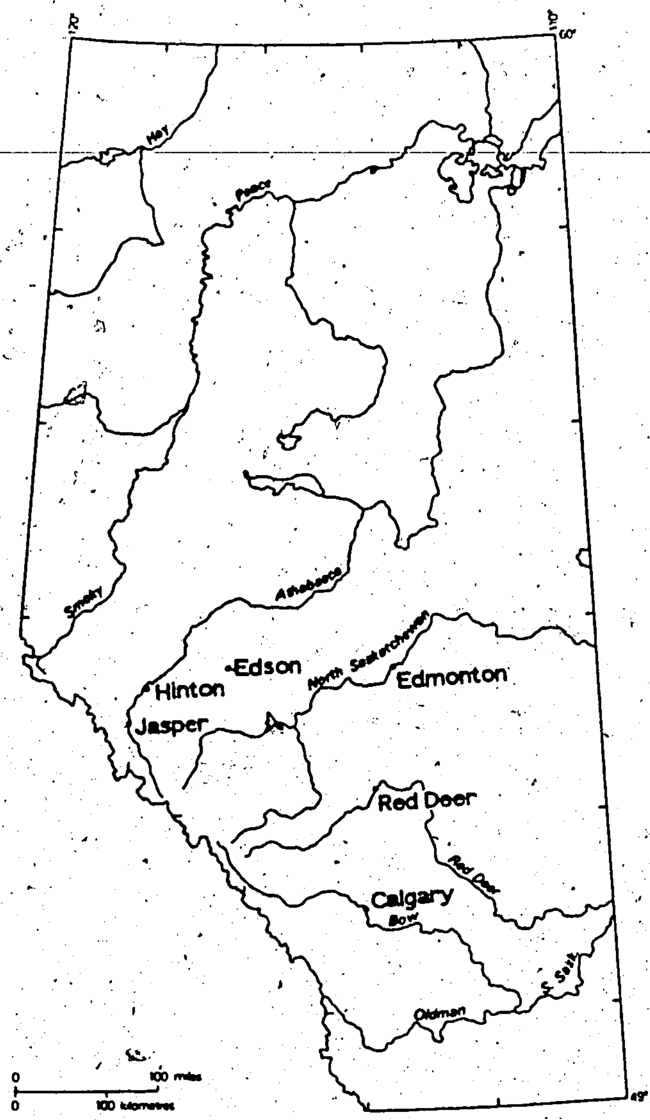


Figure 1.1 Map of Alberta Showing Locations of Hinton and Edson.

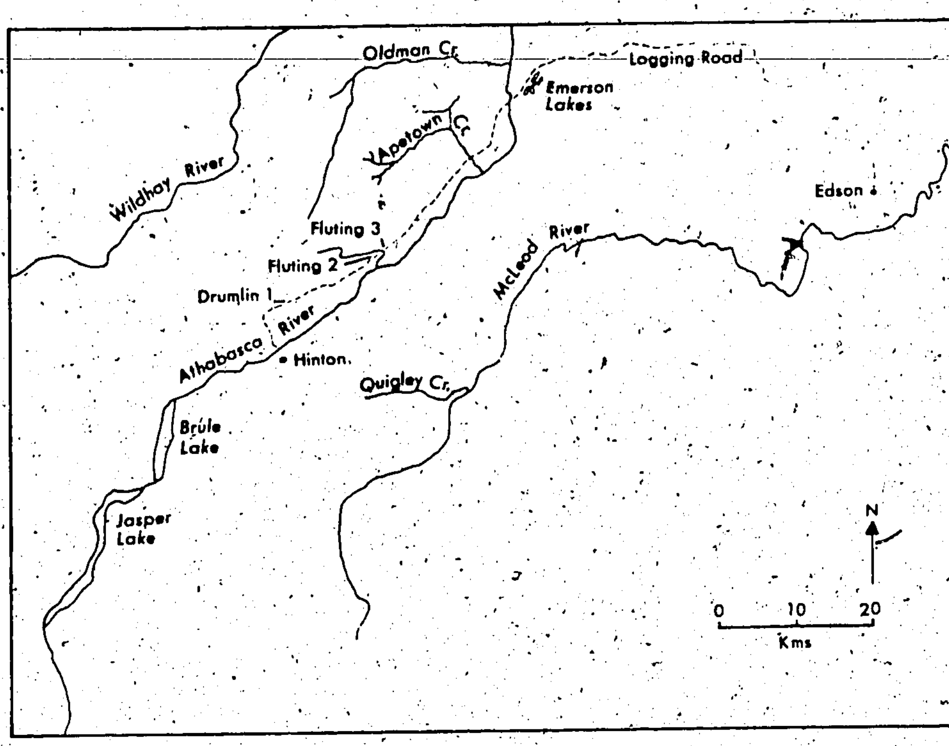


Figure 1.2 Study Area with Locations of Selected Streamlined Landforms in the Hinton/Edson Area.

and classifications proposed for glacial deposits and deals with the methods which have been used in the analyses of streamlined forms. Chapter 3 examines general theories of drumlin and fluting formation and outlines some of the properties of streamlined forms in the Hinton/Edson area. Detailed descriptions and process analyses of three streamlined forms are presented in Chapter 4. Each landform is discussed in terms of morphology, sedimentology and fabric. In Chapter 5 the interrelationships between the three streamlined forms, discussed in the previous chapter, are examined and a general model of drumlin and fluting genesis is proposed.

1.4 Introduction to Drumlins and Flutings

Drumlins are streamlined, oval-shaped landforms. In general, the steep, blunt part of the landform is located on the proximal or up-ice side whereas the gentler, sloping end is located on the distal or down-ice side. The landforms vary in size but are generally 5-50 metres high, 400-600 metres wide and 1-2 kilometres long (Flint, 1971).

Flutings, sometimes referred to as flutes or longitudinal shear marks (Clayton and Moran, 1974), are long, straight, parallel ridges with crest lines which are of similar height throughout the length of the form. Small-scale flutings less than 2 metres in height, 3 metres in width and 1 kilometre in length are most common (Hoppe and Schytt, 1953; Boulton 1976a). Larger scale forms which are 25 metres in height, 100 metres in width and 20 kilometres in length have also been reported (Flint, 1971).

Many theories have been suggested to explain the origin of these streamlined landforms. They have been adequately summarised by Muller (1974), Gillberg (1976) and Menzies (1979). It is not proposed at this stage to review the literature on drumlin and fluting formation but to provide some general comments by way of introduction to these landforms. Specific theories of drumlin and fluting formation will be discussed later with reference to the genesis of these forms in the Hinton/Edson area.

Menzies (1979) suggested that the following questions, when answered, should provide a definitive explanation of the origin of drumlins:

1. Where are drumlins located and why?
2. What is the internal composition of a drumlin and what structures exist within them and why?

3. What processes cause material, in certain areas of a glaciated landscape, to agglomerate into isolated mounds?

4. What relationship exists between drumlins in terms of spacing, distribution, density, morphometry and terrain factors and the relationship of these factors to ice flow?

5. Why is a drumlin so shaped?

The same questions are applicable to flutings and in this context a further question is thought to be relevant here:

6. What is the relationship between drumlins, flutings and transverse moraines which are sometimes found in areal association within glaciated landscapes?

In this thesis an attempt will be made to answer these questions in relation to observations of drumlins and flutings in the Hinton/Edson area. Until this study, no observations of the internal characteristics of drumlins and flutings have been reported for the area. Roed (1968, p.25) stated that these features were not studied in detail. However he identified two distinct trends of streamlined forms in the area and noted that to the south of Hinton, easterly and southeasterly trending drumlins and flutings in Marlboro till are truncated by northeasterly trending drumlins and flutings in Obed till (Figure 1.5). This trend is also displayed on the Glacial map of Canada (Prest *et al.*, 1968). Roed (1968, 1975) used this cross-cutting relationship to support his interpretation of two separate Cordilleran ice advances.

In terms of genetic process interpretations little work has been undertaken. Shaw (1980) postulated that drumlins and flutings near Edson may be related to secondary flows generated in the zone of convergence between the Cordilleran and Laurentide ice sheets. However, no field checks were undertaken to test this hypothesis in the Edson area.

1.5 Background to the Field Area

1.5.1 Relief and Physiography

The Hinton/Edson area is located within the western part of the Interior Plains region and the eastern part of the Cordilleran region of Western Canada (Bostock, 1965). Roed (1968) proposed three major physiographic divisions in the Hinton/Edson area on the basis of geomorphology and geologic structure (Figure 1.3). These divisions are the Rocky Mountain Front Ranges, the Rocky Mountain Foothills and the Interior Plains. The Interior Plains are further subdivided into local units consisting of Tablelands, Benchlands, Lowlands, Jarvis Lake Valley and Buried Valleys. Not all of these major divisions are applicable to the field area under consideration here; for example the field area does not fall within the Rocky Mountain Front Ranges (Figure 1.3).

In the field area, the Rocky Mountain Foothills are approximately 18 kilometres wide (west to east) extending from Brule Lake to Hinton where they form a narrow northwesterly–southeasterly trending belt (Figure 1.3). Within the study area, to the southeast of Brule Lake, the Rocky Mountain Foothills display a structurally controlled, trellised drainage pattern. To the north of Brule Lake the drainage pattern bears very little relationship to the structure. Both the Jarvis Lake Valley and the Athabasca River valley traverse the structural trend of the Rocky Mountain Foothills (Figure 1.3).

The Interior Plains are bounded to the west by the Rocky Mountain Foothills and are subdivided into Tablelands, Benchlands and Lowlands. Most of the field area lies within this physiographic region. Bayrock (1960) applied the term "Tablelands" to highlands in Alberta which have relatively steep slopes and flat tops. Roed (1968) identified a number of Tablelands in the field area (Figure 1.3). These are the Berland, Pinto, Athabasca and Mayberne tablelands. Because this study is largely confined to the area surrounding the Athabasca Tableland it is proposed that this be further subdivided into two units. These units are the North Athabasca Tableland and the South Athabasca Tableland which are located north and south of the Athabasca River, respectively (Figure 1.3).

The North Athabasca Tableland is a high upland plateau mostly above 1220 metres. It reaches a maximum elevation of 1677 metres in the vicinity of the Obed fire tower. The North Athabasca Tableland forms a northeast–southwest trending watershed for many of the smaller drainage basins of the local Athabasca River (Figure 1.3). The north side of this Tableland is drained by the headwaters of Oldman Creek (Figure 1.3). On the south side of this Tableland, Felix, Canyon, Baseline, Apetown and Plante creeks drain directly into the Athabasca River (Figure 1.3).

The South Athabasca Tableland is generally above 1220 metres and two points rise above 1400 metres, one to the southwest and the other to the northeast of McPherson

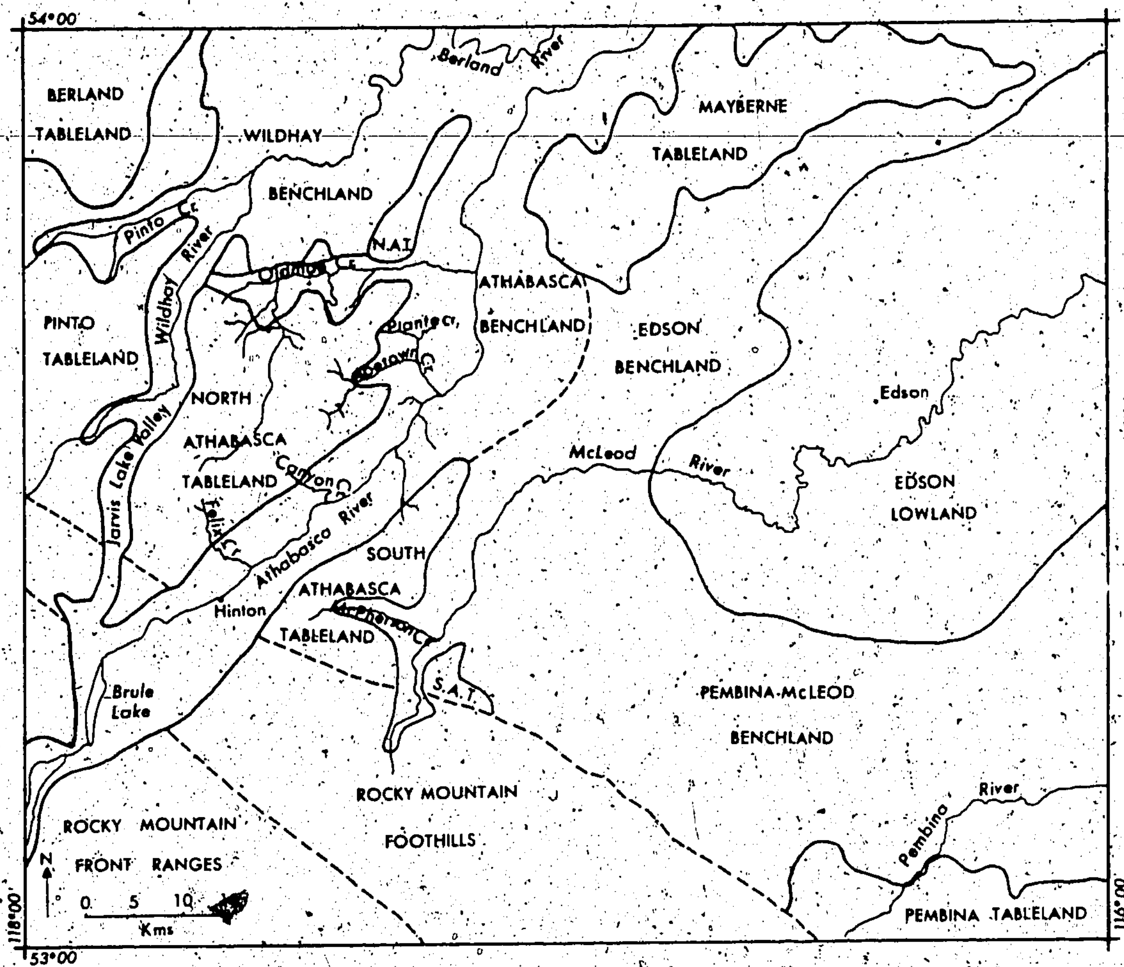


Figure 1.3 Physiography of the Hinton/Edson area (after Roed, 1975).

Creek. This area forms a drainage divide between the northwesterly flowing streams which drain to the Athabasca River and the southeasterly flowing tributaries of the McLeod River.

The Benchlands are defined as areas between the Tablelands and Lowlands and are characterised by terrace remnants generally at elevations of 1100 metres (Davis, 1932). In the field area the Athabasca Benchland broadens out towards the north where it is bounded to the east by the Edson Benchland and Mayberne Tableland and to the west by the North Athabasca Tableland (Figure 1.3). In the northeastern part of the field area the Athabasca Benchland is characterised by an undulating surface at an elevation of between 975 m and 1,150 m. In the vicinity of Plante, Apetown and Oldman creeks, the Benchland has been deeply incised by these tributaries of the Athabasca River.

1.5.2 Bedrock and Structure

The Hinton/Edson area is underlain by a variety of sedimentary rocks of Cretaceous and Tertiary ages (Figure 1.4). The western part of the study area is located in the Rocky Mountain Foothills which has undergone tectonic deformation and includes a series of subparallel faults and folds trending northwest – southeast. In general, the anticlines form ridges whereas synclines control valleys (Irish, 1965).

The western limit of the Rocky Mountain Foothills coincides with the trace of the Miette Thrust Sheet (Mountjoy, 1962). The eastern margin of the Rocky Mountain Foothills is defined at the point where sedimentary beds dip uniformly and gently to the east and locally it is marked by the east flank of the northwesterly trending Prairie Creek Anticline near Hinton (Lang, 1947) and the Pedley Fault (Irish, 1965) (Figure 1.4).

The Rocky Mountain Foothills are underlain by a thick sequence of clastic rocks which belong to the Alberta Group and Brazeau Formation of Late Cretaceous age. The Alberta Group is composed of the Cardium and the Wapiabi formations which crop out to the east of Brule Lake (Figure 1.4). Dark grey fissile shale and minor grey cherty sandstone characterise this succession. Overlying this is a sequence of transitional marine sandstones that grade into the conglomerates of the non-marine Brazeau Formation. The conglomerates are composed of quartzitic pebbles and are interbedded with sandstones (Irish, 1965). Other lithologies of the Brazeau Formation are greenish grey, thickly bedded,

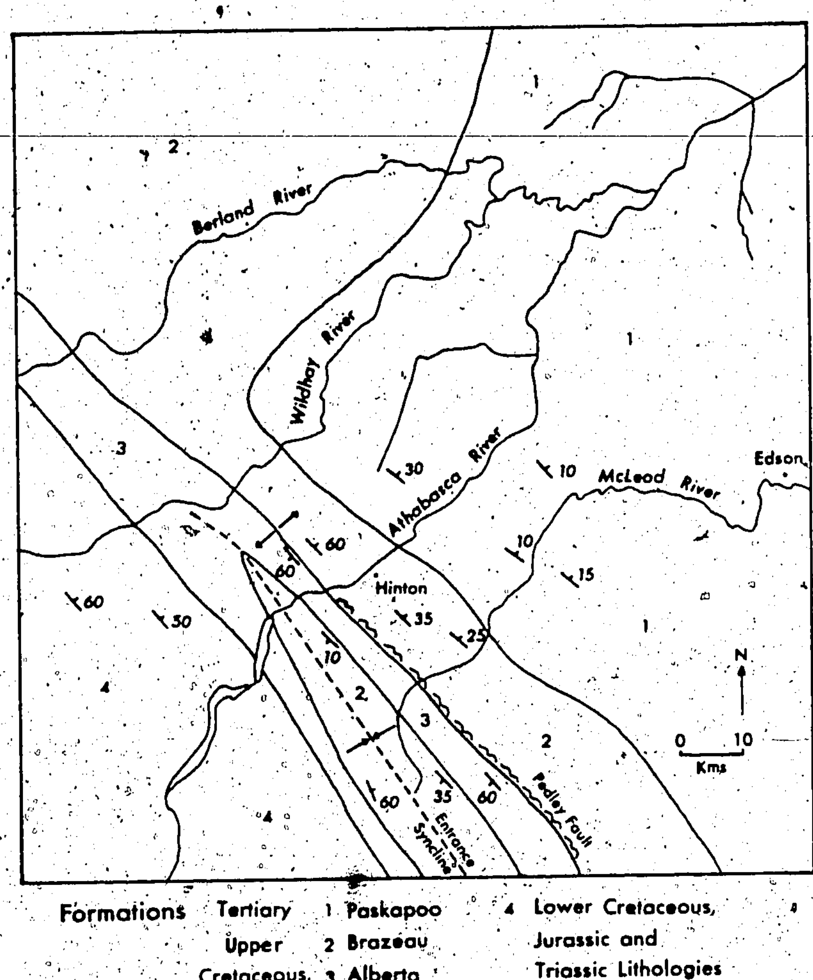


Figure 1.4 Surface Bedrock Geology (after Irish, 1965).

bentonitic and feldspathic sandstones; blocky grey mudstones; and thin coal seams. Black carbonaceous beds are common and thin, impure ironstone layers are present in some places (Irish, 1965). The uppermost bed of the Brazeau Formation is a distinctive, massive grey sandstone about 20 metres thick (Irish, 1965). From west to east, the Brazeau Formation is found generally from 4 kilometres to the east of Brule Lake to Hinton (Geological Highway Map of Alberta, 1975). The Paskapoo Formation of the Paleocene stage underlies an extensive area to the east of Hinton, extending as far east as Evansburg (Geological Highway Map of Alberta, 1975). The contact between the Brazeau and the Paskapoo formations is unclear although a discontinuity has been recognised in Hinton (Irish, 1965). Lithologies of the Paskapoo Formation consist of grey and greenish grey, thickly bedded sandstone and some grey-green siltstones and mudstones of freshwater origin (Irish, 1965; Geological Map of Alberta, 1972; McCrossan and Glaister, 1974). In addition, minor conglomerates, thin limestones, coal and tuff beds appear in this sequence (Geological Map of Alberta, 1972).

Bedrock is covered in much of the area by glacial, glaciofluvial and glaciolacustrine material (Figure 1.5). The clasts in the overburden consist mostly of local quartzites, sandstones, limestones, cherts and ironstones. No igneous or metamorphic clasts of Canadian Shield provenance were observed in the field area.

1.5.3 Glacial History and Stratigraphy

Glacial, glaciolacustrine, glaciofluvial and postglacial deposits are all preserved in the Hinton/Edson area (Figure 1.5). However, a complete stratigraphic sequence has not been observed in the area and radiometric ages are not available for the deposits (Roed, 1975). Therefore the chronology of the deposits in the Hinton/Edson area is based upon morphology, lithostratigraphy and cross-cutting relationships.

Recent studies in glacial geomorphology and geology have shown that tills can be classified in terms of genetic processes (Boulton, 1972) This presents a problem as a lithostratigraphic interpretation may sometimes be difficult without a genetic process analysis of a till sequence. Prior to our present understanding of till deposition, lithostratigraphy was more simplistic and most changes in depositional units were interpreted as different events. For instance, a section displaying several distinct tills may

Figure 1.5 Surficial Geology Map, in pocket (Roed, 1970).

either indicate a succession of glacial advances or show simply one glacial episode.

Boulton (1972, p.361) emphasised this problem:

> "It is suggested that existing models for the interpretation of ancient tills and the sequences in which they lie are often too simple and lead to erroneous stratigraphic and palaeogeographic conclusions. Till is far too often interpreted as lodgement till and it is suggested that many Pleistocene and earlier sequences currently thought of as products of repeated glacier advance and readvance may be perfectly normal products of a single retreat phase by a glacier with a thick englacial debris load."

This is possibly the case for the Hinton/Edson area and it should be pointed out that Roed (1975) himself appears uncertain about the number of glacial advances and retreats in the Hinton/Edson area. He has identified seven tills which represent:

> ... three possibly four glacier advances (p.1499) ... as many as five advances and retreats (p.1510).
>
> (Roed, 1975)

The following is a summary of the glacial history of the Hinton/Edson area proposed by Roed (1968, 1975). The first Cordilleran advance to extend beyond the Athabasca Valley in the Hinton/Edson area, termed an "early Cordilleran" advance, is based on the distribution of Gog quartzites derived from the Rocky Mountains which have been identified in the Laurentide till. One erratic similar to the Gog Group has been found by Roed in the Laurentide-Mayberne till at 1220 metres on the Mayberne Tableland (Figure 1.3) several kilometres to the east of the "known" limit of Cordilleran Ice. Other erratics of the Gog Group have been located within the Laurentide till to the southeast of Edson. Roed interpreted the presence of these erratics as evidence of a Cordilleran advance prior to the arrival of the Laurentide Ice Sheet. The alternative hypothesis that he proposed is that these erratics were deposited in a confluence between Cordilleran and Laurentide ice sheets. If the latter hypothesis is accepted it is difficult to see how the location of these erratics indicates an "early" advance because location alone does not indicate the time of deposition and later Cordilleran and Laurentide ice advances have been proposed (Roed, 1975).

The Marsh Creek advance of the Laurentide Ice Sheet which originated from the northeast, is considered to be penecontemporaneous with the "early" Cordilleran advance (Roed, 1975). The extent of this oldest Laurentide advance is thought to be to the west of Nosehill Creek and to the north of Oldman Creek (Figure 1.6). One exposure of the Marsh Creek till occurs on the south bank of the Oldman Creek (Roed, 1975). The till contains up to 12% igneous rocks of Canadian Shield provenance and its heavy mineral suite is similar to other Laurentide tills in the area (Roed, 1975). Roed commented that while the lower contact of this till was not observed, the upper contact with outwash gravel is sharp and probably erosional. The outwash gravel is interpreted as Marsh Creek outwash which is overlain, in turn, by Marlboro till.

The next major glaciation is considered to be marked by the Marlboro till of the Cordilleran Ice Sheet and the Edson and Mayberne tills of the Laurentide Ice Sheet (Roed, 1975). Marlboro till presumably marks the most extensive advance of the Cordilleran Ice Sheet which coalesced with the Laurentide Ice Sheet (Figure 1.6). Roed (1970) has mapped the Marlboro till on the North and South Athabasca Tablelands and from the Rocky Mountain Foothills northwest of Brule Lake to an area 5 kilometres to the west of Edson (Figure 1.5). Roed considered that the Edson and Mayberne tills are lithofacies of the same advance (Roed, 1975). Mayberne till occurs on the Mayberne Tableland to the northeast of the study area whereas Edson till occupies part of the Edson Lowland (Figure 1.3). The distribution of Marlboro till indicates that Cordilleran ice extended over the North and South Athabasca Tablelands and stagnated during coalescence with the Laurentide Ice Sheet in the northern part of the study area. In the southern part of the field area the distribution of Marlboro till indicates that Cordilleran ice continued to flow in a southeasterly direction towards Rocky Mountain House (Figures 1.5 and 1.6). The orientation of drumlins southeast of the study area, in the vicinity of the Embarras River, shows strong deflection of Cordilleran Ice as a result of convergence between the Cordilleran and Laurentide ice sheets (Roed, 1975; Shaw, 1980). It should be noted that Shaw and Kellerhals (1982, p.13 and p.43) have suggested that Shield erratics occur in the Athabasca and McLeod River gravels much further west and southwest than the Laurentide ice limits mapped for surface tills by Roed (1970, 1975). However, the limits they proposed for these areas, (Township 52, Range 23 and Township 50, Range 22; see Figure 1.6), are conjectural because granite clasts from the Canadian Shield were not differentiated from gneissic clasts from Interior British Columbia. Near Roche Miette in the Front Ranges, Jasper National Park, the author has observed metamorphic boulders from across the Continental Divide and it is therefore likely that metamorphic clasts were transported into the Athabasca and McLeod River valleys. Therefore the limits proposed by

Shaw and Kellerhals must be considered speculative until detailed petrologic studies are conducted.

During deglaciation from the positions marked by the Marlboro, Edson and Mayberne till limits, Cordilleran and Laurentide ice retreated to the southwest and northeast, respectively. As a result glaciolacustrine sediments accumulated where meltwater was ponded between the two ice masses, for example in the Edson Lowland and lower Oldman Creek areas (Figure 1.5). Recession of the Cordilleran glacier resulted in increasing meltwater which flowed into an extensive lake in the Edson Lowland to form the Marlboro delta. The delta occupies an extensive area and it is the main source of the sand dunes south of Edson (Roed, 1975).

In the northeastern part of the study area, the Emerson Lake Esker Complex is thought to have developed while the Cordilleran and Laurentide ice margins remained in contact during the early stages of this deglaciation (Roed, 1975). Roed proposed that, at this time, meltwater from the esker complex flowed southeastwards forming the spillway channel now occupied by Sundance Creek and supplying sediment to the glacial lake in the Edson Lowland. This meltwater also dissected part of the Marlboro Delta (Figure 1.5 and 1.6).

Roed proposed that the Marlboro ice continued to recede southwestwards as far as Brule Lake where it stabilised for an unknown time (Figure 1.5). At this stage the Pedley Outwash sediments were deposited on the Athabasca Benchlands and in the Plante Creek valley area (Figures 1.3 and 1.6).

The next proposed glaciation is marked by the Obed till deposited by the Cordilleran ice. The extent of the Obed till is shown in Figure 1.5. Roed suggested that one effect of the Obed advance was that it overrode both Pedley Outwash and Marlboro till on the Athabasca Benchland.

Evidence for the separate Obed advance is based upon the tripartite sequence of Marlboro till overlain by the Pedley Outwash, in turn overlain by Obed till. This sequence is observed along the Canadian National Railroad right of way between Pedley and Obed (Figure 1.5). It is noteworthy that samples of Marlboro and Obed tills have been analysed for heavy minerals, pebble composition and carbonate content and the results indicate that there are no differences between the tills at certain locations (Roed, 1975). At other

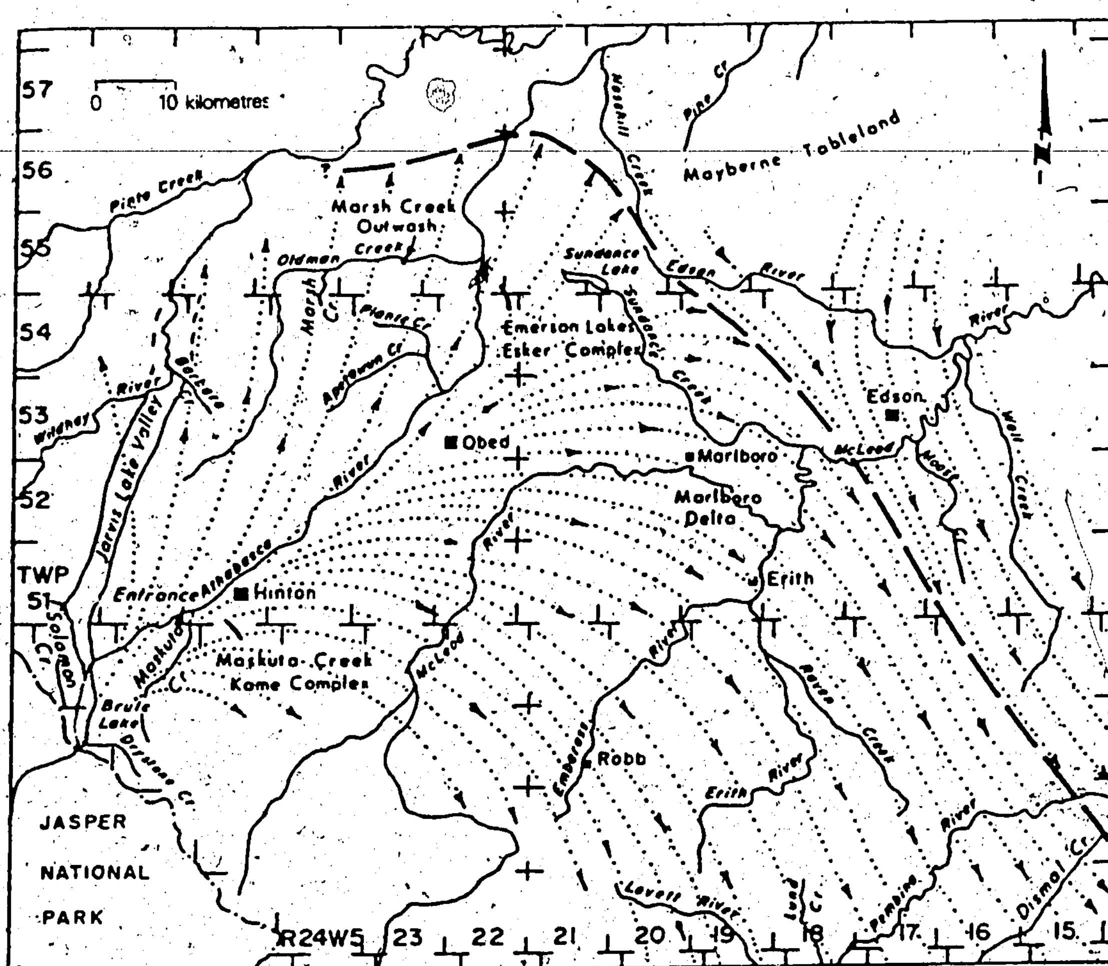


Figure 1.6 Map showing features related to the glacial history of the Hinton/Edson area and the ice flow inferred from drumlins and flutings. The suggested zone of convergence between Cordilleran and Laurentide ice sheets is shown by the dashed line (from Roed, 1975).

locations there are differences between the two tills; for example, the Obed till has more limestone clasts and a sandier matrix (Roed, 1975).

Roed commented that:

> "The Obed till and Marlboro till can be distinguished in the subsurface by superposition only where the two units are separated by the Pedley sediments."
>
> (Roed, 1968, p.61)

Roed has also supported his argument for separate Marlboro and Obed ice advances based upon morphological observations of drumlins and flutings. He postulated that truncation of the easterly and southeasterly trending drumlins, grooves and flutings in the Marlboro till by the northeasterly trending drumlins and grooves present in the Obed till is evidence for the two advances (Figure 1.5).

Roed suggested that subsequent deglaciation resulted in the deposition of lacustrine sediments in the Plante Creek and Apetown Creek valleys (Figure 1.5). An esker complex also developed at this time while ice disintegration features such as kames formed in the vicinity of Obed. Subsequently the Upper Hinton Terrace was formed during a stillstand of the Obed ice at Maskuta Creek (Stene, 1966). At a later stage, the ice front retreated to a point between Brule Lake and Entrance and at this time the Lower Hinton Terrace is thought to have developed (Stene, 1966; Roed, 1975). Finally, with increased meltwater the Lower Hinton Terrace was dissected to form the Lower Valley Train (Stene, 1966; Roed, 1975; Glover, 1979).

The Drystone Creek advance is the last glacial event proposed by Roed. This advance is considered to have been short lived involving only local alpine valley glaciers that did not extend to the main valleys. Evidence for this advance, which is based on deposits observed in the Drystone Creek valley, is considered tentative (Roed, 1968 p.91). The complete sequence of events proposed by Roed is summarised in Table 1.1.

1.6 Detailed Objectives

The objectives of this study are as follows:

1. To record the morphological and sedimentological characteristics of selected streamlined landforms in the Hinton/Edson area.
2. To conduct fabric analyses to aid process interpretations for selected streamlined landforms.

STAGE	CORDILLERAN ORIGIN	LAURENTIDE ORIGIN
EARLY HOLOCENE	Drystone Creek Till	
OR	Upper and Lower Hinton Terrace	
LATE WISCONSIN	Obed Till	? ↑
	Pedley Outwash	
EARLY WISCONSIN	Marlboro Till	Edson -- Mayberne Till
?	"Early" Cordilleran Till.	Marsh Creek Till

Table 1.1 Stratigraphic Sequence (after Roed, 1975).

3. To examine the relationships between individual streamlined landforms.
4. To construct a process model to explain the genesis of streamlined landforms.
5. To evaluate this model in the context of similar explanations for streamlined landforms, proposed elsewhere.

2. METHODS AND OBSERVATIONS

2.1 Introduction

In the Hinton/Edson area, a reconnaisance survey of glacial landforms was made during October, 1978. Subsequently, fieldwork for this study was carried out from May to August, 1979. The main part of the field programme involved analyses of both the internal and external characteristics of selected landforms from which genetic process interpretations were developed. Analyses of till, including pebble fabric, sedimentary structure, and clast concentrations were made together with observations on other properties of the deposits including texture, geometry, bed contacts and surface forms. Collectively these data provided the basis to evaluate individual deposits and the local stratigraphic sequences within which they occur. Field and aerial photographic investigations were also undertaken to determine regional relationships of glacial landforms.

2.2 Air Photo Interpretation and Field Mapping

Field and air photo investigations were undertaken to examine glacial landform relationships and specific landforms. The Alberta Provincial air photo mosaic compiled between 1949 and 1951 at a scale of 1:63,360 (83F6, 83F10, 83F11), provides an overview of the landforms within the Hinton/Edson area. Federal and Provincial air photographs at scales of 1:60,000 (Federal, 1970), 1:39,600 (Provincial, 1955), 1:31,680 (Provincial, 1964/65) and 1:15,840 (Provincial, 1969) were used for more detailed investigations of the landforms. Provincial air photographs at 1:39,600, taken before 1956, do not show many of the existing logging routes. Air photographs at 1:31,680, taken from 1963 to 1965, better display the network of roads in the field area. Photographs at this scale provide adequate coverage of the area and were used extensively in this study. Between 1965 and 1969, a major logging road was built by St Regis Pulp and Paper Mill Company in Hinton (Figure 1.2). This road runs parallel to the north side of the Athabasca River near Hinton and cuts through a number of glacigenic assemblages. This route is not present on photographs at 1:31,600 which sometimes makes exact location of specific landforms difficult. For this reason, photographs at

1:15,840, taken in 1969, have been used to analyse the orientation of road cuts through specific landforms. Federal air photographs taken in 1970 at 1:60,000 give updated information on access within the area but are unsatisfactory for landform analyses because cloud cover on the photographs reduces clarity. Interpretation of air photographs at these scales resulted in a provisional landform map and specific sites were selected for field investigations.

2.2.1 Field Surveys: Surface Morphological Investigations

For streamlined landforms surface morphology was best obtained from air photographs because landforms were obscured by thick vegetation cover. However, selected landforms were also mapped using "surveying" techniques. For process studies many investigations of landform morphology alone are incomplete without including other variables such as composition and structure.

Simple levelling was carried out using two equal height levelling rods, an Abney Level, tape measure and Brunton Compass. The levelling rods were held vertically some distance apart on the section of the landform to be surveyed. The distance between the rods was recorded and the angle of inclination was determined by backsights and foresights using the Abney Level. A directional measurement between rods was taken with the compass and the procedure was repeated several times. Although this method is not as accurate as a theodolite or transit survey, it has an advantage where dense undergrowth limits more conventional instruments. It is also a relatively quick method of surveying and it provides adequate accuracy.

2.3 Till - Definition and Classification

Because till is the main component of the surficial deposits in the Hinton/Edson area a discussion of its characteristics is relevant to the understanding of many landforms. The term "till" was originally defined as "a stiff clay full of stones varying in size up to boulders produced by abrasion carried on by the ice sheet as it moved over the land" (Geikie, 1863, p.185). Since then many definitions of till have been proposed (see Goldthwait, 1971 and Legget, 1976 for discussion). Goldthwait (1971, p.3) stressed that "till is the only sediment stemming directly and solely from glacial ice". Boulton (1976b, p.65) defines till as: "An aggregate whose components are brought together and deposited by the direct agency of glacier ice and which, although it may suffer postpositional deformation, does not undergo subsequent disaggregation and re-deposition". Lawson (1979, p.28) has defined till as "sediment deposited directly from glacier ice which has not undergone subsequent disaggregation and resedimentation". It should be made clear that the term till is an interpretation and will be applied genetically in this study. The term "diamicton" (Flint *et al.*, 1960, p. 1) will be used for descriptive purposes. It has been defined as "essentially a non sorted, non calcareous, terrigenous deposit composed of sand and/or larger particles in a muddy matrix" (Flint, Sanders and Rogers, 1960, p. 1) and is clearly a non generic term.

Many workers in the field of glacial geology and geomorphology are engaged in the ongoing process of establishing a genetic classification of tills (Dreimanis, 1976, 1982, Table 2.1). Flint (1957) proposed two terms: lodgement till (subglacially deposited directly from transporting ice) and ablation till (formed at the surface as a result of melting). At this time Hartshorn (1958) proposed the term "flow till" for deposits which were attributed to local sliding and flow during their release from ice. Boulton (1972) provided a more recent classification of tills using modern Arctic glaciers as depositional models for former ice sheets and he proposed a new term "melt out till". He described melt out till as "released either supraglacially or subglacially from stagnant ice beneath a confining overburden and in which some of the original englacial features are preserved" (Boulton, 1972, p.379). Boulton's (1972) classification of tills into lodgement, melt out and flow tills is based largely upon the process of deposition. Shaw (1977a) noted that while this classification is appropriate in such active environments as humid polar areas, it is not adequate when applied to arid polar environments. In this environment, preservation of primary structures originating during the transport of debris by ice is common due partly to the absence of large amounts of meltwater and the overall predominance of sublimation. As a result, Shaw (1977a) provided an expanded classification for terrestrial till which includes the position of transportation, the position of deposition and the process of deposition. He later modified this classification (Shaw, 1982) and it will be used here (Table 2.2).

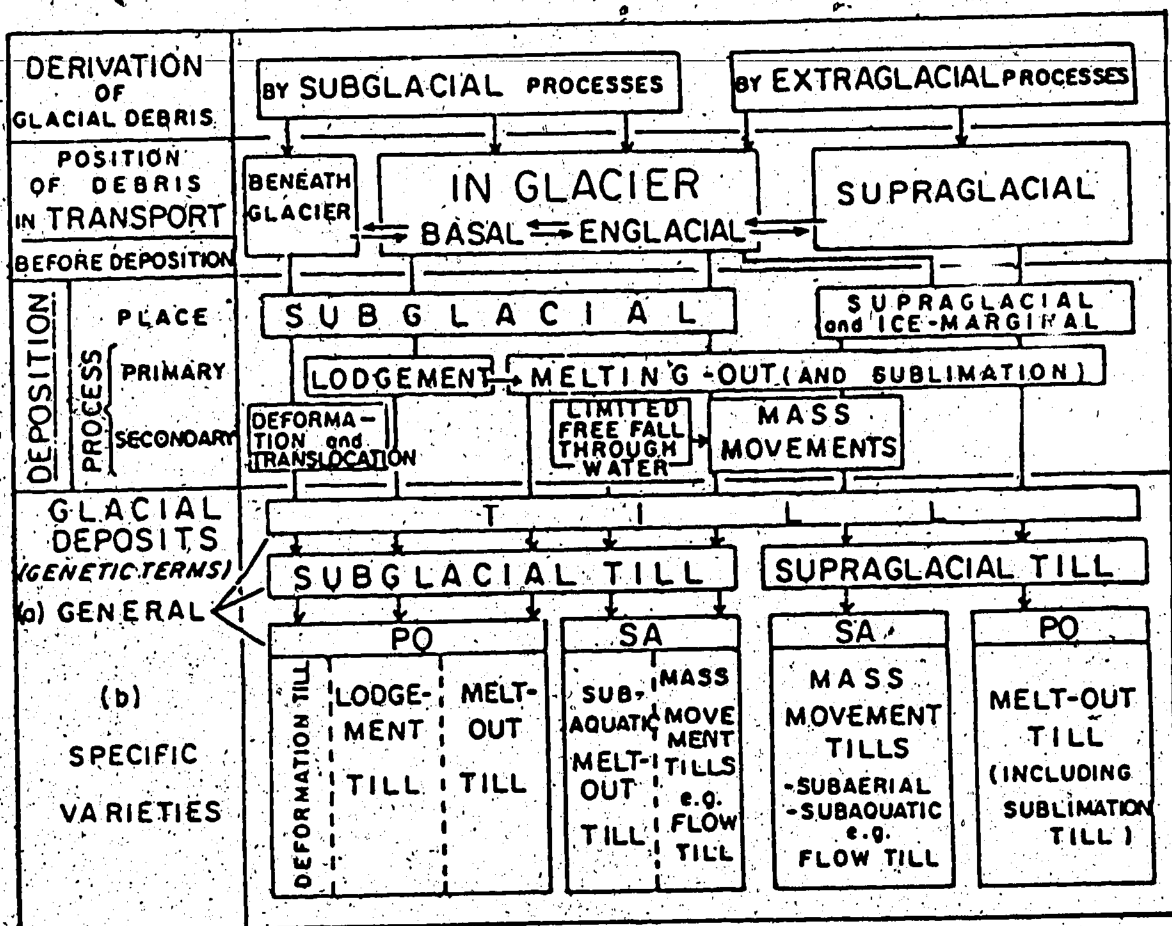


Table 2.1 Genetic Classification of Till (after Dreimanis, 1982). Upper half of table shows the factors that influence the formation and deposition of tills. Lower half shows a tentative genetic classification of tills. Abbreviations: PO – Primary or Ortho–tills, SA – Secondary or Allo–tills. (in Schluecter, 1982).

POSITION OF TRANSPORTATION	POSITION OF FORMATION	PROCESS OF FORMATION
Supraglacial	Proglacial	Lowering
Englacial	Lateral	Flow
Basal	Supraglacial	Sublimation
	Englacial	Melt-out
	Subglacial	Lodgement

Table 2.2 Genetic Classification of Till (after Shaw, 1982).

Sediments which become till may be transported in a basal, englacial or supraglacial position. The basal position is considered here as the lower, highly debris charged zone of the glacier. The englacial position is broadly equivalent to the main body of the ice between the basal zone and the supraglacial zone, on the ice surface. The position of till formation may be proglacial, lateral, englacial, supraglacial or subglacial (Table 2.2). Finally, the process of formation results in some of the following till types:

Lodgement till	Till deposition by lodgement is the plastering of debris by active ice temperate at its bed (cf. Flint, 1957; Shaw, 1980).
Basal melt out till	Till derived by stagnation of basal debris-rich ice and subsequent deposition by subglacial melting (cf. Boulton, 1972; Shaw, 1980).
Englacial melt out till	Till derived by stagnation of englacial debris-rich ice which is released and lowered by melt out processes (this term is suggested here).
Supraglacial melt out till	Till which is transported supraglacially and is lowered through melt out processes (cf. Shaw, 1982).
Flow till	Till which has been transported in a supraglacial, englacial or basal position and has been redistributed through flow involving considerable gravitational mass movement (Hartshorn 1958; Boulton 1968). The term flow till is widely used but its validity is questionable (cf. Lawson, 1979).

2.4 Till Description

Certain characteristics of the tills investigated in the field area were recorded. In particular, properties such as clast lithology, distribution, size, shape and roundness were observed. The lithological composition of clasts was analysed by shattering pebbles and cobbles to expose clean surfaces. Estimates were made as to the dominant lithologies during fabric analyses. Cobble and pebble content was visually estimated with reference to a comparative density chart (Terry and Chilingar, 1955). Clast size was analysed in the field using a classification proposed by Wentworth (1922) and a grain size comparator (developed by the Department of Geology, University College, London) was used to determine the size of sand particles in stratified materials associated with till. Clast shape was recorded using Zingg's classification of pebble shapes (in Pettijohn, 1975 p.54). This divides pebbles into four groups: tabular, equant, bladed and prolate. Pettijohn's (1975) roundness grade was used extensively in determining the roundness of clasts. Clasts are described as angular, subangular, rounded and well-rounded. Various roundness grades have been proposed (Wadell, 1932; Krumbein, 1941; Folk, 1955) but because of the descriptive nature of Pettijohn's classification it was used in preference to the other grades.

Surface textures were identified wherever possible. These investigations included observation of striae, scratches, and percussion marks or pits (Pettijohn, 1975). Surface textures were related to the position of transport of the clasts. Problems of identifying environments of transport and deposition from surface textures have been presented by Holmes (1960), Drake (1968, 1971), Goldthwait (1971) and many others. Surface textures are not always diagnostic of clast position during transport but are informative in this respect when used in conjunction with other till properties (Boulton, 1978).

Till matrix was estimated for sand, silt and clay content and till compaction was described subjectively. The degree of compaction was analysed with reference to three classes: loose, compact and very compact. These terms were applied subjectively. Loosely compacted tills were considered to be those in which the matrix could be crumpled by hand; very compact tills were those in which the matrix could be broken only by using a geological hammer and compact tills were those in which the matrix material could be broken by hand with difficulty.

Colour was identified from Munsell colour charts. Internal structures such as jointing, fissility, foliation, faulting and folding were recorded. The relationship between clasts in till and adjacent stratified materials was analysed. Till fabrics were recorded at specific sites to help determine the nature of formative processes. Some of these characteristics will be described in more detail below.

2.5 Sedimentary Structures

Pettijohn and Potter (1964) have defined primary sedimentary structures as those formed at the time of deposition or shortly thereafter and before consolidation of the sediments in which they are found. They include various types of surface markings, bedforms and bedding. Also included are structures which are produced by the activity of organisms and penecontemporaneous deformation structures produced after deposition but before consolidation of sediments (Reineck and Singh, 1980, p.8).

In terms of field methods, sedimentary structures were analysed using a variety of techniques. These included the identification of bedforms and the description of bedding observed at a micro scale within a single bed (Otto, 1938) and in a sedimentary sequence.

Measurements of the geometry of bedforms and bedding were recorded and interpreted using standard procedures in sedimentology (Muller, 1967; Bouma, 1969). Tectonic structures were observed in some sections. Faults and folds were described. Other observations included shear structures, slickensides, convolute laminations, boudinage, slump structures and clastic dikes.

Further structural properties such as debris-stratification and the relationship of till to sorted layers were documented at macro and micro scales. Conformable relationships between strata were deduced from observations of bed contacts.

2.5.1 Sedimentary relationships deduced from observations of modern glaciers

Studies on modern glaciers provide insight into their geomorphic processes. In addition, modern glaciers may provide analogues for the processes which operated in Pleistocene ice sheets. In particular, observations of structures within glaciers and sedimentological investigations in modern glacial environments provide useful comparisons to Pleistocene deposits where similar structures and sedimentary relationships may be observed. This approach is exemplified by work on Spitsbergen glaciers (Boulton, 1968, 1970a, 1970b, 1971, 1972) and by studies of the Taylor Glacier, Antarctica (Shaw, 1977a, 1977b), Tsidjiore Nouve in Switzerland (Shaw, 1980) and at Omsbreen in Norway (Shaw, 1982). Lawson (1979) also provided a comprehensive analysis of the sedimentology of the Matanuska Glacier, Alaska, which included detailed structural observations of till and stratified materials.

Research on modern glaciers has enhanced our knowledge of the sedimentology of till and also provides a better understanding of structural properties in glacial deposits. Thus, structural properties in tills such as bedding, foliation, faulting, folding, together with those properties associated with melt out and flow, now may be described more accurately in Pleistocene deposits. It should be noted, however, that some properties, which may be used to distinguish one genetic till type from another are not always mutually exclusive. For example, Haldorsen and Shaw (1982) observed certain properties of tills in southeast Norway and concluded that it was difficult to distinguish between melt out facies and flow facies. It is clear that similar sedimentary sequences can be produced by different processes and that in the final analysis a discussion of their formation must remain hypothetical.

The structural properties and sedimentary relationships of till and stratified materials observed within the glacigenic streamlined landforms in the Hinton/Edson area were given particular attention. These may be related to research on streamlined landforms and studies of till where similar properties and relationships have been reported elsewhere (Lundqvist, 1977; Kruger, 1979; Lawson, 1979; Shaw, 1979; Bouchard, 1980).

2.6 Fabric Analysis

In order to determine formative processes till fabrics were measured at selected sites on three glacigenic streamlined forms. The location of fabric sites was dependent on road cuts through the landforms. The orientation of the sections were parallel or slightly oblique to the long axis of each landform. Sample sites were controlled by access on the section face and structural properties identified within till. A stratified, random sample which involved the location of selected sites covering the section both laterally and vertically, was chosen to provide maximum fabric information for each landform.

At each fabric site the orientation and plunge of the long axes of fifty pebbles were sampled from a volume of approximately 0.5 m^3. These were measured either by a Brunton Compass or a Silva Compass and Clinometer. Orientation measurements have an estimated precision of approximately ±3° and dip measurements have an estimated precision of approximately ±2°. The till matrix was removed until a clast was located and only clasts with a minimum 2:1, a:b axial ratio were used. Clasts of greater than granule size were used and prolate clasts were preferred. Individual clasts were first carefully excavated and a pencil was inserted parallel to the long axis of the pebble. The clast was then carefully removed and the orientation and dip of the long axis checked. The pebble was then reinserted and measurement was taken *in situ*.

Macrofabric data are presented in two ways: first by mirror image circular histograms or Rose diagrams with 10° class intervals (mean dip was calculated for each sample); and second, by the eigenvector method (Fara and Schiedegger, 1963; Mark, 1973). Statistical manipulation of the data was done by computer and the fabric data are presented in the Appendix. The azimuth (A) of the principal eigenvector provides a measure of the preferred orientation and the normalised eigenvalue, S_1, provides the strength of the preferred orientation. The largest eigenvector, V_1, shows the direction of maximum clustering and represents the mean axis whereas the smallest eigenvector, V_3, indicates the direction of minimum clustering and lies orthogonal to the best plane through the data (Lawson, 1979). Significance values, $S_1 \geq S_2 \geq S_3$, show the degree of clustering of the axes around the eigenvectors V_1, V_2 and V_3 (Lawson, 1979). These values are computed by dividing the eigenvalues by the total number of readings. Therefore, S_1 measures the strength of clustering about the mean axis whereas S_3 is inversely proportional to the strength of the preferred plane of the fabric (Lawson, 1979).

An estimate of the strength of the preferred orientation, which is affected by the dip directions of the clast axes, is given by the length, R, of the three-dimensional (resultant) vector at the 0.01 significance level (Watson, 1966). The gradient of straight lines radiating from the origin is given by K which is related to girdle or cluster tendencies and C is a measure of the strength of the preferred orientation (see Woodcock, 1977 for a full discussion). These variables are displayed in Table 4.1, and the values for A, S_1 and R will be used primarily to characterise the macrofabric data. Selected distributions have been contoured according to the method of Kamb (1959) at a contour interval of two standard deviations.

2.7 Palaeocurrent Analysis

Much literature has been published recently on palaeocurrent analyses (see Potter and Pettijohn, 1977, for a review). In this study, palaeocurrent analyses were conducted on cross-bedded sand units in order to interpret the deposit. One advantage of Quaternary sediments is that three-dimensional sections can be readily excavated which permits detailed observations of the geometry of the bedding. This procedure was carried out at several sites both to observe and differentiate bedforms.

In order to measure the orientation of the foreset beds of both tabular and trough cross-bedded forms, selected exposures were cleaned to reveal a three-dimensional view of their sedimentary structures. The orientation of a particular foreset bed was then measured with a Silva Compass perpendicular to the strike of the foreset, parallel to the a–b plane in the downdip direction. Additional directional control was obtained by inspection of the cuts made parallel to the b–c plane.

Potter and Olson (1954) state that because variability at an outcrop is usually greater between than within cross-bedded units, the best practice is to measure one foreset in each cross-bedded layer. This practice yields the best estimate of the foreset dip direction for a given number of measurements (Potter and Pettijohn, 1977). This procedure was followed in the field and the arithmetic mean was calculated for each set of observations as Potter and Pettijohn (1977) propose that this is adequate for most outcrops.

3. DRUMLINS AND FLUTINGS-GENERAL DISCUSSION

3.1 Theories of Drumlin and Fluting Formation

3.1.1 Introduction

Hypotheses to explain glacigenic streamlined forms are commonly controversial. Many varied explanations have been presented for drumlins and flutings. This is partly because they are conspicuous features in many glaciated landscapes and also because the formation of large-scale forms has not been observed under modern glaciers.

Drumlins, drumlinoids and flutings, represent a gradational sequence of landforms from short, low relief mounds to elongated features many kilometres in length. The primary reason for considering these streamlined features together is that a genetic continuum may exist between drumlins, flutings and transverse moraines (cf. Lundqvist, 1969; Sugden and John, 1976; Aario, 1977a and b; Shaw, 1979, 1980).

3.1.2 Drumlins

The term "drumlin" is Gaelic in origin and refers to a round or oval shaped hill. Drumlins display a wide variety of forms and are commonly described as resembling an inverted spoon or lemniscate loop (Chorley, 1959). Drumlinoids and Blattnick moraines (Markgren and Lassila, 1980) are considered to be transitional forms between transverse features such as Ribbed or Rogen moraines and "classical" drumlins.

Early research workers (Chamberlain, 1883; Upham, 1892; Fairchild, 1907, 1929) proposed that drumlin formation resulted from the presence of "cores" around which sediments adhered. These "cores" consisted of bedrock, rock blocks and till deposits. However, although the presence of "cores" may be one initiating factor, it does not explain those forms in which they are absent. Banding of sediments within drumlins led several workers to advocate an "accretion process" (Alden, 1918; Fairchild, 1929; Hill, 1968), whereby concentric layers accumulated to form drumlins. One apparent weakness of the accretion hypothesis is that it avoids or presupposes an initiating point (Menzies, 1976). However, the agglomeration mechanism and accretion process illustrate one school of thought which postulated that drumlins were entirely depositional in origin. Other workers considered drumlins as erosional forms (Shaler, 1889; Tarr, 1894; Gravenor, 1953). Shaler's (1889) work is typical of the "erosional school". He proposed that drumlins were formed by two glaciations: during the first glaciation an irregular till surface was deposited and during the second glaciation this surface was scoured to form drumlins. Explanations involving two glacial advances are the assumption of most erosional hypotheses involving till. Tarr (1894) found that rock drumlins and till drumlins were similar in morphology and concluded that the same erosional process produced the same forms. Although this morphological inference may not be tenable, drumlins composed of bedrock are clearly erosional forms. Thus, drumlins have been explained by theories which range from entirely erosional to wholly depositional (Muller, 1971).

More recently, explanations of drumlins have concentrated primarily on stress conditions within ice and material deformation (Smalley and Unwin, 1968; Menzies, 1979; Boulton, 1982). These theories incorporate empirical and theoretical research from glaciology with investigations of drumlins and provide a different approach to drumlin genesis. They also attempt to combine both erosional and depositional hypotheses into an intergrated explanation of the forms.

3.1.3 Flutings

Glacial flutings are elongated, streamlined landforms. They are characterised by parallel ridges with crest lines which are of similar height throughout the length of the forms. Small-scale flutings have been investigated intensively. Dyson (1952), working in Glacier National Park, U.S.A., concluded that flutings represent parallel fillings in subglacial tunnels which form in the lee of boulders. Similar conclusions for small-scale flutings have been reported by other workers (Hoppe and Schytt, 1953; Boulton, 1976a). In general these flutings are formed by the squeezing up of deformable subglacial sediment into the low pressure zone occurring in the lee of rigid obstacles (Boulton, 1976a). It is clear, however, that not all small-scale flutes require rigid obstructions for their formation. McPherson and Gardner (1969) noted that flutes were formed in splaying crevasses, created by zones of high and low pressure at the terminus of the Saskatchewan Glacier, Alberta. The author has also observed flutings formed in a similar manner beneath the Athabasca Glacier, Alberta.

Large-scale flutings are variable in dimensions. They are generally greater than two or three metres in height and several hundred metres in length. Both erosional and depositional flutings occur. Gravenor and Meneley (1958) reported erosional flutings in Precambrian gneiss and porphyritic granite in northeastern Alberta, and Funder (1978) found extensive bedrock flutings in East Greeland. In the Northwest Territories, Bird (1967) reported extensive tracts of fluted ground moraine which was of depositional origin and Prest *et al.*, (1968) mapped flutings formed by the Laurentide Ice Sheet which they considered both erosional and depositional.

It is unlikely that large-scale flutings can form downglacier of boulders, although mechanisms of fluting formation have been presented where till deposition occurs in the lee of large obstructions (Shaw, 1979; Moran *et al.*, 1980). One major objection to the formation of large-scale flutings by this mechanism is that large, extended, subglacial cavities are difficult to envisage. This is because ice, deforming plastically, will normally close cavities. However, this depends on variables such as the rate of re-deformation to compensate for low pressures within cavities and pressure differentials (Rothlisberger, 1972; Nye, 1973).

Gravenor and Meneley (1958) postulated that flutings were formed by parallel high and low pressure zones alternating at the base of a glacier. They proposed that material eroded from beneath high pressure zones would be incorporated and moved down-ice in a curved path towards low pressure zones on top of fluting ridges. Therefore, ridges would be formed beneath low pressure zones and troughs beneath high pressure zones. Although Gravenor and Meneley (1958) provided some general conclusions towards the origin of flutings they did not explain why zones of high and low pressure were formed. In addition, they did not discuss the mechanism of secondary flow which would be generated by cross-stream and down-stream vector components whereby material would move obliquely with forward ice movement.

Shaw and Freschauf (1973) and Shaw (1975) developed a hypothesis to explain flutings in terms of secondary flows. By investigating till fabrics in flutings near Athabasca, Alberta, they postulated that a secondary flow mechanism in ice accounted for their herring-bone fabric pattern. Jones (1982) supported this model based on studies of flutings in the St Paul area, Alberta.

In summary, theories regarding drumlins and flutings have been fully summarised by Muller (1974), Gillberg (1976) and Menzies (1976). Formational hypotheses range from erosional to depositional. It is probably too simplistic to restrict hypotheses to either erosional or depositional explanations because for many streamlined landforms these processes occur together (Muller, 1974).

Two papers are considered to be particularly relevant to the explanation of drumlins and flutings in the Hinton/Edson area (Shaw, 1979; Moran *et al.*, 1980). Shaw investigated Rogen moraines in Jamtland, Sweden. He noted that individual ridges displayed curved horns pointing in a distal direction and that transitions from Rogen moraines to drumlins could be recognised. Transitions from Rogen moraines to drumlins and flutings have been described in the literature also by Hughes (1964), Lundqvist (1969), Aario (1977a and b) and Bouchard (1980). Shaw (1979) further described the composition and structure of Rogen moraines and noted that a large proportion of angular boulders of local origin were present within these forms. He also described the widespread occurrence of layers of sorted material in the ridges. These layers were up to 10 centimetres thick and contained silt and sand displaying graded beds, convolutions and micro faults. In particular, he emphasised that the sorted layers were horizontal and cross-cut tectonic structures. In one ridge, it was observed that the tills displayed folds and that there was evidence of thrusting. In terms of fabric analysis, Shaw commented that both up-glacier dips and girdle distributions were common in Rogen moraines and that secondary parallel peaks with steep dips also occurred.

In his interpretation of Rogen moraines (Figure 3.1), Shaw proposed that initial thrusting and folding of debris-rich ice produced a series of small basal folds. These folds, in turn, became superimposed over other folds to create a single fold complex which extended into an englacial position. The result of the englacial fold complex is that it produces relatively stagnant, debris-rich ice which is overridden by clean ice. Ice passing over the englacial ridge is forced to accelerate causing extending flow. With the onset of deglaciation the ice surface thins and a supraglacial complex develops over the landform. Basal melt out preserves the englacial ridge complex and produces the horizontal sorted layers which are indicative of cavities or layers in the melting ice. As melt out proceeds the Rogen moraine eventually forms an upstanding ridge and slumping

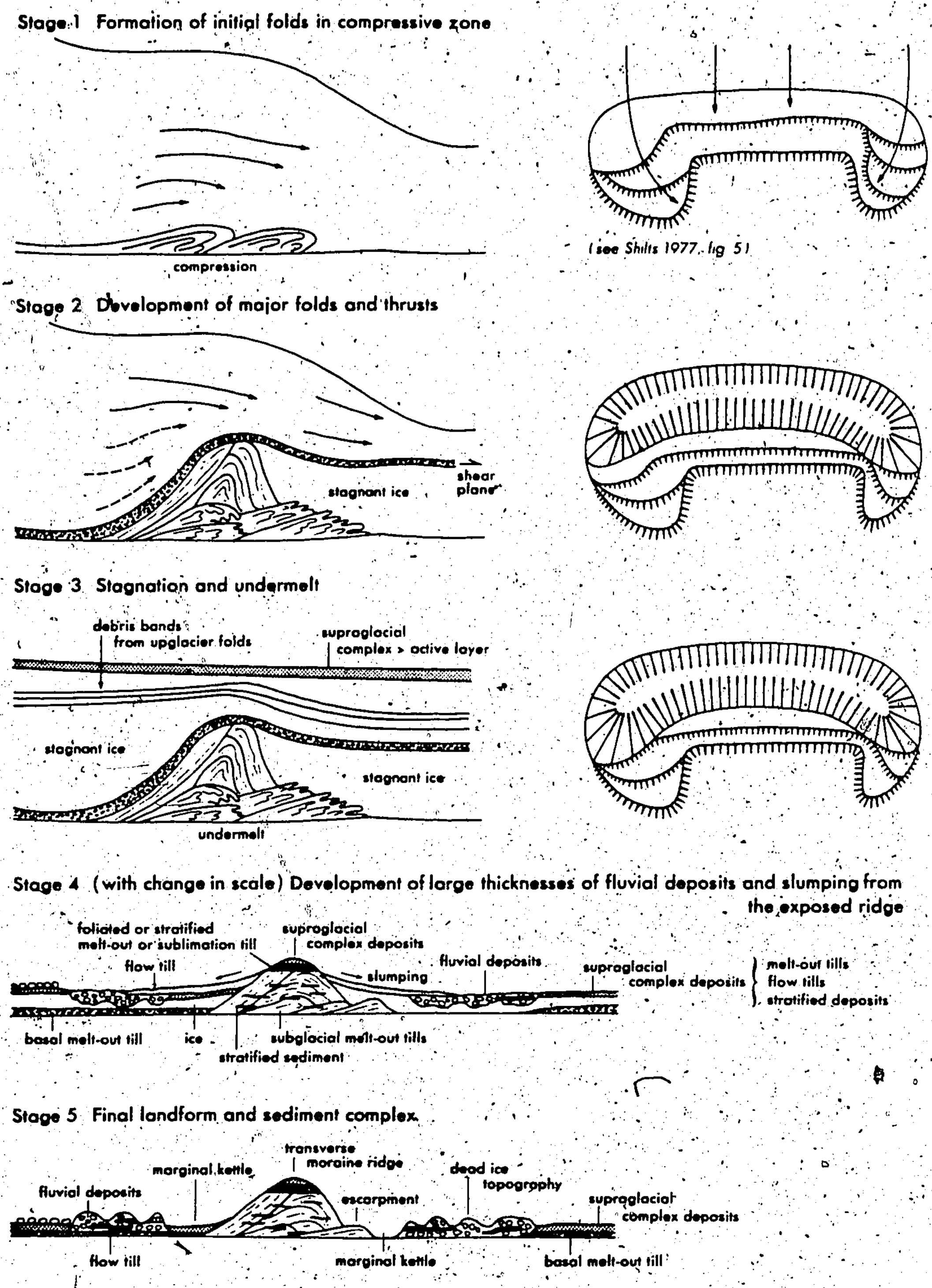


Figure 3.1 Genesis of Rogen Moraines, (from Shaw, 1979).

and flow takes place along its slope.

Shaw concluded that Rogen moraines are generated in areas of former compressive flow where stacking of debris results in transverse moraine ridges and that the preservation of this type of feature requires basal melt out from stagnant ice. Although Shaw's study was confined to Rogen moraines, he implied that a possible mechanism exists whereby these features may develop into flutings if they are overridden by extending flow. In this thesis, investigation of part of one fluting ridge showed similarities to the Rogen moraines described by Shaw and the genesis of flutings from Rogen moraines will be discussed later.

A second paper particularly relevant to this topic was published by Moran *et al.*, (1980). This paper modifies some of the ideas presented in an earlier study (Clayton and Moran, 1974) which proposed that two major terrains are formed at or near the base of Pleistocene ice sheets in North America: 1) Glacial thrust blocks; and 2) Streamlined terrain. Moran *et al.*, proposed that glacial thrust terrain was formed where the glacier was frozen to the substrate. This "frozen-bed zone" is thought to be no more than 2-3 kilometres wide at the margin of the glacier. They proposed that in this zone, elevated pore-water pressures decrease the strength of the substrate relative to the glacier and this results in thrusting. A similar mechanism has also been described by Aber (1982). Moran *et al.*, proposed that upglacier from the frozen-bed zone is the "thawed-bed" zone where movement at the bed occurs by sliding. In this zone, streamlined terrain is considered to have formed by erosion of the substrate or by moulding of thrust blocks accompanied by till deposition in the lee of these glacio-tectonic features.

Both these papers are relevant to drumlin and fluting formation. In Shaw's paper, specific landforms have been analysed and interpretations have been inferred from morphological and sedimentological observations. On the other hand, Moran *et al.*, have presented a regional approach to the understanding of drumlins and flutings. Both papers, taken together, suggest that Rogen moraines, drumlins and flutings may be initiated by obstacles to ice flow. These obstacles may result from the stacking and folding of debris (Shaw, 1979), or from glacial thrust blocks which have been incorporated in the ice (Moran *et al.*, 1980). In Shaw's explanation, the stacking and folding of debris is related primarily to flow conditions whereas Moran *et al.*, emphasise the thermal conditions in the ice.

3.1.4 Fabric Investigations of Drumlins and Flutings

Fabric analyses provide information on the direction of ice movement, principal stresses imparted by ice to debris, and may help to explain the mode of till deposition (Menzies, 1979). Investigations of drumlins and flutings have often involved fabric analyses at various levels of sophistication (Wright, 1957; Gravenor and Meneley, 1958; Savage, 1968; Shaw and Freschauf, 1973; Boulton, 1976a). Wright (1957), working in the Wadena drumlin field, Minnesota, found that till fabrics were parallel to drumlin long-axes and exhibited up-ice plunges. He concluded that the till originated from basal ice where upward curving debris bands were present. Gravenor and Meneley (1958) obtained till fabrics from a fluting field near North Battleford, Saskatchewan. They found that parallel patterns occurred near the surface of the flutings but at depths greater than two metres transverse patterns were present. They speculated that the two distinct patterns were related to two separate ice advances. Savage (1968), working on a drumlin in Syracuse, New York, demonstrated that till fabrics showed a maximum divergence of 90° at the stoss-end of the drumlin and a similar convergence in the lee, with fabrics nearly parallel to drumlin elongation along the flanks of the landform. He concluded that these patterns indicated accretional growth by lodgement on a nucleus. Fabric patterns which are parallel or convergent with fluting long-axes have also been reported and related to movement of material by secondary flows towards the centre of fluting ridges (Shaw and Freshauf, 1973; Jones, 1982).

Boulton (1970b, 1971, 1976) demonstrated that if a till is compressed against an obstruction, strong, transverse fabric patterns may be produced. In addition, Boulton (1970b, 1971) noted that clast orientations in basal, debris-rich ice displayed transverse patterns as a result of folding and shearing. Boulton (1971) also showed that fabric patterns parallel to ice flow are often associated with parallel or extending flow conditions. However, these relationships were not observed by Lawson (1979) for the Matanuska Glacier, Alaska.

In this thesis, transverse and parallel fabric patterns may be interpreted with respect to zones of compressive and extending flow, respectively. However, in fabric studies generally, there appears to be a bias whereby clearly transverse or parallel fabric patterns are often interpreted in terms of compressive or extending flow. In addition, fabrics which show no preferred orientation are sometimes dismissed as those which have been disturbed during or subsequent to release from ice. These assumptions may be questionable (cf. Lawson, 1979) and therefore caution is needed in the interpretation of fabric patterns. This will be elaborated later.

3.2 Drumlins and Flutings in the Hinton/Edson Area

Glacigenic streamlined landforms are widespread in the Hinton/Edson area and some general comments are merited before discussing the detailed characteristics of three drumlins and flutings in Chapter 4.

3.2.1 Distribution, Orientation and Composition

Streamlined landforms are well-developed on the North Athabasca Tableland, South Athabasca Tableland and Pembina-Mcleod Benchland (Figure 1.3). Three Provincial air photo mosaics, (83F/5, 6 and 11 at 1:63,360), clearly display the general morphology and orientation of drumlins and flutings. Generally, the streamlined forms radiate from Entrance to Marlboro in an arc of 80° (Figure 1.5 and 1.6). Within this arc, two dominant trends emerge. One set of streamlined landforms is oriented northeast-southwest, parallel to the Athabasca valley between Entrance and Obed, whereas the other set is oriented west northwest-east southeast between Hinton and Robb (Figure 1.5 and 1.6). Fieldwork for this study was conducted on a selection of forms on the north side of the Athabasca River between Entrance and Apetown Creek (Figure 1.2), where the streamlined forms are oriented generally northeast-southwest. Between Apetown Creek and Oldman Creek only flutings are present. They are orientated north northeast-south southwest and are masked by a veneer of glaciolacustrine sediment. Oldman Creek marks the northeast boundary for streamlined forms to the north and west of the Athabasca River.

Streamlined landforms are extensive to the south of the Athabasca River, on the Athabasca Benchland, South Athabasca Tableland and Pembina-Mcleod Benchland (Figure 1.5 and 1.6). Roed (1975) reported that in this area, the easterly and southeasterly trending drumlins and flutings in the Marlboro till have been truncated by northeasterly trending forms in the Obed till. Truncation of the two sets of streamlined landforms is clearly displayed near the junction of the Athabasca Benchland and South Athabasca

Tableland as far west as Jasper Park boundary and as far east as Obed. Roed (1975) used this relationship as evidence for two Cordilleran ice advances, but he did not explain how the drumlins and flutings were formed.

On the South Athabasca Tableland, streamlined forms are generally oriented west–east whereas they are aligned southeast–northwest on the Pembina–Mcleod Benchland. Beyond this, the drumlin and fluting field extends in a southeast direction along the Foothills to Rocky Mountain House. It has been proposed that these streamlined landforms developed in the former zone of convergence between Cordilleran and Laurentide ice sheets (Roed, 1968, 1975; Shaw, 1975). To the east of Obed, streamlined forms are orientated west–east and terminate in the vicinity of Sundance Creek. (Figure 1.5). These landforms are found interspersed with hummocky moraine, pitted outwash, deltaic deposits and glaciolacustrine sediments.

3.2.2 Drumlin and Fluting Morphology

Morphological generalisations are difficult as the landforms are highly variable in size and shape in the Hinton/Edson area. However, drumlins are seldom more than 500 metres in width, 900 metres in length and 20 metres in height. Flutings range from 25–200 metres in width, upto 15 metres in height and are less than 2.5 kilometres in length. Flutings are more extensive than drumlins. Drumlins are mostly elongated forms and are fluted on their distal sides. Transitions to flutings and conjugate forms are common. Although "classical" drumlins with a lemniscate loop plan are rare, there are two zones where the forms closely approximate this shape. These are located in the southwest quarter of Township 52, Range 24, and in the southern half of Township 51, Range 22 (Figure 1.6). The former area includes Drumlin 1, which will be discussed in detail later.

Transverse elements, that is streamlined landforms which were developed perpendicular to ice flow, are rare and Rogen or Ribbed moraines appear to be absent. However drumlinoids and forms resembling Blattnick moraines are common on the Pembina–Mcleod Benchland (Figure 1.3).

3.2.3 Drumlin and Fluting Composition

The composition of drumlins and flutings is highly variable in the field area. Landforms were found to be composed of till, stratified sand with a till veneer, and till with stratified materials. The specific composition of selected drumlins and flutings will be dealt with in Chapter 4. However one set of flutings is worthy of note. In the vicinity of Quigley Creek (Figure 1.2) several flutings were examined. Sections through these forms revealed a composition of sandstone bedrock mantled by till less than two metres thick. The till contains sandstone boulders and rounded limestone and quartzite clasts. Loess was also observed in the matrix. Estimates were made of the fluting dimensions. The forms are 20–25 metres in width, 7–10 metres in height and a minimum of 100 metres in length. They appear to be associated with topographic convexities in the landscape. Further research is suggested here as the occurrence of bedrock flutes is not widely reported in Alberta.

4. INVESTIGATION OF INDIVIDUAL DRUMLINS AND FLUTINGS

4.1 Drumlin 1.

4.1.1 Introduction

In this chapter three glacigenic streamlined landforms will be examined. Observations of the internal and external characteristics of one drumlin and two flutings will be used to infer theoretical conditions of glacier flow, thermal regime, debris in transport, and patterns of glacial decay.

The procedure which will be used to describe each landform is as follows: first, morphological and sedimentological observations will be presented followed by their interpretation. Second, fabric data will be evaluated and third, landform genesis will be postulated. Because interpretations of landform genesis involve syntheses from the previous sections it is inevitable that there will be some overlap of data. However, the aim of each section on landform genesis is to outline a probable sequence of events leading to the formation of each glacigenic streamlined form.

It should be noted that as far as possible observations and interpretations will be dealt with separately. For this reason the non-genetic term "diamicton" will be used for observations whereas the term "till" will be reserved for interpretations. Figures displaying the morphology and sedimentology for each landform are presented as observations and interpreted in the text.

4.1.2 Morphological and Sedimentological Observations

The first streamlined form to be discussed is a drumlin located on the north side of the Athabasca River valley at an elevation of 1050 metres (Figure 1.2). The drumlin is situated beneath the uppermost break of slope leading to the North Athabasca Tableland (Figures 1.2 and 1.3). Other features of similar size occur in the immediate area (Figure 4.1).

In plan, the landform appears to be part of a composite set of two or possibly three ridges which are superimposed on each other (Figure 4.2). This results in a three-pronged appearance to the northeast or distal part of the form and a single, tapered

Figure 4.1 Drumlin 1, general location of section and drumlin field.
Air photo (Provincial, 1964/65) A.S. 853-46. Scale 1:31,680.

Figure 4.2 Drumlin 1, detailed location of section.
Air photo (Provincial, 1968) A.S. 1018-9, 10. Scale 1:15,840.

end to the proximal or southwest margin of the drumlin. The long axis of the central ridge (axis 2) is ca. 1100 metres in length and is orientated 058°–232°. The long axis of the northerly fork (axis 1) is ca. 201 metres in length and orientated 042°–222°. The long axis of the southerly fork (axis 3) is ca. 804 metres in length and orientated 060°–240° (Figure 4.4). A road cutting bearing 050°–230° permits observation of the composition, structure and fabric of the drumlin sediments. The relationship of this section to the landform is illustrated in Figures 4.2 and 4.4.

The road cut is 184 metres long and is 19 metres high in the centre (Figure 4.4). The maximum relief of the drumlin is estimated to be 25 metres. Two prominent rises occur at the top of the exposure; one towards the southwest and the other in the central part. They are separated by a two metre depression (Figure 4.4). Slopes of 13° and of 8° were recorded at the southwest and northeast end, respectively.

The section displays a complex composition, texture and structure. Three diamicton units were identified, a lower diamicton, a middle diamicton and an upper diamicton.

The lower diamicton is exposed at the base of the section. Although the lower diamicton is not laterally persistent, it is observable for approximately two-thirds of the exposure. The diamicton consists of loosely compacted, silty sand with dispersed boulders, cobbles and pebble sized clasts. The principal lithologies of the boulder sized clasts are ferric arkose sandstone, orthoquartzite sandstone, massive limestone and some minor amounts of shale. This indicates a local source area for the sandstones (possible Paskapoo formation) whereas the crystalline lithologies have been derived from the Rocky Mountains around Jasper and include Gog Quartzites. Most of these clasts are subangular. Cobbles and pebble sized clasts exhibit similar lithologies but also include conglomerates, mudstones, cherts and chalcedony. The shape of these clasts varies from angular to subrounded, the latter predominating.

In the centre of the section, extensive stratified sand and gravel lenses separate the lower diamicton and the middle diamicton (Figure 4.4). These stratified sediments will be discussed in detail later. The middle diamicton occupies a major part of the section. In the central part of the section it extends from approximately 6 metres to 15 metres. The unit overlies the lower diamicton in a broadly convex manner and maximum dips of these sediments occur towards the northeast and southwest ends where respective dips of 10° and 25° are recorded.

The middle diamicton has a sandy silty matrix with a higher pebble content than the lower diamicton. The dominant clasts are limestones, orthoquartzite sandstones and ferric arkose sandstones. Chert and chalcedony are found in minor quantities and mudstones and claystones are infrequent. Clasts are rounded to subrounded, faceted and striated. The diamicton unit is loosely compacted. Three relatively continuous clayey bands are found within the middle diamicton (Figure 4.4). Small discrete blocks of medium to fine sands are also found in association with these clayey bands. These sediments are discussed below.

At the top of the middle diamicton, near its contact with the upper diamicton, are discontinuous horizontal lenses of laminated sand. Such lenses have a limited distribution and are confined to the upper layers of the middle diamicton (Figure 4.4).

The upper diamicton is 2 metres thick (Figure 4.4). The diamicton is highly calcareous and displays microcolumnar joints with calcite crystals along the joint planes. The matrix is a grey to grey-brown (10 YR 7/3), moderately compacted sandy loam. Clasts of coarse pebble size are frequent. The degree of rounding is highly variable, ranging from subangular to well rounded clasts. The pebbles are mainly of limestone and quartzite. The clasts are faceted but less frequently striated than those in the underlying units. A gravel fill occurs at the northeastern end of the exposure within this unit (Figure 4.4). Overlying the upper diamicton is a discontinuous band of fine sand and silt with a maximum thickness of 30 centimetres. Most of the grains are coated with iron and aluminium oxide giving the entire unit a pale reddish brown colour (10 YR 6/3).

The stratified components may be divided into four groups; sand lenses, sand and gravel lenses, clayey bands and a gravel fill. Each of these will be discussed in turn.

4.1.2.1 Sand lenses

Sand lenses are commonly found in association with both the lower diamicton and the middle diamicton. An extensive stratified sand lens is located between 4 and 5 metres above the base of the section and between 56 metres and 63 metres from the southwest end (Figure 4.5). Excavation of the sand lens exposed both its upper and lateral contacts with the middle diamicton but a lower

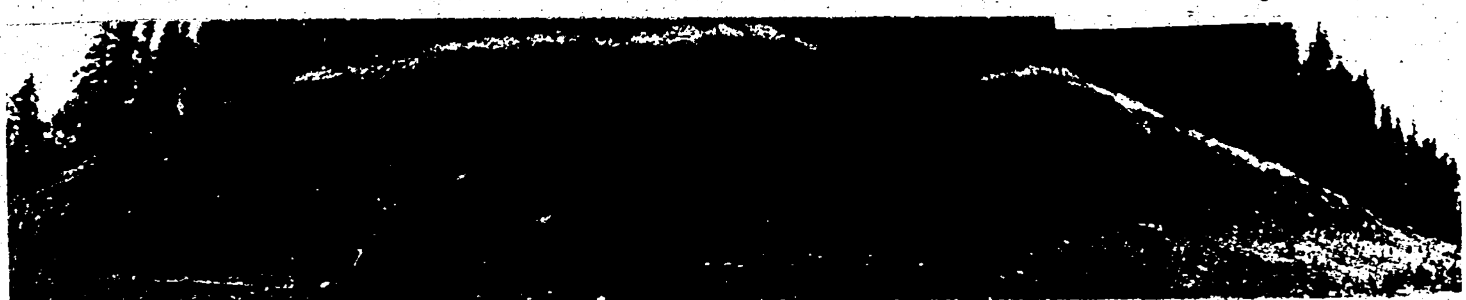


Figure 4.3 Oblique section through Drumlin 1, (see Figure 4.4).

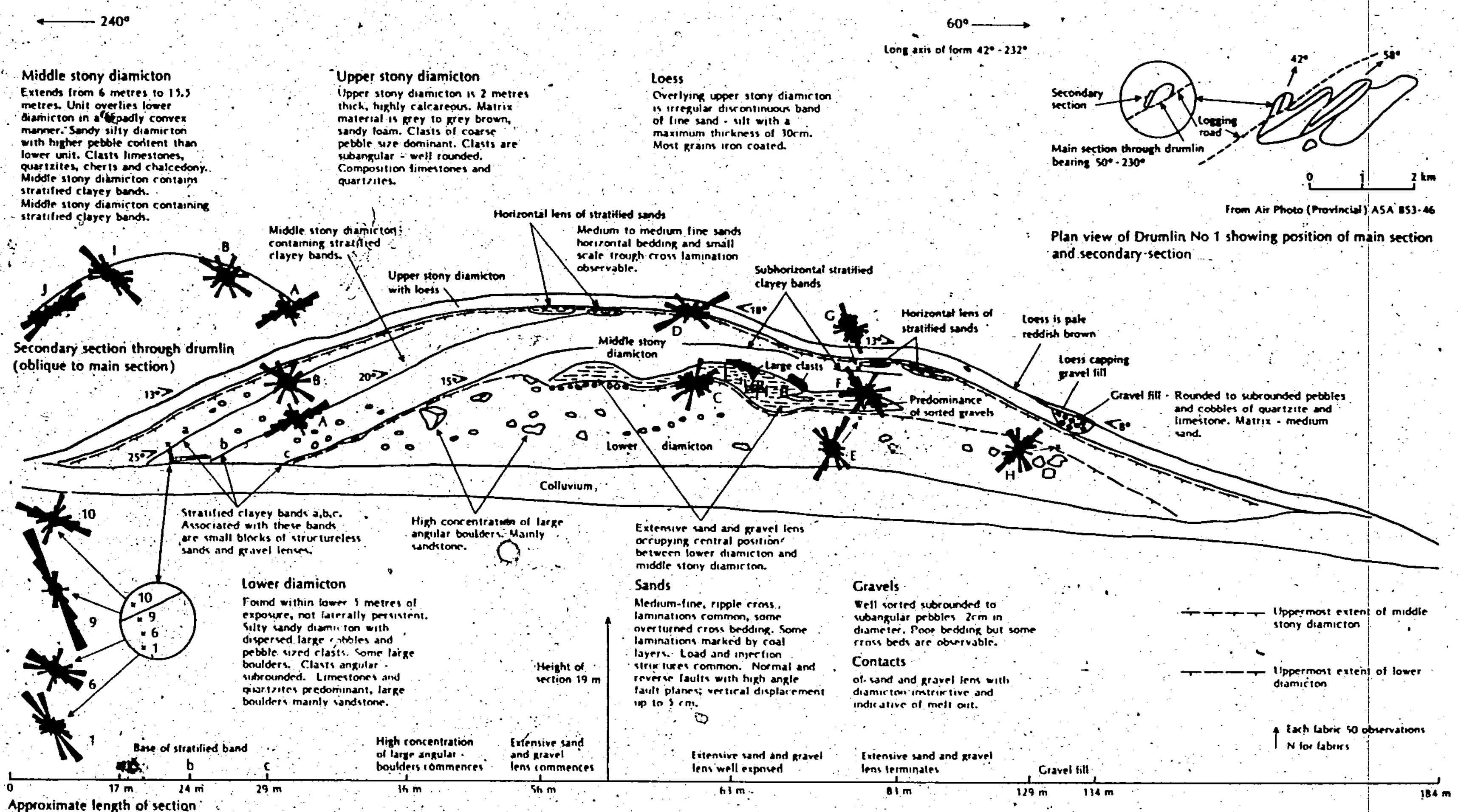


Figure 4.4 Internal Structure, Sedimentary Characteristics and Clast Orientations, Drumlin 1

Figure 4.5 General view of stratified sand lens and contact with middle diamicton. Dashed line marks contact. Position of section is at 60 metres from southwest end, (see Figure 4.4).

Figure 4.6 Close-up of stratified sand lens. Note overturned cross-beds marked by coal stringers, convolutions in fine sand and pockets of granules. Contact with middle diamicton at the top of the photograph.

contact at the base of the sand lens could not be found (Figure 4.5).

Micro-scale observations reveal that this sand lens contains a diversity of sedimentary and deformation structures. The sand grains are well rounded and the deposit is well sorted. Small pockets of granule gravel are dispersed through the lens but their occurrence is rare. Cross-bedding and ripple cross-laminations are developed in the medium grained sand, whereas the fine sand fraction generally displays ~~horizontal~~ laminations. Overturned cross-bedding is marked by coal stringers which intermittently define the laminations (Figure 4.6).

Load and injection structures are common in the fine sand and silt (Figure 4.6). These structures penetrate both horizontally and vertically into the medium coarse sand. In some places convolutions occur within the injection structures. Tectonic structures within this sand lens includes small-scale reverse and normal faults with throws of 2 to 5 centimetres (Figure 4.7 and 4.8). It is important to note that faulting is confined to the sand lens and in no place extends into the overlying or lateral diamicton (Figure 4.7 and 4.8). The upper contact with the overlying diamicton is well defined. There is no evidence of shearing on the upper surfaces of the sand lens.

The relationship of the large, angular clasts in the overlying diamicton to the upper contact of the sand demonstrates differential loading by the diamicton. One example of this is illustrated by Figure 4.7 and 4.8. These photographs show the deformation of fine sand and silt caused by a clast in the overlying diamicton. In this case a large shattered, angular claystone has penetrated into the sand lens and minor contorted bedding is visible in the underlying sands and silts (Figure 4.8). A small amount of diapirism is also observable. Beneath this clast a series of parallel, normal faults occur. The fault planes have hades of 50°-70° to the southwest. The vertical displacement of the beds, which consist of fine sand interbedded with small coal layers, is in the order of 5 centimetres.

Thin horizontal lenses of laminated sand are located in the upper part of the middle diamicton (Figure 4.4). These are variable in lateral extent and thickness but generally they are ca. 0.5 metres in length and 0.3 metres in thickness. The sand is medium fine to medium grade and displays horizontal bedding and small-scale trough cross-lamination.

Figure 4.7 Contact of middle diamicton with stratified sand lens. Note clast penetration of middle diamicton into underlying sand. Normal faults marked by coal laminations. Position of section at 63 metres from southwest end (see Figure 4.4).

Figure 4.8 Close-up of clast penetration. Note presence of loading structures in sand directly beneath clast margin.

Middle Diamicton

Gravel Lens

Stratified Sand

Lower Diamicton

Figure 4.9 Section through stratified sand and gravel lens. Both lower diamicton (bottom of tape measure) and middle diamicton (top of tape measure) are displayed. Position of section 83 metres from southwest end (see Figure 4.4).

Figure 4.10 Close-up of sand and gravel lens. Note sorting and crude cross-bedding in gravel.

4.1.2.2 Sand and gravel lenses

Approximately 5 metres above the base of the section, and 63 metres from its southwest end, there is a large sand and gravel lens (Figure 4.9). Both overlying and underlying diamictons contact the lens which is approximately 1 metre thick. The lens pinches out gradually some 10 metres to the northeast whereas to the southwest it may be continuous with the stratified sand lens described earlier. The sand and gravel lens has a horizontal contact with the lower diamicton where it is characterised by medium cross-bedded sand with small pockets of coarse sand displaying minor folds. In turn, this is overlain by a sequence of moderately sorted, subrounded fine and medium pebble gravel (Figure 4.10). Foreset beds dipping at 11°–15° were recorded and cross sets gave palaeocurrent estimates of 185°. Discrete lenses of stratified fine to medium sand with a maximum thickness of 10 centimetres occur above the cross bedded gravel (Figure 4.10).

4.1.2.3 Clayey bands

At the southwestern end of the feature three major clayey bands are prominently displayed (Figure 4.11). These bands are 2 to 11 centimetres thick and have dips of 15°–25° to the southwest. Dips decrease to the northeast of the exposure. The bands were traced laterally along the section and continue above the extensive sand and gravel lenses in the middle diamicton. However, they do not extend into the upper diamicton. The clay is grey (2.5 Y 4/2) and displays accordant laminations. Within these clayey bands, coarse pebbles are oriented parallel to the dip of the beds. Augen structures are discernable around many of these pebbles and the laminations present in the clay, are rarely truncated by the clasts. Immediately beneath the clayey bands minor sorting has occurred. The major axes of larger clasts within the upper 4–6 centimetres of the underlying diamicton generally lie parallel to the clayey bands. In places the bands bifurcate around small pockets of stratified sand and gravel and small blocks of structureless sand respectively (Figure 4.12 and 4.13). These blocks of sand are less than 2 metres thick and of similar width. They are composed of well sorted, highly compacted sand with well rounded grains and stratification is generally absent (Figure 4.13).

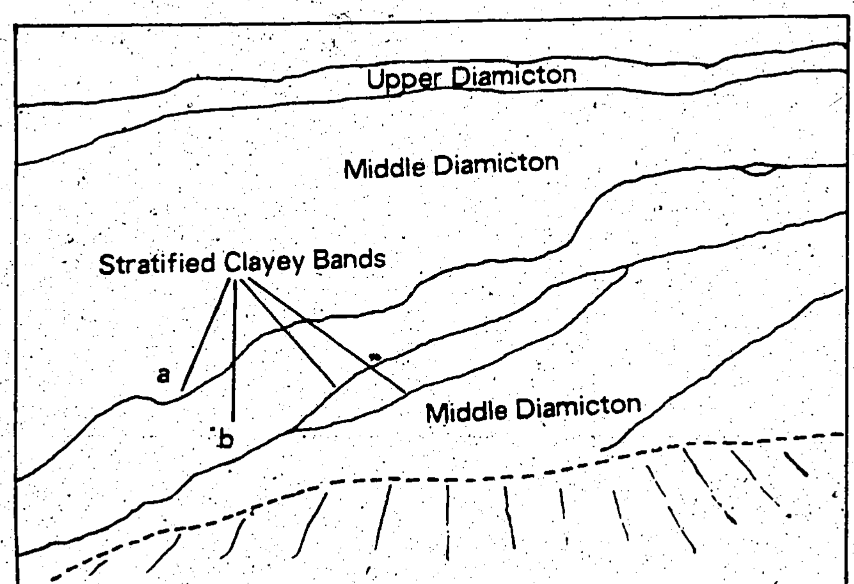


Figure 4.11 Exposure at distal southwest end of drumlin displaying stratified clayey bands (photograph with explanatory diagram). Note bifurcation of clayey band (b). Section located between 17–29 metres (see Figure 4.4).

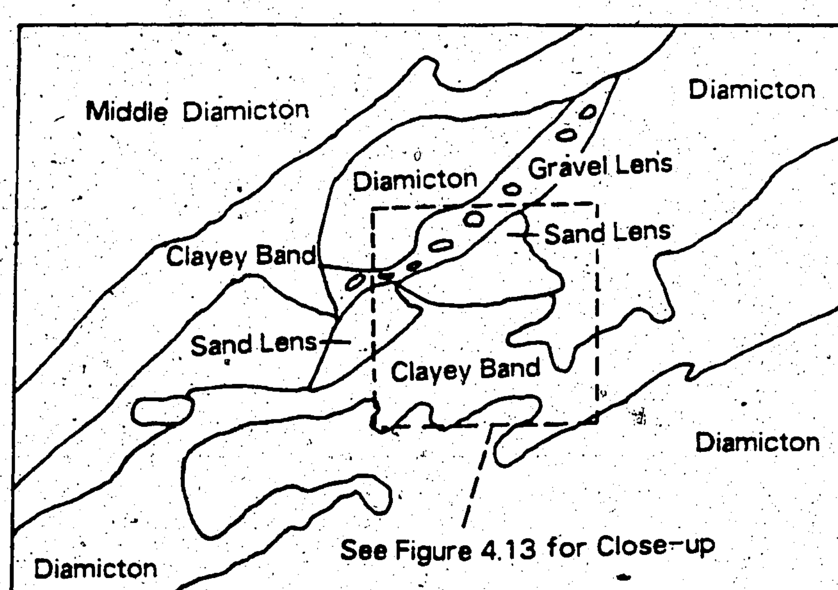


Figure 4.12 Relationship between clayey bands and blocks of sructureless sand, general view (photograph with explanatory diagram).

Figure 4.13 Relationship between clayey bands and blocks of structureless sand. Close-up of selected area indicated on explanatory diagram (Figure 4.12).

Figure 4.14 Supraglacial complex: upper diamicton with loess.

Figure 4.15 Supraglacial complex: channel fill sediments.

4.1.2.4 Gravel fill

In the upper diamicton 50 metres from the northeastern end of the drumlin, there is a trough containing a high concentration of rounded limestone and quartzite pebbles in a trough (Figure 4.14 and 4.15). The clasts are well rounded to rounded, moderately sorted and clast supported and the matrix is medium sand. No structures could be observed in the sand or gravel. Fine sand and silt, interpreted as loess covers the deposit.

4.1.3 Discussion and Interpretation

The stratigraphy of the section displays a lower diamicton overlain in the centre of the form by lenses of stratified sand and gravel. This, in turn, is overlain by a middle diamicton containing stratified clayey bands. In the upper zone of the middle diamicton, stratified sand lenses are interbedded with the diamicton. An upper diamicton containing a gravel fill overlies this unit. At the top of the section a continuous veneer of loess covers the upper diamicton.

Points to be considered in the explanation of the drumlin are:

1) The large angular sandstone clasts within the lower diamicton.

2) The presence of lenses of stratified sand and gravel.

3) The contacts of the stratified materials with the surrounding diamictons.

4) The stratified clayey bands.

5) The small blocks of structureless sand found in association with the clayey bands.

6) The fabric within the drumlin.

7) The morphology of the form.

8) The occurrence of a number of other drumlins with similar orientation in the area.

Three diamictons are exposed in the drumlin and these are interpreted as tills. The tills are proposed on the basis of texture, lithology, stratified materials, structure and stratigraphy. Both the lower and the middle till are similar in composition and degree of compaction. There are, however, significant differences between the lower and middle tills in terms of clast size, clast concentration, stratified materials, structural relationships and stratigraphic position. Many properties of the lower and middle till are similar to descriptions of the Kalix till (Lundqvist, 1969) and the Sveg till (Shaw, 1979) as lenses and layers of stratified, sorted sediments are common.

The lower till has a silty sandy matrix and is thought to represent a melt out deposit on the basis of its association with extensive, stratified sorted lenses. The presence of large, angular sandstone boulders similar to the surrounding bedrock of the area, suggests that these large clasts have been locally derived. Their confinement to the base of the section lends support to the interpretation of basal transport by ice. The absence of striae on the sandstone boulders also suggests minimal transport. However, it has been pointed out that relatively soft rocks do not always retain or permit the formation of striae (Drake, 1971). Finally, because the pebble sized clasts of the lower till are commonly faceted, and sometimes shattered, a basal environment of deposition appears likely. Goldthwait (1971) concentrated on the problem of genetically classifying till in terms of clast characteristics and concluded that the presence or absence of striae and shattered pebbles cannot be used strictly to determine subglacial, englacial or supraglacial deposition because many clasts may be basally abraded and transported to an englacial or supraglacial position. However, the local provenance of the sandstone blocks does preclude long distance transport, thereby supporting the interpretation of basal transport and deposition.

The presence of extensive lenses of statified sand and gravel, found between the lower and middle tills, indicates that englacial, fluvial conduits developed during melt out. Lenses of stratified materials deposited by englacial meltwater have been reported in till deposits (Lundqvist, 1977; Shaw, 1977b, 1982; Bouchard, 1980) but their presence within drumlins and flutings (as indicators of melt out) is less widely known. Most stratified deposits in drumlins and flutings have been explained as reworked materials which have been transported and redeposited by glacier activity (Gillberg, 1976; Menzies, 1979). The significance of the stratified lenses in this case is crucial as it indicates that drumlin formation has also involved melt out from stagnant ice.

Eskers may serve as useful analogues for the stratification observed in this drumlin. Banerjee and McDonald (1973) and Price (1973) have attributed the formation of certain esker systems to deposition of stratified materials in englacial conduits. Although esker systems provide evidence of sizeable englacial tunnels, the presence of small conduits within the ice is also well known.

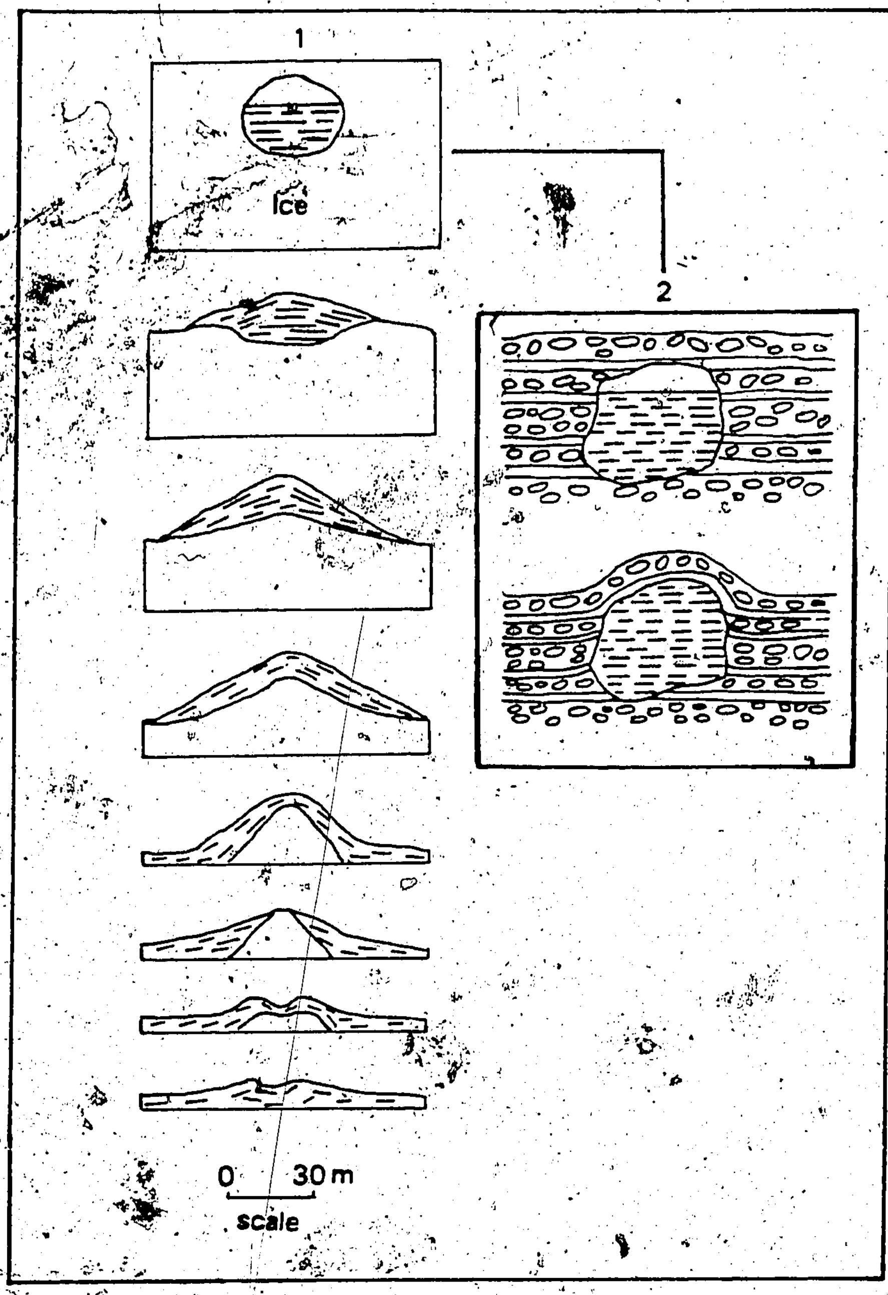


Figure 4.16 The probable sequence of events whereby an englacial stream deposit (1), can be lowered on to the subglacial floor. The glaciofluvial deposits protect the ice beneath from wasting as rapidly as clean ice either side. The result is an esker lowered from an englacial position (after Price, 1973). If debris-rich ice is present surrounding the englacial conduit (2), then the channel sediments may be lowered without disturbance during melt out. This explanation is proposed for the origin of the extensive, stratified lenses in the central part of Drumlin 1 (see Figure 4.4).

Price (1973) outlined a sequence of events whereby an englacial stream deposit can be lowered onto the subglacial floor (Figure 4.16). In this case the esker system results from slumping and collapse involving the wasting of an ice core. It is to be noted that this process involves the presence of clean ice on either side of the englacial tunnel. If, however, an englacial cavity is surrounded by debris–rich ice, and melting proceeds with a basal melt out mechanism predominating (Shaw, 1979), cavities filled with stratified materials would be preserved by the surrounding englacial debris rather than collapsing to form esker ridges as shown (Price 1973).

The above mechanism is proposed as an explanation for the extensive stratified lenses occupying the central part of the drumlin. The sedimentary structures, faults and contacts with the diamicton may be explained in terms of deposition in englacial cavities. Variability in hydrologic conditions, flow direction and rates of deposition is to be expected in an englacial system. Such conditions would be affected by the flow of water generating frictional heat (Paterson, 1981, p.138). Cavern collapse and the distribution of ice blocks may severely affect the magnitude and direction of flow and explain variability in sedimentary structure. Seasonal and weather induced variability in discharge may also be significant. Shaw (1982, Figure 18) showed a photograph of englacially deposited, stratified sediments at Omnsbreen, Norway. In certain locations the upper bed of ice rests directly on cross-bedded gravel and therefore Shaw concluded that at the time of gravel deposition a water–occupied cavity must have separated the ice roof from the sediment bed. Subsequently the ice settled on the sediment surface. This sequence, observed in the glacier at Omnesbreen, is considered to be a reasonable analogue for the stratified sediments observed in the drumlin under consideration here.

The contacts between the extensive sand and gravel lenses and the overlying till supports a process of gentle settling and draping rather than shearing. The absence of slickensides along the contact also does not support shearing. Support for a settling and draping mechanism, on the other hand, is presented by the compaction of the stratified sediments below the contact with the overlying till; clast penetration of the till into the underlying sand and silt, together with minor amounts of diapirism. Load and injection structures in the fine sand and silt are also caused by such lowering of till. In addition, load deformation and dewatering occurred by the release of the middle till unit over the stratified lenses.

The presence of collapse structures, as well as normal and reverse faults that are solely confined to the stratified lenses, suggests that final release was partly due to the melt out of small ice blocks below the sand (Shaw, 1971; McDonald and Schilts, 1975). This may have occurred before the overlying debris-rich ice melted otherwise faulting would be expected to extend into the overlying diamicton. Therefore the role of undermelting becomes important.

In summary, the lower till is interpreted as a basal melt out deposit from stagnant ice. The high content of bedrock boulders which have been locally derived possibly corresponds to a poorly attenuated facies (Shaw 1977a, 1979). The presence of stratified lenses in the centre of the section are the result of englacial cavities occupied by streams.

The middle till has a sandy silty matrix with a higher pebble and cobble content than the lower till. The upper zone of the middle till contains a series of stratified clayey bands interbedded with till. Small blocks of structureless sand are found in association with these clayey bands. The middle till is interpreted as debris which was derived from an englacial position. Melt out of the till overlying the stratified lenses is suggested by its structural and tectonic relationship with the underlying stratified sediments. The origin of the stratified clayey bands within the drumlin is problematic. There are at least four possibilities for their origin; 1) subglacially derived bodies of sediment incorporated into an englacial position: 2) sediments associated with shear planes: 3) subducted supraglacial sediments: 4) melt out phenomena.

The description of englacial debris bands presented by Boulton (1970a) from modern polar glaciers of Svalbard, is considered to be similar to the stratified clayey bands reported here. He described englacial bands of stratified debris as composed of silt, sand or gravel with low interstitial ice content. In some cases these bands were stratified and folded and Boulton postulated that the bands were originally subglacial and transported into the ice by regelation. Boulton (1970a) considered a number of mechanisms involving thrusting and basal freezing to explain the incorporation of englacial debris bands. His work is based in part on theories proposed by Goldthwait (1951) and Weertman (1961). He commented that it was difficult to reconcile the occurrence of undisturbed bedded sediments along debris bands, which are stratified and possess low interstitial ice content, with a thrusting mechanism. Thus the bands were better explained by a basal freezing mechanism involving transport to an englacial position.

The absence of slickensides, minor amounts of sorting and the relatively continuous nature of the clayey bands in the drumlin does not favour an interpretation involving thrusting. The general absence of fractured and shattered clasts within the clayey bands may also be taken as evidence against this mechanism. It is postulated here that the stratified clayey layers represent deposits from proglacial ponds which were frozen, overridden and incorporated as block inclusions by thrusting (Moran *et al.*, 1980) or regelation (Weertman, 1961; Boulton, 1970a).

The small blocks of structureless sand found in association with the clayey bands are evidence of ice frozen material (Shaw, personal communication). Similar blocks of sand have been reported in drumlins by Gillberg (1976) and attributed to transport in a frozen state. If this sand was developed *in situ* during melt out then obvious sedimentary structures would be expected. However such structures are absent. Because these "clasts" are intimately related to the stratified clayey bands, and sometimes enveloped by them, it appears that at some stage the associated bands were also frozen and quite probably derived at the base prior to being carried into an englacial position by thrusting.

Lawson (1979) has also observed numerous englacial debris bands on the warm-based Matanuska Glacier, Alaska. This is perhaps a more realistic analogue for the late Wisconsin, Athabasca Glacier than those from Svalbard in a maritime, high arctic setting. These debris bands have been attributed to the incorporation and subduction of supraglacial debris. Lawson (1979, p.19) suggested that the "layered" distribution, texture and sorting of the bands was compatible with an aeolian origin. In the drumlin, the association of "frozen" sands as clasts with the stratified clayey bands presumably precludes an aeolian origin. Lawson (1979, p.37) further describes melt out deposits in which stratified debris bands were common. These beds, formed of clayey silts, were preserved by melt out within the till although their origin was not clear.

It may be possible to produce stratified clayey bands solely through melt out of alternating layers of debris-rich and debris-poor ice. This would involve migration and washing of fines from overlying debris into layers of melting, clean ice. Such a mechanism has not been described in the literature for stratified clayey bands although Shaw (1979) has postulated a similar process for stratified, sorted lenses of sand and gravel in the Sveg tills of Sweden. This mechanism may be possible but is thought unlikely for an explanation of the clayey bands here.

The stratigraphic relationship of the middle till to the surrounding units requires further explanation. It is worth noting that the dip of the clayey bands, located predominantly at the southwest end of the drumlin, decreases towards the northeast; that the interbedded till is conformable with the clayey bands and that the clasts immediately beneath the bands in the till are parallel to the dip of the clayey bands. This pattern apparently reflects the melt out of conformable bands of debris-rich ice formerly in an englacial position, above the lower till and the stratified sand and gravel lenses. The dip of the clayey bands at the southwest end of the section is partly explained by differential melt out of clean and debris-rich ice which results in draping of the middle till over the lower unit. Finally, the upper till is considered as a supraglacial complex. Supraglacial streams present on the surface of the ice are indicated by the gravel fill.

The uppermost sedimentary unit is loess deposited after the withdrawal of ice from the area. The probable source of the loess were the shores of Brule Lake and the floodplain of the Athabasca River (Dumanski *et al.*,(1972). The calcareous nature of the loess appears to be the dominant factor in the development of the Brunisolic Gray Luvisols mantling the drumlin and the flutings in the area. Iron oxides derived from the weathering of limestone and dolomite fragments within the loess is responsible for the red horizons within the Brunisolic Bm horizons (Dumanski *et al.*, 1972).

4.1.4 Fabric Analysis

Fabric analyses were conducted at a number of sites to aid process interpretation (Figure 4.17). Various authors place different emphases on fabric analyses for the interpretation of glacial landform genesis. For example, Menzies (1979) commented that some authors working on drumlins and flutings (e.g. Savage, 1968; Shaw and Freschauf, 1973) have developed hypotheses solely on the basis of fabric analysis. Menzies suggests that this places too much emphasis on the significance of till fabrics. Andrews (1971) has also pointed out the problem of standardising fabric measurements whereas

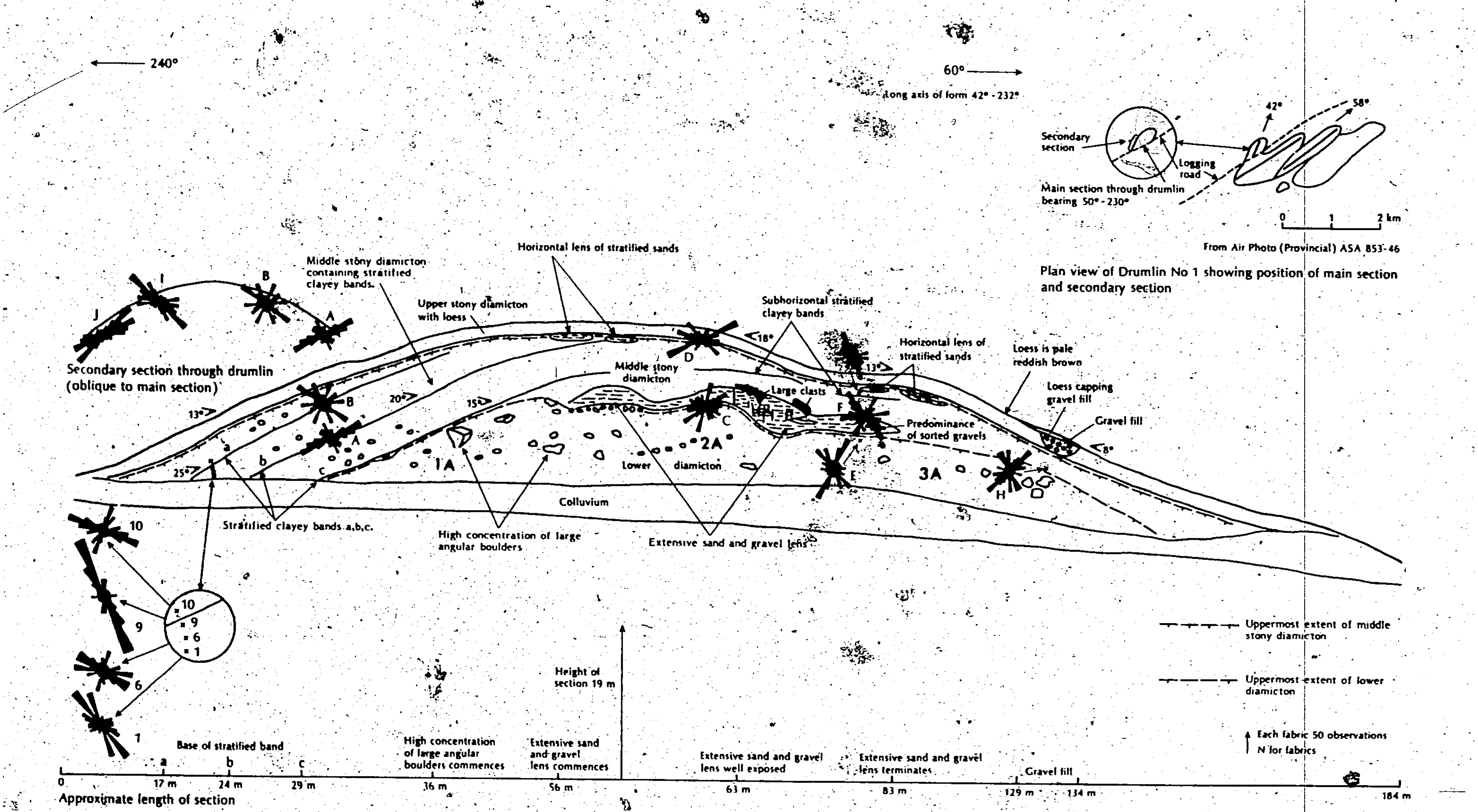


Figure 4.17 Fabric Locations on Drumlin 1.

many other workers have suggested inadequacies in till fabric data analysis (Menzies 1979, p.328). Boulton (1971) and Shaw (1979, 1982), have used fabric analysis widely in some of their work and although the initial criticism of Menzies is relevant, fabric analysis must be used in conjunction with other criteria for evaluating till genesis. In particular, Boulton (1971) and Lawson (1979) have undertaken fabric analysis in modern glacial environments where till genesis can also be observed. Lawson (1979) shows that different facies in the ice which are distinct isotopically and texturally, also have distinct fabrics. However, it is the author's opinion that a conservative approach to fabric analysis is necessary in the Hinton/Edson area. In the case of Drumlin 1, the position of the section is not perpendicular to the long axis of the drumlin which sometimes makes fabric comparisons difficult. Furthermore, complex facies occur and therefore fabric patterns are expected to be diverse. In addition, the bedrock topography is highly irregular and fabric orientations are affected by this (Boulton, 1971). Perhaps the most important problem to be resolved is whether the fabric patterns indicate glacier flow conditions or clast reorientation during subsequent release from the ice. Fabric orientations are known to be affected by differential melt out, flow, solifluction, mass movement and slumping (Boulton, 1971; Lawson, 1979; Menzies, 1979; Shaw, 1982) and it is often difficult to isolate these properties from fabric patterns.

Fifteen fabric investigations were conducted on Drumlin 1. Three have been displayed as three-dimensional patterns and twelve as Rose diagrams (Figure 4.17). Nine of the fabrics are transverse to the form (axis 2) which is orientated at 058°–232° or obliquely transverse to axis 1, 042°–232°. This contrasts with the findings of some workers (Wright, 1957; Minell, 1973; Shaw and Freschauf, 1973; Menzies, 1976; Jones, 1982) who have observed parallel or subparallel orientations to drumlin and fluting long axes.

In the lower till three-dimensional fabrics for sites 1A, 2A and 3A (Figures 4.17 and 4.18) indicate transverse orientations to the direction of former ice flow, considered to be from the southwest to the northeast (225°–045°). The azimuths of the principal eigenvectors are 135°, 132° and 343° respectively. At each site, however, the strength of the clustering around the principal eigenvector is weak (S_1=0.50, S_1=0.56, S_1=0.44). This indicates a high dispersion of clast axes. The general transverse patterns of the

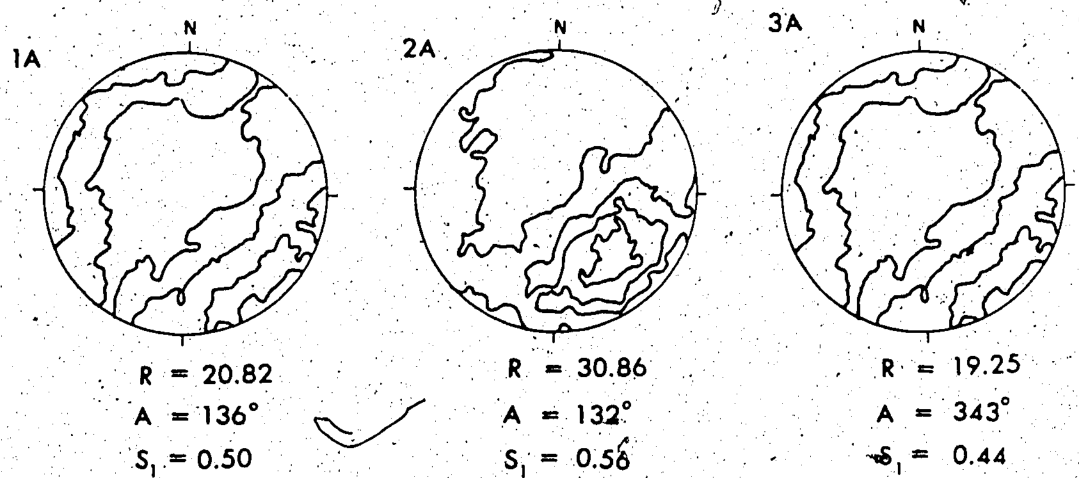


Figure 4.18 Contour Plots of Individual Fabrics, Drumlin 1.

See Figure 4.17 for Sample Location. Contour Interval is Two Sigma.

fabrics in the lower till are thought to indicate compressive flow within the ice (cf. Boulton, 1971). The interpretation of the lower till as a melt out deposit is not initially supported by the S_1 values. According to Lawson (1979, p.106) low S_1 values for principal eigenvectors were not characteristic of melt out till from the Matanuska Glacier, Alaska. The S_1 values he obtained were greater than 0.75. On the basis of statistical analyses alone the three-dimensional fabrics observed in the lower till would be more typical of Type 1, sediment flows (Lawson, 1979, p.106). However, Lawson noted that melting increases the scatter of individual particle orientations about the calculated mean and Boulton (1971) commented that fabric orientations change rapidly in melt out till undergoing downslope creep. This implies that the interpretation of the lower till as a melt out deposit in which the clasts have undergone some redistribution is not problematic.

Fabrics 1, 6, 9 and 10 (Figure 4.17) were obtained from the middle till at the proximal end of the drumlin section. Fabrics were sampled in a small area approximately 1 m^2, located adjacent to clayey band (a). Sites 1, 6 and 9 (Figure 4.17) are located in the till beneath this clayey band and site 10, is above this band. Fabrics 1 and 9 are strongly transverse to the drumlin axis and fabrics 6 and 10 display orientations which are oblique to the long axis of this landform. The general transverse pattern of these fabrics is thought to indicate a strong compressive flow element in the proximal zone of the drumlin (A. Dreimanis, personal communication).

Twenty nine metres from the proximal end of the section, site A exhibits a fabric which is subparallel to the drumlin whereas site B, located 4 metres above site A, displays a wide scatter of pebble orientations (Figure 4.17). Site D (Figure 4.17) shows a fabric pattern similar to fabric A, also with a modal class at 60°–70°. Both fabrics A and D are in the same plane marked by stratified clayey band (b). These fabric patterns may be taken to indicate extending flow in upper ice. Alternatively their patterns may be coincidental.

Sites C, F and E (Figure 4.17) show a dispersed fabric pattern. These fabrics are interpreted as indicating disturbance due to melt out of debris both above and below an extensive englacial cavity marked by the lenses of stratified material in the centre of the drumlin. Sites C, F and E are all located within 1 metre of these stratified sediments and therefore disturbance of the pebble orientations during cavity collapse appears likely.

Site G, within the middle till, occurs directly above stratified clayey band (c) and has a transverse fabric. Because the site is located beneath a surface depression it may indicate reorientation during melt out"?". Site H shows a multimodal Rose diagram with both parallel and transverse elements which may also indicate a similar process.

In summary, the fabric patterns show considerable variability. Fabrics may indicate ice flow characteristics, disturbance during melt out and reorientation during flow. In certain cases (fabrics 1, 6, 9 and 10) fabric orientations are consistently transverse to the drumlin and therfore support is given for compressive flow in this zone. Fabrics A and D may indicate extending flow (cf. Boulton, 1971). Other fabrics are thought to indicate reorientation during melt out.

Rose diagrams are limited in the amount of information that they show compared to three-dimensional plots (Andrews, 1971) and therefore the use of this technique may have disadvantages. Boulton (1971) summarised that any attempt to infer genesis by till fabric alone is extremely difficult as so many different processes can produce similar results. This seems to be the case here and therefore the characteristics of stratigraphy and sedimentary structures are considered to be the most reliable data for interpreting landform genesis.

4.1.5 Landform Genesis

Certain theories of drumlin formation cannot be applied to this landform. The correspondence between the surface morphology and the internal structure of the drumlin cannot be explained by an exclusively erosional hypothesis. Erosion is also ruled out morphologically by the apparent superimposition of the ridges that compose the form. The widespread occurrence of stratified units does not support simple accretion through lodgement. Lastly, variability in fabric patterns indicates that a secondary flow mechanism, discussed elsewhere by Shaw and Freschauf (1973) and Jones (1982), is unlikely.

From the topographic setting of the drumlin certain ice flow conditions may be inferred. It should be noted that morphologically similar drumlins are present nearby which suggests that the forms may have been generated under similar ice conditions (cf. Rose and Letzer, 1977). These drumlins are located within the northeast–southwest trending Benchlands of the Athabasca River valley. It may be assumed that the lower part of the ice which occupied the valley between Hinton and Obed was confined by the valley walls whereas the upper part of the ice may have been unconfined on the Tablelands directly to the north and south of the Athabasca River valley. This configuration may have produced zones of longitudinal extending flow combined with zones of transverse compression in the Athabasca River valley area and these flow conditions have been associated with drumlin and fluting development (Gillberg, 1976; Aario, 1977b; Shaw, 1980). Further factors affecting ice flow in the area near the drumlins may be provided by exposed bedrock surfaces. In the Athabasca valley near Hinton, bedrock knolls and undulations may have initiated certain drumlins (cf. Boulton, 1970b; Gillberg, 1976) and created localised zones of compressive and extending flow within ice. Although large boulders of local bedrock are present in the lower till, no bedrock core is exposed and therefore drumlin formation by initial agglomeration around such a core cannot be established.

One main concern of drumlin formation is to explain how material is agglomerated (Menzies, 1979). From the evidence it is proposed that the drumlin consists largely of melt out till. Therefore the following problems are raised: first, is the drumlin composed entirely of melt out till?; second, is there a moulded form underneath the melt out deposits? and third, has the drumlin been created under active or stagnant conditions? The first problem cannot be addressed as the section only dissects part of the drumlin. However, the second problem merits discussion. In the section the middle till which is approximately 8 metres thick, drapes over a lower glacigenic suite. In one sense, this may suggest that an accretion theory is applicable whereby a concentric shell of melt out till has been deposited over a smaller mass but this still avoids or presupposes an initiating point. If, however, the lower suite is moulded into a drumlin under active ice conditions and later stagnant ice conditions result in the release of debris over the drumlin, then the internal characteristics and morphology may be explained. Thus the drumlin may be considered the product of a proto-drumlin ridge, englacial melt out till and supraglacial till.

One explanation for the genesis of the drumlin is as follows and is illustrated by Figure 4.19. It is proposed that the lower till represents a basal melt out till. The high concentration of boulders and large clasts of local origin confined to the lower diamicton, suggest that they were initially incorporated in ice by shearing of the substrate. It is postulated that this basal debris–rich ice became stagnant beneath upper ice (Boulton, 1970b). It may be that the debris content retarded ice flow (Russell, 1895) and that the flow conditions were as described earlier. Compressive flow in the lower ice may be inferred from the transverse fabrics of sites 1A, 2A and 3A. At this stage the materials were frozen and of high strength. The upper ice, which was overriding, flowed past and moulded the debris in the lower complex into the drumlin form. Conditions in the upper ice are thought to have been generally uniform or extending flow (Fabric A and D). Streamlining, therefore, was a function of differential flow between the material in the drumlin and the overriding ice (Shaw, 1980). In this case, it is suggested that the overriding contained subglacially derived sediments now transported in an englacial position. During the final stages of glaciation of this site it is proposed that the upper ice became stagnant. At this time extensive englacial channels developed in cavities within melting ice. Sorted sand and gravel were deposited in these cavities. Deposition of the middle till over the channel sediments resulted in deformation, dewatering and compaction of the sand and gravel which formed lenses or tubes. During melt out and lowering of the sediments, disturbance of the till took place in the vicinity of channel sediments (Fabrics C, F and E). Debris released at the surface was by melt out and supraglacial streams were present. This is illustrated by the upper till and gravel fill. It is probable that this layer inhibited surface melting and that basal melting became a predominant mechanism (Boulton, 1970b; Shaw, 1979). The rapid evacuation of water through englacial channels combined with basal melt out permitted the preservation of the englacial facies and structure (Boulton, 1970b). During the final stages of deglaciation, the supraglacial complex was lowered over the form and loess was deposited.

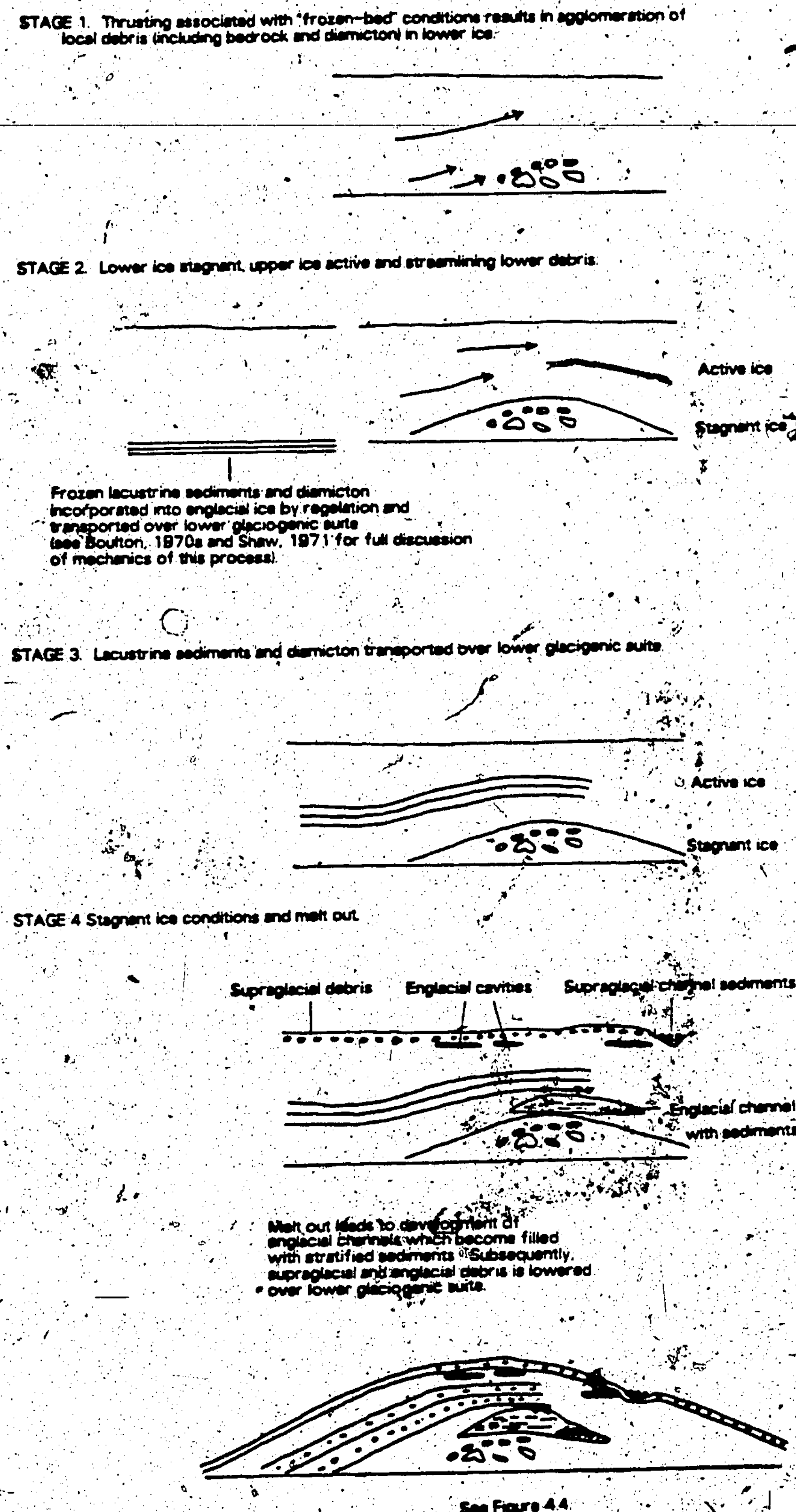


Figure 4.19 Genesis of Drumlin 1.

4.2 Fluting 2

4.2.1 Morphological and Sedimentological Observations

The section to be described occurs in a fluting on the west bank of Canyon Creek (Figure 4.20) at an elevation of 1050 metres. An air photograph shows that the section is located at the northeastern end of an extensive linear ridge which is 2 kilometres long and trends 68°-248° (Figure 4.20). This fluting is located at the base of the uppermost break in slope leading to the summit of the North Athabasca Tableland. The width of the fluting is highly variable measuring 160 metres at the northeastern end and 400 metres at the southwestern end. The section cuts obliquely through the the northeastern margin or distal end and measures 96 metres in length and 6-10 metres in height (Figure 4.21). It reveals a complex assemblage of diamictons and stratified materials (Figure 4.22).

Three diamicton units are recognised. These units are called lower, middle and upper diamictons on the basis of their stratigraphy. Both the lower and middle diamictons are similar whereas the upper diamicton is clearly distinct on the basis of clast size and the content of stratified material.

The lower diamicton is a discontinuous unit confined to the lower 2 metres of the section (Figure 4.22). It consists of a silty sandy matrix with a high clast content. Extensive stratified deposits are interbedded with diamicton. Clasts sizes in the diamicton are highly variable ranging from coarse pebbles to boulders. The dominant sizes are very large pebbles to small cobbles. Large cobbles and boulders are preferentially located towards the base of the section. Most clasts in the modal size range are subrounded although well rounded and subangular forms are present. The larger cobbles and boulders are generally subangular. Clast lithologies include ferric arkose sandstones, orthoquartzites, limestones, angular coals and mudstones. Limestones and orthoquartzites are the dominant lithologies. These clasts show both locally derived material from the Hinton area and further-travelled clasts from the Jasper area. Some clasts are striated and shattered. The unit is moderately compacted. The stratified content will be considered later.

The middle diamicton consists of a silty sandy matrix with a high proportion of well rounded pebbles and cobbles. The unit is approximately 1.5-3 metres thick. Most clasts

Figure 4.20 Fluting 2 and Fluting 3, general location of sections. Sections through Fluting 2 and Fluting 3 indicated by arrows. Fluting 2 is to west.
Air photo (Provincial, 1965) A-S. 858-90

Figure 4.21 Fluting 2 and Fluting 3, detailed location of sections.
Fluting 2 is in foreground.

are subrounded. In composition, limestones and quartzites are dominant. There are few striated clasts but pitted forms are common.

At some locations the diamicton displays a platy, fissile structure. In the central part of the section the fissility is horizontal to subhorizontal whereas towards the south end of the section the platy structure is parallel to the dip of the southwestern limb (Figure 4.24). Augen structures are also present where the clasts are dipping parallel to the dip of this limb. Stratified deposits are less frequent in this unit compared to the lower unit but horizontal sand lenses are common. Further discussion will be presented later.

The upper diamicton is confined to the upper 1.5 metres of the section. It is composed of subangular to subrounded pebbles in a matrix of silty clay. The matrix displays a platy structure with coarse and medium joints. Clasts are composed of quartzites and limestones. Pitted clasts are common but striae are rare. Towards the northern end of the section a gravel lens is exposed within the upper diamicton. Clasts in this lens are pebble sized and rounded to subrounded. They are supported by medium sand that is subrounded and structureless. Covering the uppermost 30–50 centimetres of the exposure is a red brown capping of fine silt interpreted as loess.

4.2.1.1 Stratified materials

Most of the stratified materials are found within the lower 4 metres of the exposure and are interbedded with the lower and middle diamicton. Representative groups of stratified deposits are described below.

4.2.1.2 Clayey inclusions

Clayey inclusions are widely dispersed in the lower diamicton. They resemble large "clasts" and are therefore distinct from the stratified clayey bands discussed in Drumlin 1. The clayey inclusions contain rounded clasts of large pebble size. The inclusions are angular or hemispheric in shape. An example of this deposit is illustrated by Figure 4.25. This clayey inclusion is hemispherical in shape and less than 0.5 metres in radius. The clay is grey (2.5 Y 4/2) and displays laminations which have been folded in a concave pattern. Small clasts within the inclusion are aligned conformably with these laminations. This clayey inclusion is truncated on one side by a large, angular cobble. A shear plane is observed above the inclusion and cobble,

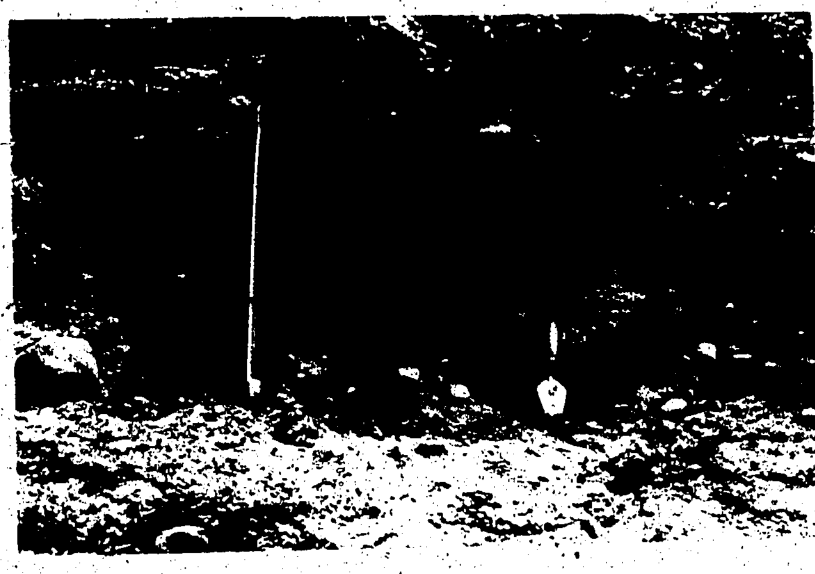


Figure 4.23 Contact between lower and middle diamictons. Position of section, 45 metres from south end (see Figure 4.22).

Figure 4.24 Contact between middle and upper diamictons. Note dipping fissility and rounded clasts in middle diamicton. Upper diamicton displays subangular clasts. Position of section, 5 metres from south end (see Figure 4.22).

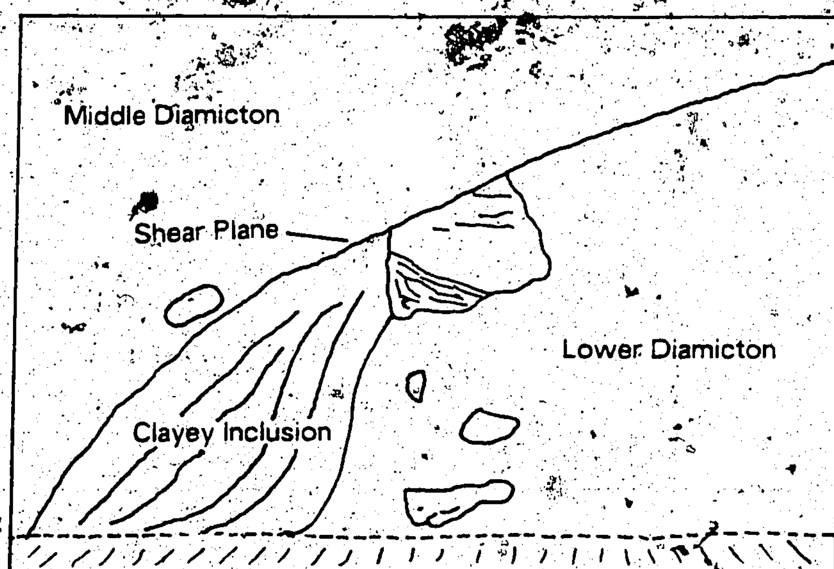


Figure 4.25 Contact between lower and middle diamictons marked by shear plane (photograph with explanatory diagram). Position of section, 8 metres from south end.

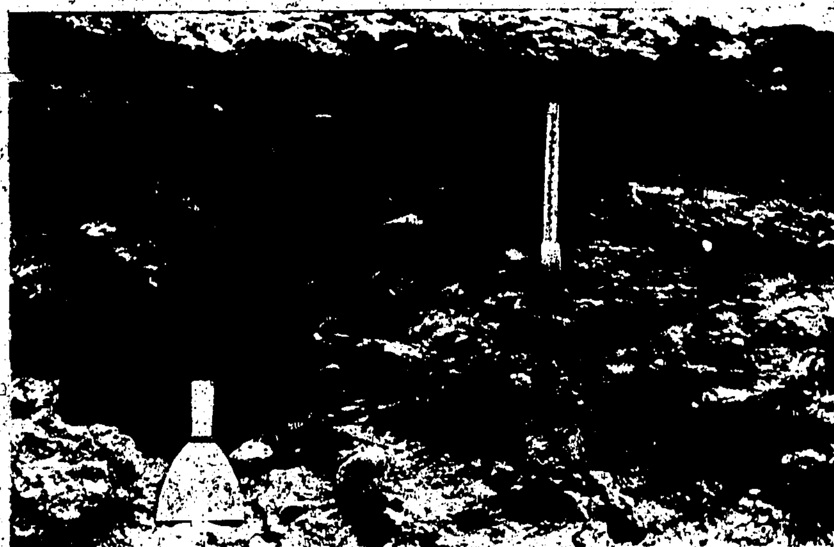


Figure 4.26 Stratified sand lens interbedded with lower diamicton. Position of section: 16 metres from south end.

Figure 4.27 Close-up of stratified lens (tape measure marks position on Figure 4.26). Note deformation and apparent foliation in sand together with pockets of granules.

dipping at 25° to the south–southwest and penetrates into the diamicton. Minor slickensides are present in the diamicton where the shear plane occurs (Figure 4. 25).

4.2.1.3 Sand and gravel lenses

Generally, two types of lenses containing sand and gravel are present: horizontal lenses and deformed lenses. Horizontal lenses containing stratified sand and pockets of granule gravel occur throughout the length of the section. These lenses are up to 20 centimetres thick and can be traced for 5 metres in some places. In the central part of the section, horizontal lenses containing stratified sand and gravel are successively interbedded with diamicton. Some horizontal lenses are disrupted laterally by dikes of stratified material whereas others terminate in diamicton with no obvious disturbance. Specific examples of horizontal stratified sand and gravel lenses are described below.

A horizontal, thin lens containing medium grade sand and small lenses of granules is illustrated in Figure 4.26 and Figure 4.27. This lens is approximately 15 centimetres thick and extends laterally for 4 metres. Foliation of the sand layers is common. Another horizontal lens of stratified, medium grade sand is illustrated in Figure 4.28. This lens is less than 20 centimetres thick and extends 4–5 metres laterally. Micro ripple cross–lamination and small scale trough–cross beds are displayed in the sand.

Deformed lenses of sand and gravel are common in the lower diamicton but are less frequent in the middle diamicton. A contorted sand lens with a central fill of diamicton is shown in Figure 4.29 and Figure 4.30. These structures are similar to the loop and hook–like overfolds described by Dzulynski and Walton (1965) in sandstones.

A deformed lens of sand and gravel is also illustrated by Figure 4.31. This lens dips both subhorizontally and vertically. It contains coarse sand, granules and small pebbles. Clasts within the lens are subrounded to subangular and are composed of limestones and quartzites. The coarse sand is often foliated and the deposit is poorly sorted.

Clastic dikes of sand and gravel cross–cut both the lower and middle diamictons. These dikes contain medium grade sand and clasts which are less than

Diamicton

Stratified Sand

Diamicton

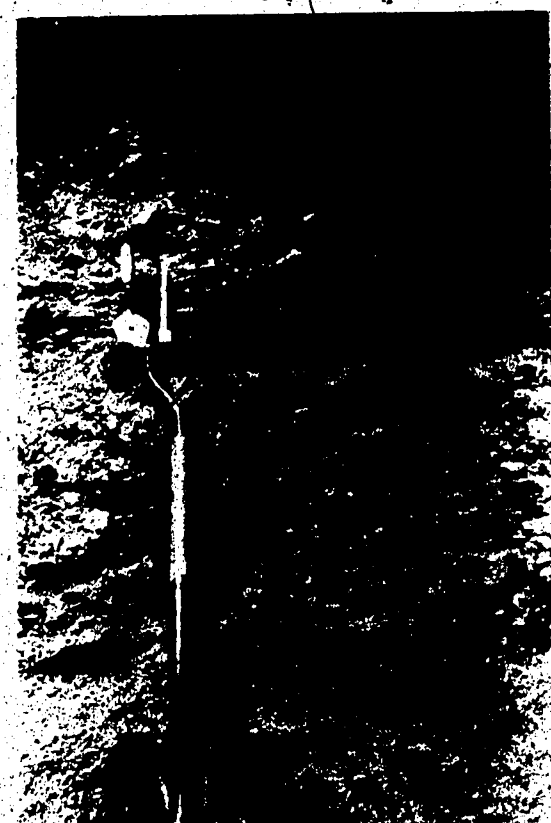


Figure 4.28 Horizontal lens of stratified sand interbedded with diamicton. Micro ripple cross-lamination and small-scale trough cross-beds displayed in sand. Position of section, 70 metres from south end (see Figure 4.22).

Figure 4.29 Deformed sand lens. Position of section, 50 metres from south end (see Figure 4.22).

Figure 4.30 Close–up of deformed sand lens. Note "hook–like" structure in sand with central fill of diamicton.

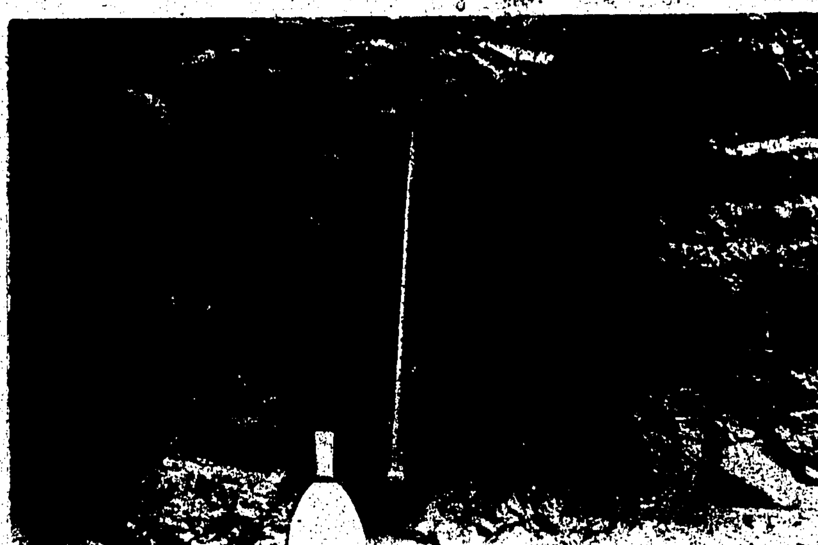


Figure 4.31 Deformed lens of sand and gravel in lower diamicton. Position of section, 17.5 metres from south end (see Figure 4.22).

coarse pebble size.

4.2.2 Discussion and Interpretation

The section through the fluting shows a complex relationship between diamictons and stratified materials. The lower diamicton and middle diamicton are interpreted as melt out tills on the basis of stratigraphic position; their association with stratified materials; and their strongly preserved primary structures which include fissility, augen structures and shear planes. The upper diamicton is interpreted as supraglacial till on the basis of stratigraphic position, clast shape and the presence of a gravel fill which represents a supraglacial channel deposit. The lower till is associated with a deformed series of stratified deposits whereas horizontal layers, lenses and stringers of stratified sand and gravel are commonly interbedded with the middle diamicton.

The stratified clayey inclusions within the lower till are interpreted as proglacial lacustrine sediments which have been incorporated and reworked by the overriding glacier. Laminations and small clasts within the inclusions suggest that these sediments were deformed, frozen and transported during glacial advance. The angular to subrounded shape of these inclusions implies that they were locally derived. The presence of striated and shattered clasts in the lower till and shear planes associated with the clayey inclusions indicates transport of debris in a basal position within the ice.

Both horizontal and deformed lenses of stratified sediments represent the presence of cavities developed during melt out of ice layers under stagnant ice conditions. This process has been described by Shaw (1979) to account for stratified layers in Sveg till in Sweden and a similar interpretation has been forwarded by Bouchard (1980) for the stratified facies in till of the Temiscamie area, Quebec. By this interpretation the horizontal lenses are syndepositional with melt out till. In the section under consideration here, it is notable that deformed lenses of stratified sediments are found interbedded with the lower till. In the middle part of the section these beds are horizontal which is as expected for melt out involving slow deposition on an even surface (Boulton, 1970b; Shaw, 1979). However, in some places deformation of the lower zone has occurred after melt out of the stratified layers. This is demonstrated by loop and hook-like overfolds in the stratified layers which indicate "plastic-glide" during slumping (Dzulynski and Walton, 1965). It is postulated that deformation of the more competent beds represented by the sand layers took place within soft, plastic till during the melt out process. Furthermore, the interpretation that deformation by slumping occurred after melt out of the stratified layers with the observation that this was confined to the lower zone of the section is informative. It is suggested that the sediments in the lower layers were mobile while debris in the upper ice was still frozen. Thus a basal melt out process was likely. As basal melt out proceeded dewatering and differential compaction of the sediments may have resulted in subsequent deformation associated with slumping and flow. Uneven distribution of the underlying topography and inneffcient pore water expulsion from the sediments may have contributed to the reorientation of melt out deposits.

The presence of clastic dikes is also thought to represent injection structures associated with slumping. These sediment-filled dikes were probably preserved by syndeposition of debris during melt out of ice from the base upwards. The foliated structure of the horizontal, stratified layers interbedded with the middle till indicates that dewatering and differential compaction of the sediments took place after flow and slumping were arrested in the lower layers. One lens, which is located toward the upper part of the section (Figure 4.28), displays a variety of sedimentary structures including micro ripple cross-lamination and small-scale trough cross-bedding. Deformation structures are absent from this lens and it is additionally concluded that overburden pressures were less than those in the base of the section. Preservation of the bedding may also be due to a slow melt out process and gentle lowering of this layer over the till.

In summary, the lower till and interbedded stratified deposits are interpreted as a basal melt out till. Structures displayed by stratified sediments and till demonstrate that slumping and sediment flow has occurred. Thus it is concluded that this layer indicates primary melt out and secondary redistribution through flow. The middle till represents a primary melt out deposit derived from englacial ice. This till has not undergone as much secondary disturbance as the lower till and hence the stratified layers are horizontal and well preserved. The upper diamicton is interpreted as a supraglacial till and includes a remnant supraglacial channel complex.

4.2.3 Fabric Analysis

The position of the section with respect to the long axis of the fluting permits investigation from the centre to the southern margin of the form (Figure 4.21). Eight two-dimensional Rose diagrams (Figure 4.32) and six three-dimensional fabric diagrams (Figure 4.33) are presented from Fluting 2. Eleven fabrics were taken from the lower till; two fabrics were obtained from the middle till and one from the upper till. As in Drumlin 1, there is a significant variation in fabric orientations.

Fabric sites 5, 6, 7, 8 (Figure 4.32) and three-dimensional sites 4A, 5A and 6A (Figure 4.33) are located towards the centre of the fluting. Fabric 8, located in the upper diamicton shows no preferred orientation. This is to be expected in a supraglacial till complex where a wide scatter of clast orientations is likely. Fabric 5 is located near a dike and also shows scattered orientations with a general transverse trend. This pattern may reflect till deformation by slumping"?". Fabric 7 is located in the middle till and shows a strong modal orientation which is rotated 10° clockwise from the fluting axis. This pattern is interpreted to indicate former ice flow direction. The azimuths of the principal eigenvectors for fabrics 4A, 5A and 6A are all oblique to the central axis of the fluting in a down-ice direction (225°–045°). The azimuths range from 185° to 230° and all these three-dimensional sites have upglacier dips. The inclinations of these eigenvectors range from 3° to 10° and the S_1 values are weak ranging from 0.45 to 0.59. Mark (1974, p.1370) suggested that the fabrics for melt out till are essentially englacial fabrics "with varying degrees of modification". This usually entails the reduction of dips and fabric strengths during melting of ice surrounding the clasts. The low dips for fabrics 4A, 5A and 6A may demonstrate this characteristic and indicate a melt out origin where primary ice flow direction has been preserved. The primary ice flow in this case is speculated to be oblique to the fluting axis and, if correct, this supports a process involving movement of debris towards the centre of the fluting ridge. The unimodal fabric of Site 6 may also support this hypothesis.

Sites 1 to 4 inclusive and fabrics 1A, 2A and 3A are located toward the margin of the form (Figure 4.32). These fabrics show complex patterns. However, fabrics 2, 3 and 3A display similar orientations with clockwise rotation less than 20° from the fluting axis. The azimuth of the principal eigenvector for Site 1A is parallel to the fluting axis and

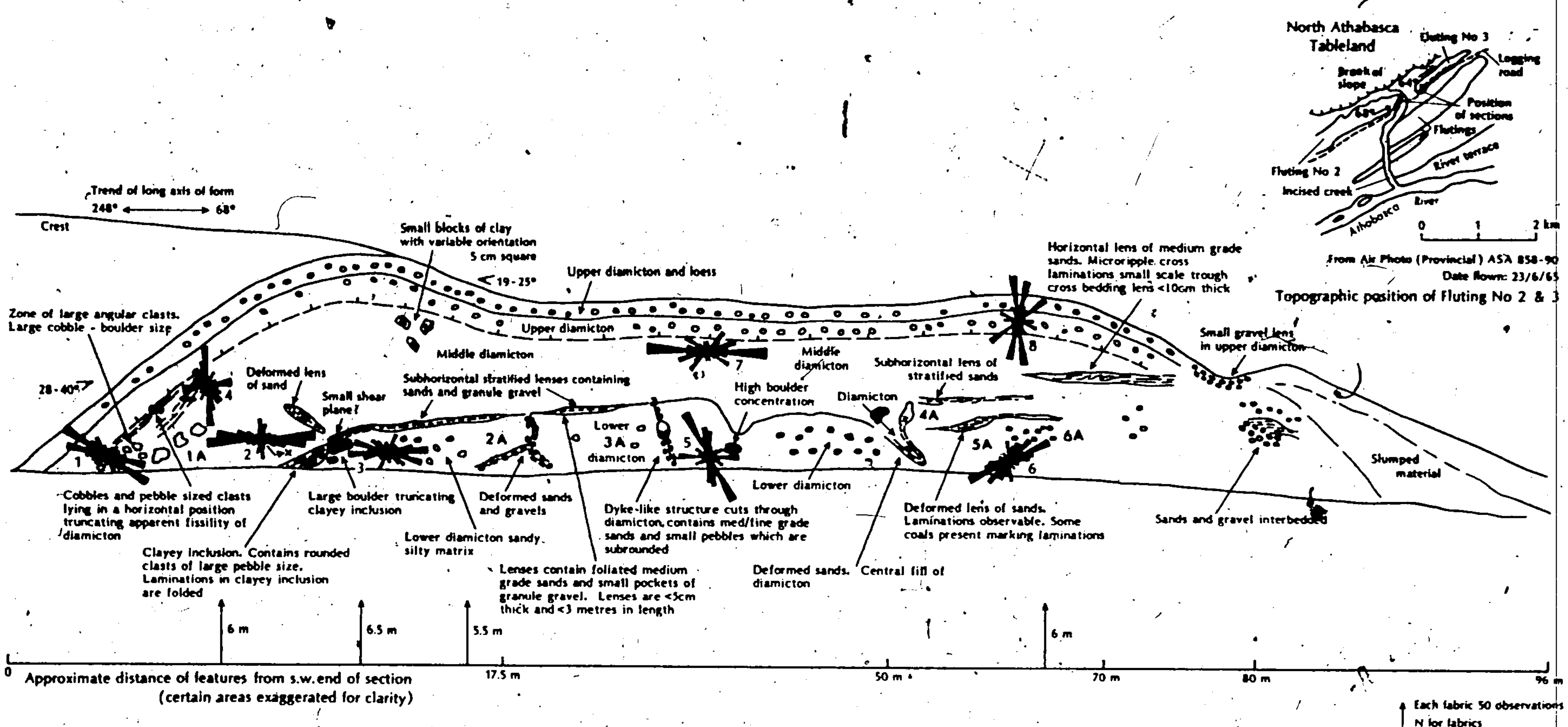


Figure 4.32 Fabric Locations on Fluting 2.

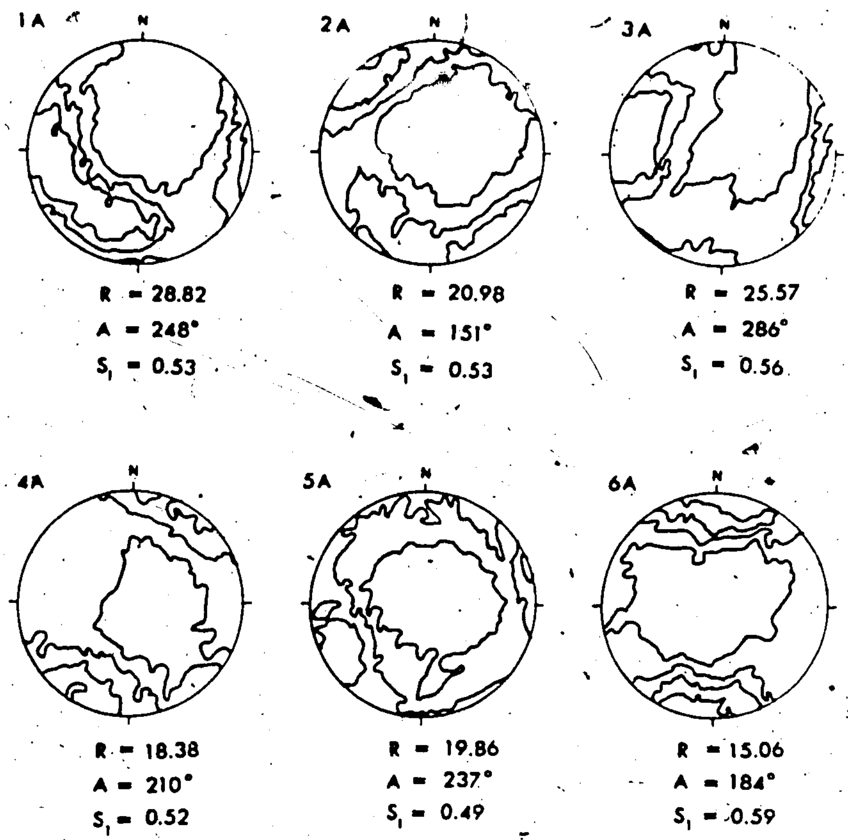


Figure 4.33 Contour Plots of Individual Fabrics, Fluting 2.

See Figure 4.32 for Sample Location. Contour Interval is Two Sigma.

shows an upglacier dip. These fabrics (2, 3 and 3A) may indicate that ice flow direction was generally parallel to the fluting axis.

Fabric 2A, derived from the lower till near a deformed sand and gravel lens, has an eigenvector azimuth which is transverse to the fluting axis. Fabric 3A, located near a dike, has an eigenvector azimuth which deviates some 40° from the fluting axis but shows an upglacier dip. Both fabrics 2A and 3A show that the strength of clustering around the eigenvectors is weak. It is concluded that these two fabric patterns are due to reorientation of clasts by slumping and flow.

Fabrics 1 and 4 are located on the flank of the section (Figure 4.32). Fabric 4 displays a multimodal pattern with a transverse peak and fabric 1 shows a strong modal orientation at 120°–130°. These fabrics are thought to show reorientation during melt out.

In conclusion, although the fabric orientations are variable, two general trends emerge. First, fabrics located in the middle of the fluting show alignment either parallel or convergent to the axis of the form (Sites 6, 4A, 5A and 6A). Second, fabrics towards the outer margin of the fluting show alignment which is either parallel or more commonly rotated clockwise away from the fluting axis (1, 2, 3, 7, 1A and 3A).

4.2.4 Landform Genesis

Three units have been observed from the section; a lower unit which is interpreted as a basal melt out till, a middle unit interpreted as a melt out till derived from an englacial position and an upper unit which represents a supraglacial melt out complex. A dominant characteristic of the exposure is the association of stratified layers with till.

Earlier in this thesis the theories of drumlin and fluting formation were discussed briefly and it was noted that there are both erosional and depositional explanations. Erosional theories assume that differential accretion, and/or flow conditions were responsible for preferential distribution of debris parallel direction of ice flow. Accordingly, the relief in this part of the Athabasca River valley may have resulted from post–depositional erosion of troughs, or alternatively the ridges may have been sites of high debris loads at or near the glacier bed. However, an erosional hypothesis is precluded for Fluting 2 because melt out till is dominant. If an erosional explanation is forwarded then it is a prerequisite that melt out till and supraglacial sediments were deposited and streamlined during a later advance. This sequence is not consistent with the observed sedimentological evidence. Thus a depositional mechanism is proposed to explain the fluting stratigraphy. The question is then raised as to how this material was agglomerated to form the fluting ridge. There are two major concerns: was differential accretion responsible for landform genesis or was glacier flow such that debris was preferentially concentrated in linear ridges within the ice? The process of differential accretion is related fundamentally to the movement of debris into cavities created in the lee of obstacles. This debris may have been water-soaked or deforming plastically (Dyson, 1952; Hoppe and Schytt, 1953). However this theory raises certain problems; it is difficult to explain the regular patterns in the spacing of fluting ridges by this explanation and a further problem is to account for the maintenance of cavities with respect to overburden pressure. In support of the theory, it is known that small-scale flutings develop in the lee of obstructions from observations of modern glacial environments (Dyson, 1952; Hoppe and Schytt, 1953; Boulton, 1976a). In addition, water filled cavities have been encountered during drilling and tunnelling in glaciers (Fisher, 1963; Paterson and Savage, 1970) which suggests that for temperate glaciers at least, cavities containing sufficient water are not closed by ice flow (Paterson, 1981). Therefore the objection involving overburden pressure may not be applicable and the maintenance of debris-filled cavities is not problematic.

The alternative model involving kinematics and particularly secondary flow (Shaw and Freschauf, 1973) is based on theoretical assumptions which are supported by fabric orientations in certain flutings. While secondary flows are evident in some glaciers (Shaw, 1980) the type of motion which Shaw and Freschauf (1973) envisaged, where adjacent helicoidal flow cells produce large fluting ridges is not supported by the fabric analyses.

It is proposed that the fluting was formed by an accretion mechanism where plastically deforming sediments were squeezed into a cavity which extended longitudinally relative to ice flow direction. Support for this is given by the fabric sites in the centre of the form (Sites 6, 4A, 5A and 6A). The mechanism is thought to be self-generating as progressive accretion causes the cavity to move down-ice resulting in further accretion and so on. This process may include lodgement (Shaw 1977b) and also the development of a lee-side till (Hillefors, 1973). Lee-side till is interpreted as the product of debris flows and glaciofluvial sediments which are deposited in cavities developing in the lee of obstacles beneath the glacier. Hillefors (1973) also noted that during the formation of lee-side till, clasts were removed from upper ice and dropped into stratified sediments in the cavities. Hillefors (1973) also mentioned that debris-rich bodies or "dead-ice bodies" may become detached from upper ice and may fill lee-side cavities. It is possible that such processes combined with lateral accretion of material caused the fluting to extend downglacier.

It is considered that, at some stage, the accreted sediments became stagnant in the fluting ridge and that subsequently the upper englacial ice overrode the ridge. In order for this to take place the sediments are thought to have undergone marked geotechnical changes principally from low internal shear strength, due to high pore water content, to a much higher shear strength (Menzies, 1982). If pore water was lost through dissipation or by *in situ* pore water freezing then the shear strength of the material would increase sufficiently to maintain its form (Menzies, 1979; 1982). It may be that certain amounts of water in the fluting ridge were lost through the permeable substrate, via meltwater conduits and also into the cavity which was migrating down-ice.

In summary, it is proposed that the sediments in the fluting were initially agglomerated to form the ridge and that pore water dissipation and freezing resulted in an increase in shear strength to preserve the fluting. It is proposed that two zones were created within the ice, a lower zone of stagnant debris and an upper zone of englacial ice which was overriding, streamlining and extending (Hillefors, 1973; Shaw, 1979). At a later stage the upper ice became stagnant. Basal melt out resulted in the formation of lenses and layers of stratified material interbedded with till where some primary structures such as shear planes were preserved. In some places the lower glacigenic suite was subjected to slumping and folding during release from ice. These facies are represented in the lower zone of the section. Melt out of englacial ice which was debris-rich also resulted in successive layers of till and stratified sediment. These sediments were subsequently deposited over the lowermost glacigenic suite. It should be noted that the stratified sediments do not indicate debris flows because of their "draping" relationship with clasts of the underlying and overlying tills (cf. Shaw, 1979). Melt out of englacial debris over the lower complex may have resulted in some rotation of clasts away from the fluting long axis producing the observed fabric patterns. This interpretation has been used for the fabrics from the sediments in the outer zone of the section. The final stage of melt out is marked by the lowering of a supraglacial complex over the form. This is represented by the upper till and supraglacial channel sediments.

4.3 Fluting 3

4.3.1 Morphological and Sedimentological Observations

This fluting is located ca.240 metres to the northeast of Fluting 2 (Figure 4.21) at an elevation of ca. 1060 metres and is found 165 metres to the south of the break of slope leading to the North Athabasca Tableland (Figure 4.22). The fluting has a narrow, linear shape with a streamlined appearance. The fluting ridge is 1200 metres long and 200 metres wide and the orientation of the long axis is 64°–244°. Other flutings with similar orientations, and of variable length and width, are found in the same area (Figure 4.20). The maximum height of the fluting is located at the southwest or proximal end of the ridge where the exposed section is located. The section is 97 metres long and 6.7 metres at its highest point in the centre, with symmetrical shallow dipping convex slopes either side.

For ease of description the section will be divided up into a lower zone, the central zone and an upper zone. The bottom 2–3 metres of the section is covered by slump material and therefore no observations were made in this part of the section.

The lower zone is considered as the lowermost exposed 1 metre of the section. Two facies are displayed within this area: a silty sandy diamicton and horizontal–subhorizontal lenses of stratified sand (Figure 4.35). The silty sandy diamicton contains clasts which are well dispersed. Limestones, quartzites and sandstones are dominant while angular shattered clasts of shales and clay–iron stones are present in minor quantities. Most clasts are less than 10 centimetres in diameter. Large boulders are infrequent. Cobbles are subrounded to rounded and display pitted faces but little striation. The diamicton is loosely compacted.

Horizontal and subhorizontal lenses of stratified sand occur at both ends of the section. Towards the northeastern end of the exposure these stratified layers are less

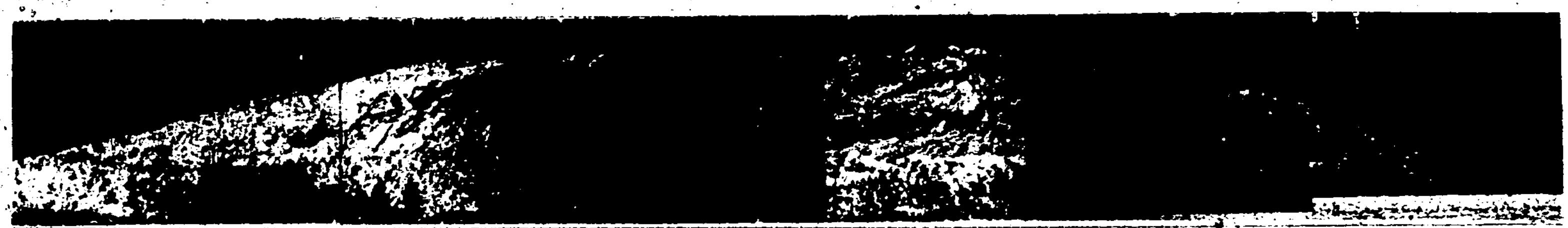


Figure 4.34 Section and proximal end of Fluting 3 (see Figure 4.35).

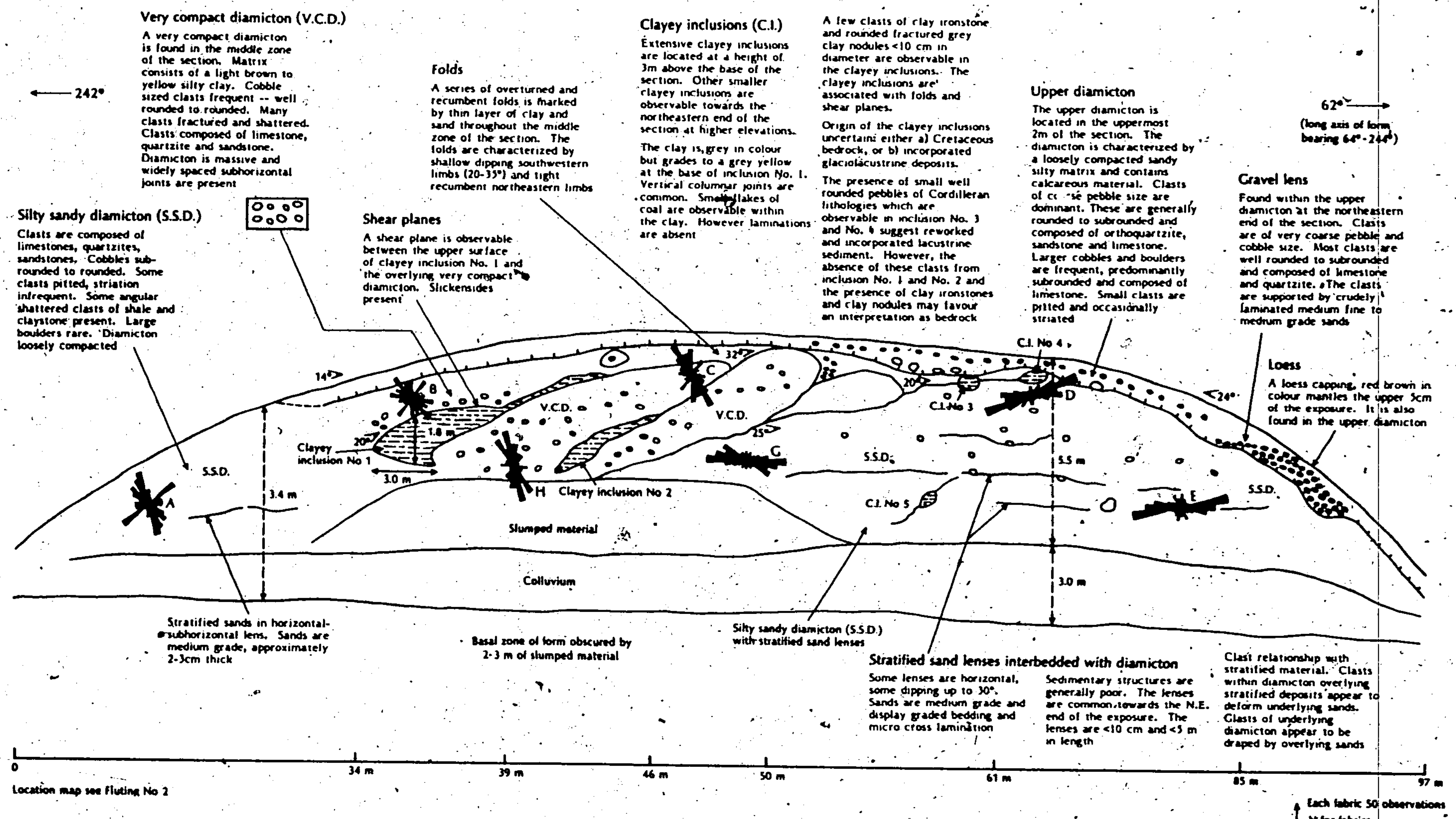


Figure 4.35 Internal Structure, Sedimentary Characteristics and Clast Orientations, Fluting 3.

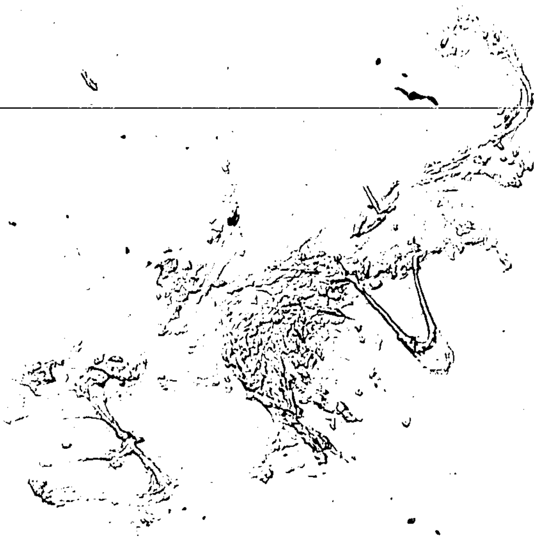
than 10 centimetres thick and up to 5 metres long. These layers are less common at the southwestern end of the section. The stratified sand is of medium grade sand and displays micro ripple cross-lamination and small-scale trough-cross beds. There is no evidence to show truncation or cross-cutting of these beds by either the overlying or underlying clasts. Certain clasts from the diamicton show two relationships with the stratified layers; clasts within the diamicton appear to deform the sand below and clasts of the underlying diamicton are draped in a shallow fashion by the overlying stratified sand layers (Figure 4.36). Towards the northeastern end of the section one sand layer dips at 30°. Crude laminations are observable in the sand but are poorly developed in comparison with the horizontal lenses.

The central zone of the section is characterised by large clayey inclusions, very compact diamictons, shear planes and folds. Two clayey inclusions are well exposed 34 metres and 46 metres from the southwest end of the section (Figure 4.37). They are termed 1 and 2 respectively. Both inclusions are located approximately 3 metres above the base of the section. The lowermost part of clayey inclusion 1 (Figure 4.37) is covered by slumped material and therefore any possible contact with the lower glacigenic suite could not be ascertained. However, beneath clayey inclusion 2, diamicton was located which suggests that the features are discrete bodies within the diamicton.

Clayey inclusion 1, is 3 metres thick and 5 metres long (Figure 4.37). The clay is grey in colour (5 Y 7/1) with abundant columnar joints. Small flakes of coal are present in the clay but laminations are absent. At the base of the inclusion the clay grades to a yellow colour (2.5 Y 7/3) and contains fractured and shattered clay nodules. Clay-ironstones are also present. The upper area of this clayey inclusion is devoid of clasts.

Clayey inclusion 2 is similar to inclusion 1 but clasts are absent (Figure 4.35). Both the clayey inclusions are dipping towards the southwest, clayey inclusion 1 at 20° and clayey inclusion 2 at 30°. A third clayey inclusion, which measures 1 metre in diameter, is located 1.5 metres from the top of the section and 35 metres from the northeastern end of the exposure. It lies above a shear plane and enclosed by diamicton. This inclusion contains small well rounded pebbles of limestone and quartzite.

A very compact diamicton surrounds clayey inclusions 1 and 2. Cobble sized clasts are dominant and they are well rounded to rounded. Some clasts are fractured and



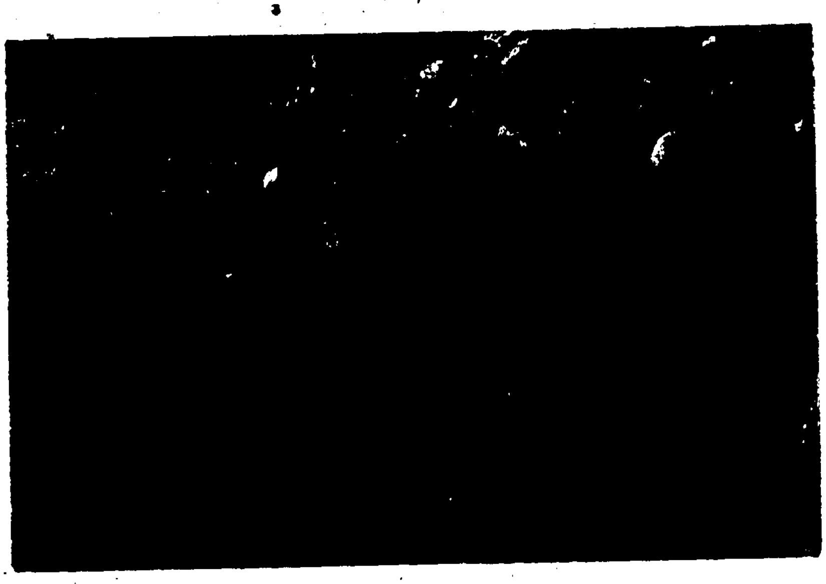


Figure 4.36 Relationship between clasts and stratified layers. Note "draping" of clasts by overlying stratified layer. Position of section, 68 metres from southwest end (see Figure 4.35).

Figure 4.37 Section through Fluting 3, showing stacked debris. Clayey inclusion no. 1, is visible in centre. Note shear planes above inclusion and folds (top right). Position of section, 37 metres from southwest end (see Figure 4.35).

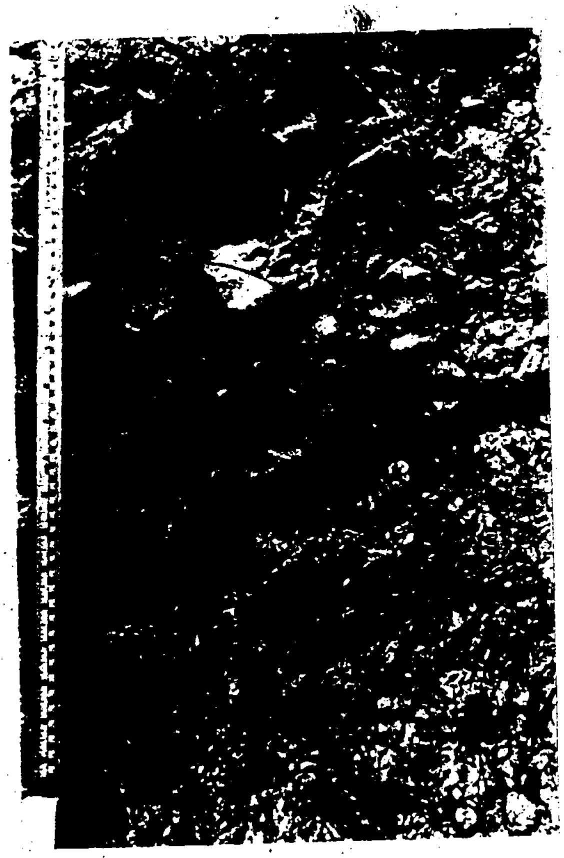


Figure 4.38 Close-up of contact between clayey inclusion and very compact diamicton. Note shear plane marking contact.

shattered. The clasts are composed of quartzites, sandstones and limestones. The matrix consists of a light brown to yellow coloured silty clay (5 Y 7/3) with a small proportion of very fine sand. Small flakes of coal and fine pebbles are found within the matrix. The diamicton is massive and widely spaced subhorizontal joints are present.

Shear planes are found in association with clayey inclusions, very compact diamicton and folds. For example, a shear plane dipping at 20° towards the southwest is located between the very compact diamicton and the underlying clayey inclusion. Minor slickensides and mylonitic clays are found in this shear zone together with small sand lenses. Clasts within the diamicton above the shear plane are crudely oriented parallel to the dip of the shear. Beneath the shear plane the clayey inclusion displays prismatic and columnar joints. The former type are more common towards the upper part of the inclusion.

A series of asymmetric, overturned and recumbent folds is marked by layers of clayey material throughout the middle zone of the fluting section (Figure 4.35). These folds display shallow dipping southwestern limbs at 25°–35° and tight, recumbent northeastern limbs. The true orientation of the axial plane is not known, however the folds are thought to be transverse to the former direction of ice flow and truncation of folds by other forms indicates a degree of superposition (cf. Whitten, 1969). Discrete inclusions of clayey material, diamicton and sand have been incorporated within the folds and these materials are generally oriented parallel to the southwesterly dipping limbs (Figure 4.35).

The upper unit occupies the top 2 metres of the section and is characterised by a diamicton, gravel fill and loess. The diamicton contains rounded to subrounded clasts in a sandy silty matrix. The clasts are predominantly coarse pebble size but some large cobbles and boulders are also observable (Figure 4.35). The clasts are orthoquartzite, sandstone and limestone. Most of the clasts are pitted and some clasts are striated.

At the northeastern end of the section a gravel fill is present (Figure 4.35). Clasts are of very coarse pebble and cobble size. Most clasts are well rounded to subrounded and are composed of limestone and quartzite. They are supported by crudely laminated medium fine to medium grade sand. Although sedimentary structures are not easily observed within the sand, horizontal laminations are present. A capping of loess mantles the section.

4.3.2 Discussion and Interpretation

The dominant internal features exposed by the section are the horizontal lenses of stratified sand, clayey inclusions, very compact diamicton and tectonic structures. A general stratigraphic sequence is as follows. The uppermost deposit is an upper diamicton and a gravel fill. Occupying the central portion is a zone of tectonically deformed sediments consisting of very compact diamicton and clayey inclusions. Sandy silty diamicton with stratified layers occurs in the proximal and distal zones of the tectonically deformed sediments.

The silty sandy diamicton is interpreted as a melt out till on the basis of its association with the horizontal stratified layers. These stratified layers are interpreted as sediments deposited in cavities within melting ice as explained for Fluting 2. The relationship of the stratified layers to the clasts in the till also indicates a melt out process as described for Fluting 2. It is significant to note that the presence of discrete layers of stratified sediment, lying horizontally and subhorizontally adjacent to the folded complex, may indicate that these layers were unaffected by the preceeding tectonic deformation. In addition, the presence of undisturbed primary sedimentary structures within the layers supports deposition after folding. It is postulated that the melt out till and interbedded stratified layers were deposited by undermelting. Shaw (1979) originally proposed this explanation for the sorted layers beneath the folds observed in Rogen moraine and he noted that the stratified layers cross-cut the folds. In this fluting section the folds have not been cross-cut by stratified layers and therefore Shaw's explanation may be only partially applied.

The clayey inclusions are interpreted either as proglacial sediments or weathered bedrock which has been incorporated within ice. The presence of small well rounded pebbles of Cordilleran origin within inclusions 2, 3, 4 (Figure 4.35) suggest that initial deposition of this sediment was associated with a proglacial lacustrine or fluvial environment. By this explanation, small proglacial ponds and glaciofluvial outwash were overridden by the advancing glacier and some of this material was incorporated into the ice as frozen, erratic blocks. The absence of laminations within the inclusions may reflect alteration and reworking by ice or they may represent original, massive bedding of the incorporated material. In the case of clayey inclusion 1, the presence of clay-ironstones, resembling nearby bedrock, indicates that they have been derived from local Tertiary sediment, and consequently the entire unit may be of local origin.

The presence of folds and shear planes indicates that ice flow was compressive. These phenomena are often associated with ice sheets which are frozen to their bed in their outer margins (Moran, 1971; Boulton, 1972; Berthelsen, 1979; Shaw, 1979; Moran *et al.*, 1982). This will be discussed in more detail later. It is noteworthy that the shear planes are commonly associated with clayey inclusions suggesting thrusting of such erratic blocks from basal layers of the ice. It is possible that the presence of water in the clay layers inhibited complete freezing of the blocks and acted as decollement planes to facilitate thrusting.

The very compact diamicton, in the central part of the section, associated with the clayey inclusions and folds is interpreted as glaciotectonic deformation sediment. The term till is not used directly here as there is still some debate as to whether such a sediment constitutes "till" (see Schluechter, 1982). The lateral repetition of diamicton with clayey inclusions and slickensides along shear planes indicates that the diamicton has been stacked, folded and thrusted under pressure from the southwest and the configuration of deformed beds corresponds closely to glaciotectonic structures reported by Moran (1971). The compaction of the sediment and the presence of subhorizontal joints within the diamicton are thought to be the result of ice loading and shear. The response of the sediment to these processes may have resulted in water expulsion, compaction and brittle fracture rather than fluid flow (Boulton 1970b).

The uppermost unit is interpreted as a supraglacial melt out deposit. The upper diamicton is interpreted as a supraglacial melt out till and the presence of large, well rounded boulders may illustrate that there has been reworking of these clasts by glaciofluvial activity. The gravel fill, on the other hand, is interpreted as a supraglacial stream deposit and it provides support for the inference of lowering of the uppermost unit onto the underlying glaciogenic sediments. This is given by the undisturbed nature of glaciofluvial gravels which are underlain by horizontally laminated sand on the northwest slope of the fluting section. Loess has been deposited over the form subsequent to withdrawal of ice from the area.

4.3.3 Fabric Analysis

Eleven fabric samples were taken from the section. Seven two-dimensional Rose diagrams (Figure 4.39) and four three-dimensional fabric diagrams (Figure 4.40) are presented. The Rose diagrams will be discussed first.

Fabrics A and B were taken from the melt out till at the southwest end of the exposure (Figure 4.39). These fabrics are multimodal and show no preferred orientation although fabric A displays both parallel and transverse peaks. These fabrics are thought to be characteristic of melt out till which has been disturbed by flow (cf. Shaw, 1982).

Fabrics D, E and G are located at various heights on the fluting section and are distal to the central folded zone (Figure 4.39). They were obtained from the basal melt out till which is found in association with horizontal stratified sand lenses. Each fabric sample displays a unimodal pattern with orientations ranging generally from 60°–100°. The long axis of the form is 64°–244°. Site D is parallel to the form whereas sites E and G have subparallel orientations. These fabrics (D, E and G) are taken to indicate ice flow directions which have been preserved during melt out. In the centre of the section fabrics H and G are located in the very compact diamicton (Figure 4.39). These fabrics display unimodal patterns and they are transverse to the direction of the fluting long axis. These patterns are to be expected in such a fold complex.

Fabric sites 1A and 2A are located in the very compact diamicton (Figure 4.39). Site 1A is situated within the diamicton 1 metre to the southwest of clayey inclusion 1. Site 2A is located at the same elevation in the very compact diamicton midway between clayey inclusion 1 and 2 (Figure 4.39). Fabric 1A and 2A are both transverse to the form and show S_1 values of 0.66 and 0.79 respectively (Figure 4.40). This demonstrates that there is a high degree of clustering around the principal eigenvector azimuths in both cases. Indeed, fabrics 1A and 2A show the strongest S_1 values for all fabrics undertaken in this study. Thus clear bipolar patterns are displayed by the fabric diagrams. The association of the high strength of fabric 2A with the centre of the fold complex is expected from a zone of maximum compression. In this area clasts have been rotated at right angles to former ice flow. In addition, at these sites the inclination of the azimuths for the principal eigenvectors is low (6°–15°) and may indicate that the angle of plunge for the fold complex is low.

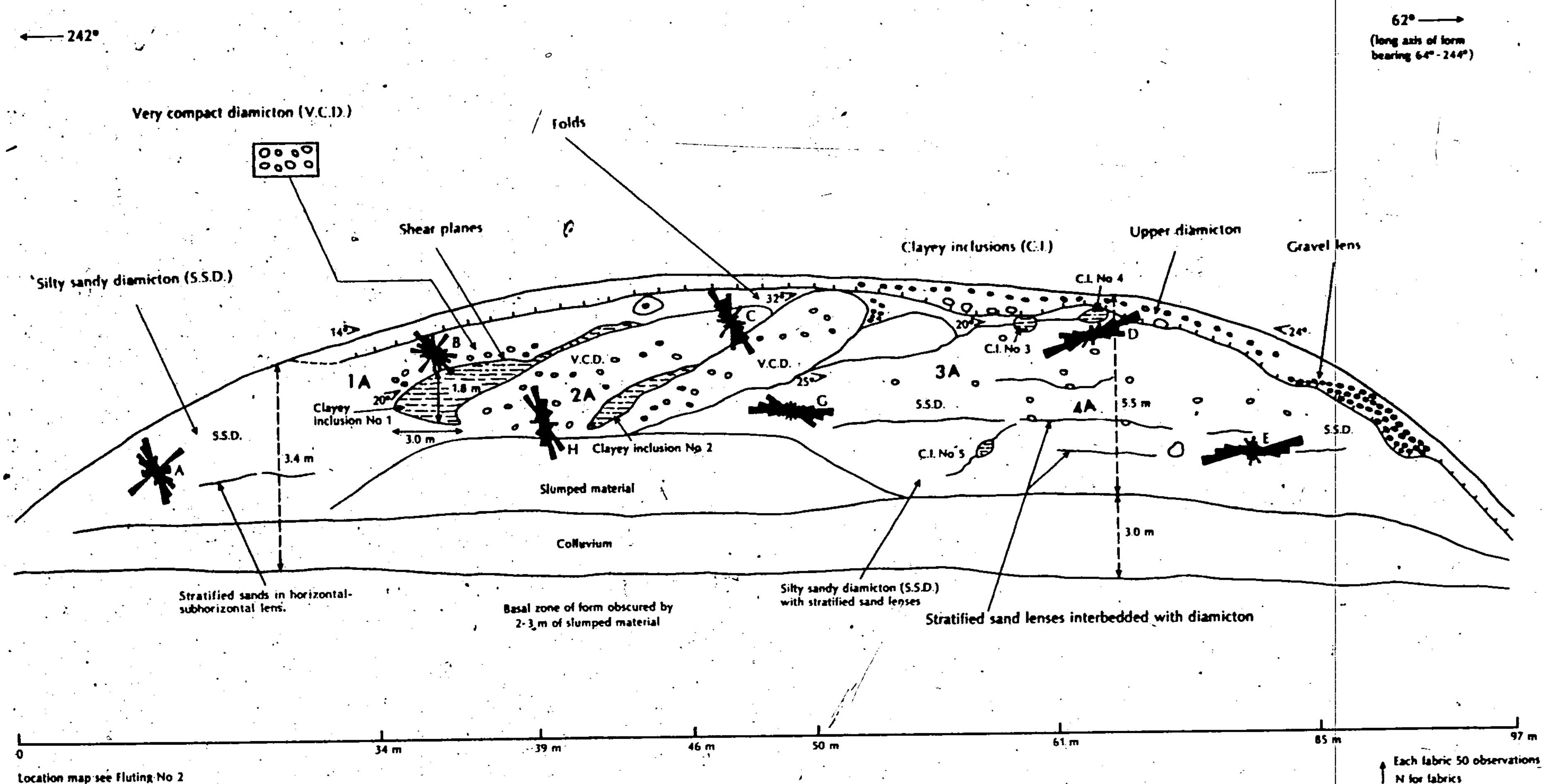


Figure 4.39 Fabric Locations on Fluting 3.

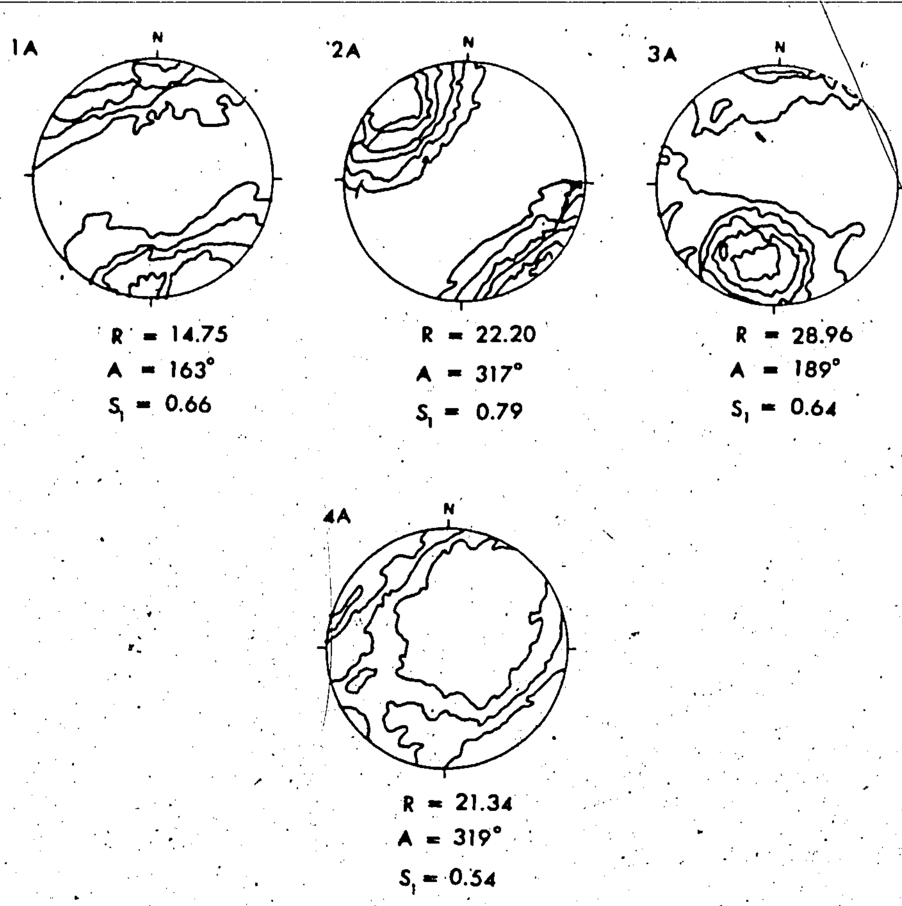


Figure 4.40 Contour Plots of Individual Fabrics, Fluting 3.

See Figure 4.39 for Sample Location. Contour Interval is Two Sigma.

Fabric 3A was obtained 0.5 metres below one of the limbs of the fold complex, in the melt out till (Figure 4.39). It has a moderately high strength (S_1=0.64) but a preferred orientation which is rotated 20°–30° clockwise of a transverse position (Figure 4.40). It shows convergence towards the fluting axis and and is thought to indicate lee–side agglomeration of debris downglacier from the fold complex.

Fabric 4A was obtained from the melt out deposit at the northeast end of the section. It is different from the other three–dimensional fabrics because it has a relatively low strength (S_1=0.54) and shows a girdle distribution. It should be noted that whereas sites G, D and E are generally parallel to the fluting long axis, fabric 4A is generally transverse to the form. This fabric may be explained by reorientation of clast long axes by melt out or alternatively by lee–side agglomeration of debris.

In summary, three groups of fabrics are revealed. First, the multimodal orientations of sites A and B are strikingly different from all the other fabrics and are taken to indicate melt out and subsequent redistribution by flow. Second, fabrics 1A, 2A, C and H show a high degree of conformity at right angles to the former ice flow. These four samples were obtained from the folded and stacked, central diamicton and likely indicate compressive flow. Third, fabrics distal to the fold complex are generally parallel or convergent to the fluting long axis. These fabrics are thought to represent the former ice flow. Their preservation is also characteristic of melt out conditions. Fabric 3A may indicate that ice flow was converging.

It is notable that at this section fabric analysis may be used with more confidence than similar analyses for Drumlin 1 and Fluting 2. This is in part due to the presence of clearly different till/diamicton units. Each unit displays similar fabric patterns within it which vary significantly between units. Furthermore sedimentologic evidence, structural observations and fabric are corroborative. A summary of three–dimensional fabric data for the three streamlined landforms is presented in Table 4.1.

4.3.4 Landform Genesis

In recent years there has been a growing interest in glaciotectonic processes, particularly for research undertaken in Scandinavia (Berthelsen, 1973, 1979; Aber, 1979; Shaw, 1979) and in North America (Kupsch, 1962; Moran, 1971; Moran *et al.*, 1980).

SAMPLE NUMBER	VECTOR STRENGTH (R)	EIGEN VALUES (S_1)	(S_2)	(S_3)	PRINCIPAL AZIMUTH (A°)	EIGEN VECTOR PLUNGE (P°)
DRUMLIN 1.						
1A	20.82	0.50	0.34	0.16	135.8	14.0
2A	30.86	0.56	0.28	0.16	132.3	33.9
3A	19.25	0.44	0.40	0.15	343.0	7.8
FLUTING 2.						
1A	23.82	0.53	0.39	0.07	248.1	27.4
2A	20.98	0.53	0.37	0.10	150.6	2.8
3A	25.57	0.56	0.28	0.16	286.0	18.2
4A	18.38	0.52	0.32	0.16	210.3	8.2
5A	19.86	0.49	0.35	0.15	237.2	10.3
6A	15.06	0.59	0.28	0.13	183.6	3.3
FLUTING 3.						
1A	14.25	0.66	0.22	0.12	163.0	6.2
2A	22.20	0.79	0.12	0.09	317.0	15.0
3A	28.96	0.64	0.22	0.14	189.4	26.5
4A	21.34	0.54	0.35	0.11	319.4	1.0

Table 4.1 Summary of Three-dimensional Fabric Data.

These discussions have addressed the problem of large-scale sediment deformation with respect to glacier position and concluded that subglacial thrusting and proglacial thrusting are dominant processes. Moran (1971) presented a comprehensive analysis of large-scale subglacial thrusting and later modified some of these ideas (Moran *et al.*, 1980). In these papers it was proposed that thrusting takes place in the thin marginal, "frozen bed zone" (2-3 kilometres wide) where the glacier advances over permafrost. Aber (1982) expanded this theory and proposed that large-scale sediment deformation involves two stages: 1) initial stage of proglacial or ice marginal thrusting and stacking of "floes" during glacier advance over permafrost, 2) subsequent stage of subglacial shearing and penetrative deformation of previously thrusted "floes". However, it has been demonstrated that large-scale sediment deformation occurs in a variety of positions in or near a glacier and under different glacier regimes. For example, Shaw (1977a, Figure 4) showed that folding of debris-rich ice occurs in an englacial position in the cold-based Taylor Glacier, Antarctica. Goldthwait (1974) and Mickelson and Berkson (1974) demonstrated that during glacier retreat, till ridges or "minor moraines" are formed by "squeeze up" of basal till into transverse crevasses under the terminus of certain Alaskan glaciers. In other studies, however, the origin of transverse moraines resulting from "ice push" have been ascribed to frontal readvance of an ice margin during a period of of general recession (Elson, 1968; Christiansen, 1979). Thus glaciotectonic landforms may be generated during ice advance and retreat involving subglacial, englacial or proglacial positions affected by glacial pushing and/or overriding.

Fluting 3 displays a sequence of folded and stacked debris at the proximal end of the ridge. In the lee of this complex a melt out deposit containing horizontal stratified layers demonstrates that deposition occurred after deformation. On the basis of internal structure and fabric, this fluting is considered comparable with Rogen moraines described by Shaw (1979) and it may be that the form was generated by similar processes. Indeed, there is a strong case for supporting the contention that under certain circumstances Rogen moraines may develop into flutings.

The questions are under what conditions did the stacking and folding of debris take place and was the debris folded subglacially or proglacially? First, consider the ideas of Moran *et al.*, (1980). They proposed that stacking and thrusting of debris occurs along a narrow zone at the glacier margin which is frozen to its bed. During advance, slices of permafrost may become detatched from the substratum, frozen onto basal ice and transported forward. This mechanism essentially involves plucking of large blocks of material from the bed (Moran *et al.*, 1980). They postulated that optimum conditions occurred where the glacier advanced up–slope and over buried aquifers. It has also been suggested that ice marginal thrusting takes place where an ice sheet with a frozen margin and warm interior advances over permafrozen strata (Aber, 1982). Aber suggests that if the substratum is of hard rock or is frozen to a great depth, some erosion may occur rather than thrusting. On the other hand, if a soft unfrozen bed is present it would be too weak to support thrusting. Consequently, Aber argues that a substratum consisting of soft rocks and sediments which are permafrozen in the upper several tens of metres, provides a situation conducive to thrusting.

It is possible that limited permafrost existed in front of the glacier which advanced down the Athabasca River valley in the Hinton/Edson area and the presence of soft, permeable bedrock in the area may have offered ideal conditions for the development of confined aquifers at and under the glacier margin. This may have produced elevated pore–water pressures which facilitated decollement in a manner described by Moran (1971) Moran *et al.*, (1980). Alternatively the ice may have thrust material proglacially as described by Aber (1982). Both these models would permit marginal or englacial stacking of debris. If this is so, then the glaciotectonically deformed sediments in Fluting 3, consisting of local bedrock, glaciolacustrine sediment and diamicton, may be explained. Subsequently, this debris may have been streamlined and moulded under thawed–bed conditions by the overriding glacier to form the fluting (Moran *et al.*, 1980).

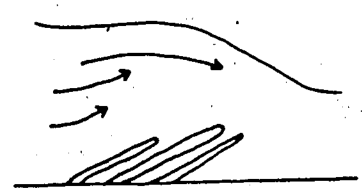
An alternative explanation for the stacking of debris in Fluting 3 is presented by Shaw (1979) in his discussion of Rogen moraines. Here, a series of overlapping units is created by small–scale overfolds in basal debris–rich ice under compressive flow conditions. Further folds which are formed upglacier in more rapidly flowing ice then catch up with these distal folds creating more stacked folds that are eventually thrusted and buckled. These are subsequently overridden in a manner similar to that described by Boulton (1970b), so that stagnant debris–rich ice occurs beneath active debris–rich ice. This explanation is also apparently consistent with the observed stacked complex at the proximal end of the section.

Two possible explanations have been presented for the stacked debris. It is suggested here that the stacked complex is representative of folded debris-rich ice in which thrusting has occurred. The fabric orientations (1A, 2A, C and H) support the inference of compressive flow in the stacked zone and are consistent with a basal thrusting mechanism under an ice margin. It is proposed that subsequent to stacking, material was added by a process of lee-side agglomeration and streamling to form the fluting. In this case debris and ice were transported into the low pressure zone in the lee of the stacked debris. The apparent parallel orientations of the fabrics distal to the folds (C, D and E) may illustrate this process and fabric 3A may indicate convergence. Thus the general flow conditions may have been similar to those described by Sengupta (1966) for current crescents. It is postulated that in the proximal zone of the obstacle compressive flow conditions were present whereas distal to the obstruction the flow in upper ice was extending. At some stage, stagnant ice conditions occurred in the lee of the obstacle. Because one would expect differential flow between upper and lower ice, streamlining and fluting of the lower debris should occur (Shaw, 1979). The response of the moving basal ice to the obstacle may be comparable to the conditions described by Boulton (1970b, Figure 5) whereby basal debris becomes incorporated into an englacial position to produce high englacial debris loads in the upper ice.

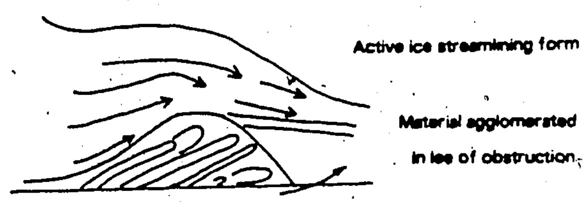
With the onset of regional ice stagnation, melt out becomes the dominant process. The horizontal stratified sand lenses, interbedded with melt out till are thought to be syndepositional and originate in cavities within melting debris-rich ice. The final stages of fluting deposition were marked by the release of supraglacial debris, including a channel fill over the fluting form. During this process the till, now forming the upper flanks of the ridge, may have been redistributed by flow. This is consistent with fabric patterns A and B. Loess was then deposited over the form.

An alternative interpretation to account for the streamlined nature of Drumlin 1, Fluting 2 and Fluting 3 may involve the role of meltwater. Extensive networks of meltwater channels occur perpendicular to the trend of the Athabasca River valley between Entrance and Obed (Figure 1.5). In this area meltwater channels sometimes cross-cut streamlined landforms (Figure 4.20). In addition, meltwater may have been channeled in the troughs lying parallel to the long-axes of drumlins and flutings (Figures 4.1, 4.2 and 4.20). The effects of limited, meltwater erosion may have been to enhance and streamline drumlins and flutings during and after their emergence from ice. To what extent the streamlined forms in the Hinton/Edson area are the product of meltwater activity remains speculative but it is thought that the role of fluvial erosion during deglaciation may be part of an integrated explanation of their forms. Landform genesis is summarised by Figure 4.41.

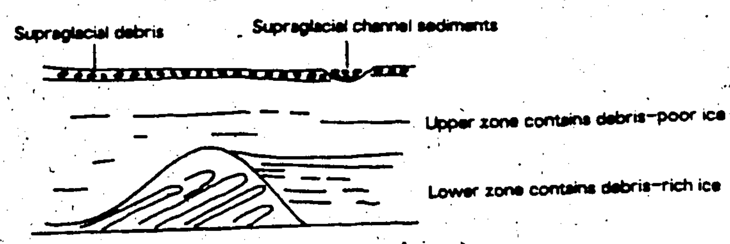
STAGE 1. Thrusting and stacking of debris (including bedrock and diamicton) in "frozen-bed zone"



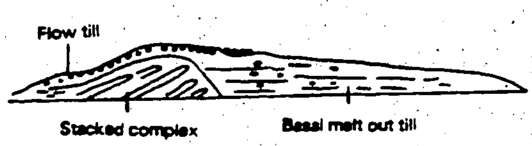
STAGE 2 Development of transverse feature similar in origin to a Rogen moraine (see Figure 3.1) with lee-side agglomeration of debris downice of obstruction.



STAGE 3. Stagnation and melt out



STAGE 4 (with change in scale) Fluting shows proximal stacked debris with basal melt out till predominantly in lee of obstruction (see Figure 4.35)



See Figure 4.35

Figure 4.41 Genesis of Fluting 3.

5. SUMMARY AND CONCLUSIONS

5.1 Introduction

The purpose of this study was to determine the genesis of certain streamlined landforms in the Hinton/Edson area. Detailed studies of three streamlined landforms have been presented. In this chapter formational processes for these three landforms are discussed and a genetic model is advanced for drumlin and fluting development. An additional objective is to evaluate earlier proposals for the origin of drumlins and flutings and test these against the observed properties of the streamlined forms in the Hinton/Edson area.

In considering the three landforms together it is realised that the positions of the sections through the forms are not ideal. The section through Drumlin 1 is oblique to its main axis, the section through Fluting 2 is at its distal end and the section through Fluting 3 is at its proximal end. However, given the similarities in their composition, structure and stratigraphy, it is felt that generalisations regarding their genesis are warranted.

5.2 Summary of the sedimentological characteristics of the forms

5.2.1 Upper Sections

An upper till and gravel fill occur as the uppermost deposits for each landform. The upper tills, taken together, are characterised by a sandy silty matrix with an abundance of pebbles and cobbles which are well rounded to subrounded. Lithologically, the dominant clasts are limestones and Gog quartzites from the Jasper area. Gravel fills are found in association with the upper tills. These show fluvial characteristics, each deposit having rounded pebbles and cobbles in a matrix of medium sand which displays horizontal laminations. Each gravel fill is a discrete entity with no interfingering of till. Evidence for sediment flows is therefore lacking and it is consequently concluded that the upper tills are supraglacial melt out deposits and that the gravel fills are supraglacial fluvial channels. These deposits were lowered during ice thinning by direct insolation, fluvial thermoerosion and sublimation. Subsequently, loess covered each form.

5.2.2 Middle Sections

Middle tills are present in Drumlin 1 and Fluting 2. They are characterised by a sandy silty matrix with a high proportion of rounded cobbles. Lithologically, the dominant clasts are limestones and quartzites from the Jasper area, although some locally derived clasts, including sandstones and shales, are present in minor amounts. Stratified sand and gravel occurs as intratill beds within the middle section of Drumlin 1 and Fluting 2. In Fluting 3, these sediments occur in proximal and distal positions with respect to the central folded debris zone. The stratified sediments form layers, lenses and tubes through till. Primary structures within these sediments include micro ripple cross–lamination, small–scale trough cross–beds and horizontal lamination. Deformation structures occur in some stratified sediments and include faults, folds and injection structures. Three stratified clayey bands are present in the middle till of Drumlin 1. These beds are laminated, sorted and associated with blocks of structureless sand.

There is considerable evidence that some lenses of stratified, sorted materials, interbedded with diamicton, are formed by melt out (Shaw, 1971, 1979; 1982; Johansson, 1972; Bouchard, 1980; Lawson, 1981; Haldorsen and Shaw, 1982; Proudfoot, (personal communication). Such is the case in the middle sections of the streamlined forms discussed here. However, a number of workers (Boulton, 1968, 1971, 1972; Lawson, 1979) have also identified stratified layers in association with diamicton which they have interpreted as sediment flows. It is clear that both processes are operative in modern glacial environments (Boulton, 1972; Lawson, 1979; Shaw, 1982) and a major problem is finding criteria which permit distinctions to be made between flow facies and melt out facies in Pleistocene deposits (Haldorsen and Shaw, 1982).

It should be made clear that the stratified clayey bands in Drumlin 1, which display stratification and sorting, are not considered primary melt out features. It is proposed that these bands represent layers of sediment incorporated in the ice, which have been subsequently released without disturbing their previous structures.

The middle sections of Drumlin 1 and Fluting 2 and the sediments to the proximal and distal end of the folded zone in Fluting 3, exhibit melt out structures and therefore the till is classified as a melt out deposit. Several examples of melt out structures observed in this study are as follows:

(a) the widespread occurrence, both horizontally and vertically, of discrete lenses of stratified sediments.

(b) the penetration of clasts from overlying till into extensive, stratified, sorted lenses (Drumlin 1).

(c) the convex-upwards nature of the contact between extensive, stratified, sorted lenses and the overlying till (Drumlin 1).

(d) the draping of stratified, sorted lenses over clasts of the underlying till (Fluting 2 and Fluting 3).

(e) the well preserved nature of the sedimentary structures in the lenses.

(f) the presence of horizontal layers of stratified sediments that are found in association with folded and sheared units indicating that the stratified layers were deposited after deformation.

While some of the properties given above may also be representative of sediment flows, properties (b), (c) and (d) are considered diagnostic criteria for melt out. For example, it would be difficult to reconcile property (c) within Drumlin 1, with a process involving sediment flow and, far easier to explain the draping relationship (d) from Fluting 2 and Fluting 3 by melt out.

5.2.3 Lower Sections

The lowermost sediments in Drumlin 1 and Fluting 2 consist of till which contains a high proportion of locally derived clasts consisting of sandstones, coal and mudstones together with further-travelled limestones and quartzites. Local transport and lack of comminution is illustrated by angular, sandstone boulders in the lower till of Drumlin 1. The clayey inclusions in Fluting 2 and Fluting 3, are also interpreted as local glaciolacustrine sediments derived from the substratum.

Tectonic features, which include shear planes and folds, are common in the lower section of Fluting 2 and central zone of Fluting 3. These features, together with the sediments they deform, are thought to demonstrate thrusting and stacking of basal debris in the ice. In addition, the chaotic nature of the sediment in the lower section of Fluting 2 may illustrate agglomeration of basal, debris-rich ice. The presence of some of the tectonic features in the deposits are attributed to melt out whereby certain structures were preserved.

5.3 Summary of Fabric Analyses

Fabric analyses of the three sections raise some unresolved questions concerning the use of this method in genetic process interpretations. In particular, one question is how many measurements are required to provide a representative sample of each form? Seventeen, fourteen and eleven fabrics were taken on Drumlin 1, Fluting 2 and Fluting 3, respectively, and these samples are considered adequate. However, with fabric analyses it is always difficult to know how many investigations are necessary for a representative sample.

It is also clear that testing fabrics by three-dimensional analysis does not necessarily clarify our understanding of landform genesis. However, three-dimensional analysis using contour plots with two sigma intervals is recommended as it permits comparisons with other work in this field (Lawson, 1979; Shaw, 1982). It may be that as this technique becomes more widespread and standardised in fabric studies, more sensitive criteria will be produced for the genetic interpretation of till.

In this study, till fabrics in the streamlined forms do not always show strong patterns. For example on Drumlin 1, six out of fourteen Rose diagrams do not display definite preferred orientations. This "negative" evidence may be significant in itself but makes process interpretations difficult. It could also be argued that such patterns could be used to support virtually any process which is chosen. The reason for this is that so many processes can produce similar results (Boulton, 1971 p.70). In contrast five out of seven Rose diagrams on Fluting 3 display fabrics which do show strong preferred orientations. Given such variations, it appears that placing too much emphasis on the significance of till fabrics as a means of proving or disproving hypotheses may be unwarranted (Menzies, 1979).

In terms of genetic conclusions from the fabric data, which show preferred orientations, there is some support for compressive ice flow in the proximal zones of the streamlined forms (Drumlin 1 and Fluting 2). However, in the distal zone of the streamlined forms, Fluting 2, in particular, fabrics are generally parallel to ice flow direction or convergent with the long axes of the streamlined forms. In addition, a significant number of individual fabrics are not the result of ice dynamics but display patterns associated with collapse, flow and slumping. These processes have occurred during or after the release of sediment from ice.

5.4 Drumlin and Fluting Genesis

From the observations presented, it is possible to postulate a general sequence of events leading to the formation of certain streamlined forms in the Hinton/Edson area. It should be noted that because process explanations have been inferred from only three sections, not all streamlined forms should be interpreted using the same mechanism. The explanation presented here provides a model against which other streamlined forms in the Hinton/Edson area should be tested.

The controversial nature of drumlins and flutings has resulted largely from a reluctance by various workers to accept the concept of equifinality whereby many processes may produce morphologically similar landforms. A certain amount of dogma (Gravenor, 1953; Clayton and Moran, 1974) has surrounded research in this field and it is probable that no single explanation will ever account for all drumlins and flutings.

From the observations, it is proposed that folding and stacking of debris has acted as an initiating point for drumlin and fluting formation. This is clearly displayed at the proximal end of Fluting 3. As for Drumlin 1 no trigger mechanism is discerned due to the position of the section with respect to the gross form.

Folded and stacked debris may be produced in a number of ways; by stacking basal debris in compressive flow zones near a glacier margin (Shaw, 1979), by stacking and overriding permafrozen "floes" beyond an ice margin (Aber, 1982) and by lodgement of debris in the proximal zone of bedrock obstructions (Gillberg, 1976). Thrust terrain (Moran, 1971; Clayton and Moran, 1974; Moran *et al.*, (1980); Fenton, 1983) has been proposed for the initiation of streamlined terrain in the Prairies of North America. This process is related to thrusting in a "frozen-bed" zone, two to three kilometres wide at the glacier margin. Both the process explanations of Shaw (1979) and Moran *et al.*,(1980), seem to provide the "best fit" for the genesis of Fluting 3. By these interpretations a transverse feature, similar in origin to a Rogen or Ribbed moraine (Lundqvist, 1969), acted as a nucleus for fluting formation. Comparible observations were made by Aario (1976, 1977a and b) for crescentic ridges in Finland which are found in association with drumlins and flutings. He noted that crescents have been observed frequently at the proximal sides of drumlins. This evidence may be used to support a hypothesis proposed by Shaw (1979, 1980) that Rogen moraines may develop into drumlins and then into flutings. The morphology of Drumlin 1, may indicate a transitional phase between a transverse form and a "classical" drumlin. In this study the evidence does not show any fundamental stratigraphic differences between drumlins and flutings and morphological variations are the major distinguishing features. Hence they appear as transitional forms.

The explanation proposed here for the streamlined forms is that folded and stacked debris has developed as a result of a thrusting mechanism with conditions similar to those described by Moran *et al*., (1980) and Aber (1982) where ice and substrate were frozen with resultant glaciotectonism during glacial advance. At a later stage, under warmer conditions, final moulding and streamlining occurred with flow conditions analogous to those described by Sengupta (1966) for current crescents. By this explanation, a zone of laterally divergent flow is expected in basal ice at the proximal end of the obstruction. In the lee of the obstacle, a low pressure zone is expected where there is convergent flow on the outer part of the fan developed in the "wake" of the obstruction. In the zone immediately distal to the obstruction a zone of slow deposition would occur. In the upper ice the flow is thought to be overriding, and may be parallel or extending (Shaw, 1979). Under these conditions pressure melting on the proximal side of the transverse feature is expected (Boulton, 1975a). The generation of meltwater in the proximal zone of the obstacle is likely to produce two effects; first, it would enhance basal sliding in that area and second, meltwater may migrate towards a lower pressure zone in the lee of the obstacle and may refreeze (Boulton, 1970a, 1980). The development of a cavity which is filled with a slurry-like material, meltwater and ice is envisaged in the lee of the obstruction. Therefore the properties of the deposits should display some of the characteristics of lee-side till (Hillefors, 1973), lodgement till and sediment flows. Subsequent to the deposition of the material, dewatering and refreezing of the sediments are expected. Differential flow between debris-ice mixtures is considered to have retarded flow in the lower zone (Russell, 1895) and the effect of overriding upper ice is thought to have produced streamlining (Shaw, 1980). The upper ice may have incorporated some debris by thrusting (Goldthwait, 1951) or basal freezing (Weertman, 1961; Boulton, 1970a). These sediments may have been derived from a basal position up-ice from the transverse form.

It is noteworthy that Jones (1982), investigating the Lac La Biche drumlin and fluting field, Alberta, provided support for the model proposed by Moran *et al.*, (1980). He suggested that drumlin and fluting formation involved thrusting and plucking of blocks of basal debris under "frozen-bed" conditions and compressive flow. Jones (1982) also postulated that under "thawed-bed" conditions, material was transported to the lee of the obstacles as a result of converging secondary flow cells (cf. Shaw and Freschauf, 1973). In the Hinton/Edson area, Fluting 3 supports a process of thrusting and stacking of debris with lee-side agglomeration. However, the fabric patterns in the lee of the stacked complex do not support directly the secondary flow motion proposed proposed by Shaw and Freschauf (1973) and Jones (1982). Therefore, an explanation involving enhanced, plastic flow (Weertman, 1957) with lee-side deposition (Hillefors, 1973) is preferred here.

The size of drumlins and flutings is considered to be directly dependent upon the amount of material available in the ice which was transported to the lee-side, the size and extent of the cavity, the duration and consistency of ice flow and the sediment carried by streams into the cavity. It is also thought to be related to the shear strength of debris-ice mixtures and the stresses applied by glacier ice (Reed *et al.*, 1962; Hill, 1968; Smalley and Unwin, 1968; Gravenor, 1974; Rose and Letzer, 1977). With stagnation and climatic amelioration, melting of debris-rich ice resulted in deposition of till and stratified material. Englacial meltwater tunnels and cavities became filled with stratified deposits which were preserved as intratill beds and were "let down" syndepositionally as melt out till. Supraglacial sediments melted out at the same time and the thickness of these deposits insulated upper ice so that surface melting was arrested. Undermelting and underconsolidation of till led to slumping, folding and faulting of till and some intratill sands. Certain primary fabrics were altered during these processes. However, other fabrics remained unaffected by secondary processes and characterise ice flow conditions as they were preserved by slow release of englacial debris. Finally, supraglacial sediments were deposited over the drumlin and fluting ridges to mantle the forms and loess was deposited.

5.5 Concluding Remarks and Recommendations

Three streamlined landforms have been interpreted in terms of a composite process model involving erosion and deposition. Drumlins and flutings are seen as developing from transverse features. A combination of thrusting, stacking and folding of debris with lee-side deposition supports explanations proposed by Shaw (1979) and Moran *et al.*, (1980) for similar landforms. Although thrusting is thought to be associated with "frozen-bed" conditions, streamlining is thought to occur under active ice conditions. Preservation of the drumlins and flutings is attributed to melt out under stagnant ice.

It may be concluded that existing models for the interpretation of drumlins and flutings, and the sequences in which they lie, have often been interpreted in terms of one or two types of till where many are present and that composite explanations, rather than purely erosional and depositional models, may be more correct.

Further research on drumlins and flutings in the Hinton/Edson area is recommended to test the model proposed here. In addition, detailed studies of bedrock flutings described earlier would also contribute to our understanding of glacigenic streamlined landforms in Alberta.

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APPENDIX

DRUMLIN1 1A	AZIMUTH	INCLINATION	DRUMLIN1 2A			DRUMLIN1 3A		
1	72	33	1	184	56	1	312	13
2	10	5	2	195	16	2	0	90
3	10	4	3	127	35	3	140	17
4	270	51	4	154	42	4	170	7
5	246	33	5	98	24	5	12	4
6	12	10	6	65	59	6	320	12
7	270	16	7	59	31	7	110	14
8	335	14	8	256	5	8	290	20
9	171	22	9	135	33	9	178	26
10	258	21	10	183	37	10	230	26
11	27	14	11	107	46	11	178	4
12	272	41	12	152	39	12	98	13
13	328	4	13	203	40	13	299	4
14	24	1	14	280	63	14	14	17
15	332	41	15	135	24	15	267	25
16	96	29	16	188	43	16	78	7
17	89	18	17	133	39	17	138	42
18	25	30	18	155	13	18	108	25
19	168	21	19	212	17	19	177	25
20	169	15	20	142	58	20	253	24
21	354	1	21	130	25	21	358	13
22	185	25	22	296	84	22	73	21
23	294	23	23	4	54	23	110	2
24	230	9	24	244	10	24	69	8
25	260	28	25	162	33	25	0	90
26	296	43	26	249	26	26	282	9
27	165	5	27	93	29	27	180	12
28	335	14	28	279	31	28	354	14
29	50	14	29	212	4	29	27	13
30	320	42	30	123	20	30	0	90
31	274	42	31	127	47	31	168	8
32	2	20	32	276	28	32	137	5
33	225	39	33	52	36	33	22	21
34	65	8	34	336	19	34	162	24
35	105	23	35	140	33	35	162	20
36	321	35	36	99	69	36	180	38
37	345	27	37	138	25	37	133	37
38	291	7	38	132	16	38	137	33
39	173	25	39	155	7	39	109	23
40	230	2	40	126	10	40	138	11
41	256	1	41	103	27	41	172	12
42	106	15	42	116	45	42	242	34
43	106	16	43	149	21	43	133	24
44	1	21	44	99	34	44	0	19
45	270	11	45	302	42	45	135	42
46	165	12	46	271	6	46	107	25
47	191	65	47	158	41	47	65	2
48	140	28	48	285	14	48	74	18
49	35	14	49	189	20	49	218	32
50	290	30	50	261	9	50	280	26
TOTALS			TOTALS			TOTALS		

--DRUMLIN1 SITEA

1	318	42
2	311	65
3	241	15
4	236	15
5	236	35
6	306	40
7	66	12
8	66	15
9	326	10
10	54	3
11	52	35
12	96	15
13	62	15
14	79	17
15	77	15
16	122	44
17	88	32
18	34	11
19	96	50
20	16	45
21	259	30
22	256	25
23	332	22
24	286	15
25	345	20
26	6	12
27	345	5
28	226	20
29	334	22
30	14	17
31	288	24
32	244	22
33	334	20
34	301	7
35	261	15
36	256	20
37	256	40
38	300	27
39	6	25
40	264	13
41	248	35
42	326	0
43	298	24
44	294	30
45	26	52
46	344	5
47	246	15
48	244	50
49	318	15
50	334	25
TOTALS		

--DRUMLIN1 SITEB

1	26	20
2	266	5
3	56	15
4	304	5
5	80	5
6	56	10
7	334	15
8	314	28
9	264	5
10	347	17
11	267	20
12	296	25
13	250	8
14	320	10
15	294	18
16	16	30
17	304	12
18	21	20
19	14	0
20	334	13
21	336	28
22	264	25
23	248	30
24	46	20
25	281	15
26	358	5
27	302	12
28	336	20
29	0	10
30	354	7
31	78	10
32	244	15
33	54	15
34	36	5
35	56	45
36	340	25
37	341	5
38	272	23
39	308	22
40	312	35
41	251	18
42	276	24
43	284	10
44	8	35
45	304	5
46	304	10
47	264	35
48	26	15
49	306	22
50	28	18
TOTALS		

--DRUMLIN1 SITEC

1	288	15
2	258	7
3	16	17
4	288	2
5	24	18
6	314	16
7	336	32
8	14	43
9	274	22
10	296	24
11	20	70
12	28	5
13	56	18
14	38	15
15	224	8
16	291	0
17	264	23
18	346	17
19	58	49
20	316	47
21	276	12
22	242	5
23	260	29
24	350	7
25	256	21
26	266	4
27	254	3
28	304	6
29	324	5
30	230	26
31	298	15
32	14	2
33	346	22
34	300	38
35	274	26
36	200	11
37	288	16
38	316	26
39	234	15
40	200	37
41	326	28
42	230	8
43	304	25
44	324	37
45	250	26
46	240	30
47	265	17
48	265	10
49	240	26
50	240	28
TOTALS		

--DRUMLIN1 SITED

1	244	2
2	288	4
3	286	15
4	318	17
5	274	16
6	208	28
7	354	53
8	212	22
9	284	22
10	264	2
11	326	8
12	338	18
13	334	36
14	242	2
15	226	13
16	288	27
17	254	7
18	208	22
19	278	37
20	280	7
21	264	6
22	312	24
23	298	26
24	232	16
25	244	4
26	214	16
27	324	12
28	256	12
29	300	16
30	288	16
31	312	11
32	246	5
33	296	8
34	316	10
35	320	13
36	296	18
37	232	23
38	246	0
39	344	20
40	302	55
41	274	7
42	306	2
43	260	32
44	258	0
45	250	16
46	250	15
47	214	2
48	250	14
49	224	26
50	290	2
TOTALS		

-DRUMLIN1 SITEE

1	260	24
2	198	8
3	324	16
4	216	25
5	160	60
6	0	90
7	206	7
8	326	25
9	186	6
10	206	35
11	0	90
12	246	22
13	206	15
14	230	22
15	314	2
16	354	43
17	226	5
18	260	20
19	326	5
20	204	25
21	312	34
22	310	15
23	344	5
24	300	30
25	294	30
26	294	30
27	288	30
28	194	24
29	302	20
30	196	2
31	182	6
32	206	10
33	196	23
34	318	10
35	192	40
36	268	7
37	270	32
38	206	7
39	204	4
40	250	8
41	288	9
42	336	3
43	352	5
44	344	11
45	332	12
46	314	15
47	318	13
48	204	8
49	264	11
50	216	16
TOTALS		

--DRUMLIN1 SITEF

1	214	20
2	344	20
3	296	0
4	16	65
5	216	15
6	216	15
7	216	15
8	226	15
9	262	26
10	262	0
11	320	18
12	256	3
13	316	22
14	216	24
15	216	24
16	240	12
17	326	42
18	306	80
19	328	10
20	336	13
21	316	0
22	290	5
23	266	32
24	26	32
25	2	8
26	310	10
27	284	6
28	236	33
29	206	12
30	328	12
31	14	0
32	256	5
33	330	5
34	316	16
35	298	18
36	340	26
37	270	15
38	244	16
39	284	16
40	262	33
41	276	7
42	332	4
43	284	15
44	236	5
45	322	7
46	310	30
47	340	8
48	322	25
49	320	26
50	302	15
TOTALS		

--DRUMLIN1 SITEG

1	228	7
2	186	20
3	266	5
4	201	7
5	326	25
6	256	10
7	318	20
8	286	25
9	314	25
10	302	20
11	358	20
12	286	0
13	340	12
14	256	4
15	16	17
16	324	15
17	342	15
18	344	2
19	342	10
20	338	28
21	352	0
22	6	5
23	250	5
24	9	5
25	288	5
26	288	5
27	246	0
28	336	20
29	224	25
30	234	35
31	204	40
32	268	25
33	212	36
34	316	36
35	234	15
36	346	30
37	266	33
38	266	10
39	276	20
40	344	20
41	302	52
42	332	35
43	302	38
44	216	5
45	216	15
46	348	34
47	16	10
48	298	40
49	296	30
50	296	32
TOTALS		

--DRUMLIN1 SITEH

1	299	14
2	352	4
3	4	13
4	332	6
5	322	6
6	332	30
7	28	3
8	314	2
9	358	10
10	334	27
11	356	26
12	328	34
13	330	40
14	0	35
15	0	6
16	44	16
17	230	26
18	34	2
19	236	36
20	254	6
21	246	19
22	246	6
23	224	6
24	268	4
25	226	16
26	256	19
27	220	0
28	210	6
29	254	3
30	258	15
31	284	36
32	340	18
33	288	20
34	8	28
35	220	25
36	290	15
37	338	2
38	304	11
39	54	32
40	38	0
41	24	2
42	54	8
43	42	18
44	250	14
45	294	12
46	278	6
47	328	48
48	328	41
49	222	18
50	54	40
TOTALS		

--DRUMLIN1 SITEI

1	102	32
2	316	37
3	126	32
4	110	62
5	68	44
6	350	56
7	336	33
8	60	12
9	304	52
10	306	66
11	288	42
12	336	4
13	324	34
14	334	20
15	354	53
16	322	20
17	312	25
18	314	44
19	298	32
20	296	48
21	342	38
22	286	19
23	338	34
24	254	58
25	314	42
26	210	34
27	356	20
28	32	11
29	88	55
30	246	12
31	342	64
32	338	54
33	264	5
34	272	15
35	314	25
36	50	43
37	314	18
38	320	40
39	120	26
40	308	30
41	296	46
42	308	30
43	270	18
44	266	18
45	254	10
46	156	40
47	288	15
48	266	4
49	316	20
50	314	20
TOTALS		

--DRUMLIN1 SITEJ

1	68	15
2	66	5
3	30	18
4	320	2
5	54	6
6	92	4
7	84	17
8	348	34
9	58	22
10	328	11
11	82	4
12	80	16
13	56	26
14	66	27
15	334	35
16	30	12
17	94	26
18	124	18
19	72	13
20	80	25
21	60	14
22	60	3
23	62	11
24	132	2
25	90	18
26	104	35
27	80	19
28	38	12
29	90	2
30	48	3
31	98	4
32	78	21
33	20	15
34	66	23
35	90	17
36	54	22
37	54	22
38	72	12
39	78	13
40	124	12
41	62	8
42	58	16
43	94	25
44	50	17
45	100	1
46	74	4
47	106	14
48	44	36
49	46	12
50	88	2
TOTALS		

-DRUMLIN1 SITEONE

1	256	8
2	294	25
3	292	6
4	306	18
5	20	32
6	54	4
7	36	25
8	30	8
9	36	60
10	280	30
11	306	24
12	290	2
13	40	26
14	6	23
15	276	32
16	6	35
17	46	5
18	256	5
19	18	40
20	276	36
21	286	20
22	278	36
23	22	6
24	18	33
25	282	38
26	16	42
27	346	15
28	268	2
29	324	10
30	297	22
31	198	45
32	316	20
33	286	28
34	266	10
35	294	28
36	16	20
37	252	6
38	184	8
39	36	0
40	296	20
41	266	15
42	288	12
43	290	15
44	276	8
45	256	2
46	339	30
47	276	8
48	288	28
49	282	8
50	290	25
TOTALS		

-DRUMLIN1 SITESIX

1	238	20
2	246	0
3	216	10
4	316	25
5	326	30
6	336	26
7	316	20
8	336	20
9	266	12
10	326	40
11	326	15
12	326	20
13	334	35
14	334	40
15	326	35
16	328	30
17	338	30
18	338	22
19	336	26
20	354	10
21	320	30
22	354	25
23	6	5
24	234	30
25	341	24
26	266	5
27	0	25
28	0	32
29	306	24
30	226	20
31	298	30
32	316	30
33	336	25
34	6	4
35	136	27
36	6	4
37	336	27
38	266	0
39	336	29
40	336	30
41	336	32
42	302	25
43	334	75
44	6	16
45	334	24
46	322	8
47	204	19
48	186	4
49	276	15
50	316	10
TOTALS		

--DRUMLIN1 SITENINE

1	306	5
2	196	0
3	0	5
4	316	6
5	316	5
6	316	0
7	308	25
8	356	5
9	296	3
10	272	4
11	306	2
12	316	16
13	306	16
14	290	12
15	236	3
16	296	12
17	304	12
18	298	25
19	4	15
20	256	10
21	276	16
22	258	32
23	276	10
24	296	20
25	298	15
26	306	12
27	286	12
28	284	15
29	326	36
30	16	60
31	256	5
32	46	22
33	14	48
34	316	15
35	276	2
36	296	15
37	216	3
38	270	10
39	246	3
40	296	7
41	16	30
42	309	15
43	334	12
44	356	12
45	296	12
46	276	24
47	276	25
48	326	32
49	260	7
50	380	74
TOTALS		

-DRUMLIN1 SITETEN

1	296	34
2	286	27
3	310	12
4	336	36
5	276	46
6	260	28
7	220	30
8	262	24
9	236	0
10	226	16
11	360	90
12	288	14
13	196	0
14	222	8
15	260	26
16	276	8
17	338	15
18	318	23
19	316	15
20	266	16
21	10	15
22	236	25
23	316	16
24	246	16
25	286	24
26	316	23
27	236	50
28	302	30
29	314	26
30	318	32
31	344	14
32	334	22
33	298	30
34	316	40
35	256	16
36	336	10
37	300	23
38	300	18
39	328	26
40	336	28
41	316	33
42	320	35
43	338	30
44	296	42
45	288	38
46	336	28
47	248	20
48	6	14
49	300	42
50	268	5
TOTALS		

--FLUTING2 1A

1	224	38
2	251	31
3	156	53
4	158	48
5	278	38
6	204	31
7	275	13
8	184	15
9	90	22
10	173	26
11	198	39
12	247	25
13	87	4
14	268	33
15	336	30
16	82	6
17	283	10
18	171	36
19	272	5
20	95	4
21	224	26
22	198	43
23	328	27
24	198	33
25	267	18
26	126	4
27	204	27
28	113	20
29	195	34
30	212	45
31	204	36
32	145	16
33	206	28
34	288	33
35	140	18
36	256	14
37	288	14
38	188	40
39	238	26
40	130	42
41	177	19
42	90	45
43	110	12
44	273	28
45	238	19
46	265	16
47	247	34
48	312	14
49	235	41
50	294	13
TOTALS		

--FLUTING2 2A

1	146	29
2	216	35
3	351	19
4	17	11
5	190	13
6	324	15
7	187	36
8	227	0
9	235	60
10	170	14
11	215	23
12	112	8
13	297	13
14	167	12
15	315	13
16	141	45
17	293	32
18	192	32
19	313	23
20	224	53
21	246	15
22	128	15
23	326	8
24	235	59
25	187	42
26	215	18
27	227	22
28	358	6
29	286	12
30	162	20
31	241	34
32	306	14
33	102	11
34	333	37
35	139	2
36	350	5
37	319	8
38	259	17
39	313	11
40	254	27
41	332	10
42	132	13
43	27	12
44	131	10
45	281	6
46	209	35
47	249	31
48	340	16
49	117	30
50	338	11
TOTALS		

--FLUTING2 3A

1	191	40
2	281	1
3	328	38
4	0	44
5	331	4
6	189	1
7	344	1
8	235	20
9	234	17
10	152	42
11	137	18
12	298	14
13	230	19
14	284	32
15	190	30
16	10	39
17	351	30
18	291	14
19	82	22
20	96	10
21	35	8
22	166	21
23	312	14
24	284	42
25	289	39
26	274	3
27	320	8
28	268	22
29	287	11
30	289	37
31	312	35
32	296	54
33	271	17
34	128	52
35	100	30
36	285	31
37	131	6
38	235	30
39	294	20
40	270	13
41	260	14
42	275	16
43	182	74
44	270	14
45	310	48
46	211	42
47	110	4
48	228	43
49	158	50
50	94	13
TOTALS		

--FLUTING2 4A

1	204	14
2	315	36
3	330	16
4	339	16
5	60	7
6	198	21
7	190	16
8	160	2
9	266	26
10	28	8
11	275	54
12	310	46
13	220	31
14	186	0
15	187	16
16	238	6
17	43	14
18	311	64
19	28	11
20	103	5
21	95	36
22	284	20
23	226	33
24	33	8
25	206	23
26	20	14
27	166	20
28	340	64
29	65	26
30	187	24
31	6	8
32	285	49
33	232	40
34	168	17
35	194	26
36	208	24
37	356	27
38	235	18
39	109	0
40	40	4
41	62	12
42	296	12
43	145	22
44	236	17
45	5	45
46	82	18
47	290	39
48	37	8
49	113	10
50	203	45
TOTALS		

--FLUTING2 5A

1	243	16
2	180	31
3	222	34
4	23	14
5	243	20
6	263	40
7	268	14
8	279	3
9	324	9
10	273	20
11	170	26
12	47	22
13	245	11
14	252	17
15	246	15
16	295	32
17	179	69
18	60	13
19	131	21
20	24	10
21	3	14
22	257	6
23	359	21
24	344	19
25	326	24
26	14	11
27	210	57
28	177	2
29	117	41
30	215	38
31	310	27
32	122	6
33	215	7
34	76	16
35	157	28
36	83	73
37	35	33
38	330	9
39	307	6
40	222	11
41	219	20
42	257	23
43	339	25
44	241	10
45	73	2
46	220	31
47	28	14
48	136	19
49	104	23
50	255	9
TOTALS		

--FLUTING2 6A

1	310	35
2	224	10
3	295	30
4	139	12
5	260	12
6	220	32
7	266	5
8	344	25
9	344	6
10	356	8
11	145	20
12	14	9
13	358	1
14	352	6
15	331	38
16	355	4
17	359	11
18	259	45
19	2	8
20	16	9
21	145	21
22	126	27
23	42	19
24	180	10
25	12	24
26	22	2
27	180	14
28	114	5
29	350	24
30	168	52
31	100	17
32	168	49
33	358	5
34	181	14
35	28	38
36	190	21
37	72	30
38	110	35
39	189	2
40	91	1
41	158	25
42	212	18
43	71	21
44	221	10
45	181	26
46	35	3
47	204	6
48	124	28
49	215	9
50	195	11
TOTALS		

--FLUTING2 SITE1

1	304	18
2	274	27
3	306	46
4	258	34
5	337	2
6	280	16
7	302	4
8	332	2
9	308	1
10	360	0
11	322	2
12	258	2
13	288	28
14	310	0
15	290	36
16	286	26
17	298	2
18	286	11
19	308	42
20	292	32
21	292	30
22	274	6
23	8	28
24	258	42
25	286	38
26	308	25
27	240	8
28	318	7
29	278	7
30	264	42
31	320	23
32	308	11
33	340	6
34	304	11
35	290	27
36	250	8
37	320	10
38	344	9
39	310	11
40	46	55
41	288	22
42	240	26
43	338	3
44	316	19
45	224	4
46	216	23
47	288	17
48	356	19
49	296	12
50	234	7
TOTALS		

--FLUTING2 SITE2

1	236	7
2	358	10
3	354	7
4	356	40
5	276	16
6	346	15
7	268	2
8	6	20
9	340	30
10	264	18
11	276	32
12	290	36
13	314	11
14	266	5
15	342	28
16	240	18
17	288	37
18	274	28
19	264	56
20	260	13
21	208	16
22	356	30
23	284	18
24	296	20
25	14	12
26	276	4
27	274	10
28	288	10
29	262	6
30	262	35
31	268	4
32	228	6
33	14	36
34	12	2
35	250	3
36	264	13
37	292	13
38	267	12
39	274	12
40	276	6
41	308	23
42	264	5
43	296	6
44	286	6
45	276	60
46	254	17
47	276	8
48	256	25
49	248	12
50	264	6
TOTALS		

FLUTING2 SITE3

1	308	2
2	248	11
3	307	10
4	234	6
5	264	7
6	280	10
7	23	45
8	204	2
9	298	11
10	222	7
11	222	8
12	282	6
13	270	30
14	216	6
15	22	10
16	276	0
17	264	8
18	307	6
19	290	6
20	274	3
21	278	30
22	348	12
23	290	16
24	304	16
25	267	22
26	314	3
27	268	18
28	320	25
29	256	15
30	262	8
31	262	6
32	260	16
33	290	53
34	320	29
35	256	16
36	300	11
37	256	40
38	326	28
39	290	2
40	282	2
41	268	25
42	284	15
43	356	25
44	232	4
45	0	0
46	260	26
47	12	10
48	347	25
49	250	4
50	204	28
TOTALS		

--FLUTING2 SITE4

1	316	45
2	276	50
3	26	2
4	318	49
5	266	18
6	7	60
7	327	33
8	258	6
9	348	64
10	228	36
11	348	40
12	298	12
13	326	52
14	314	40
15	348	21
16	280	2
17	256	54
18	256	40
19	298	6
20	354	24
21	256	74
22	180	45
23	266	15
24	304	2
25	359	30
26	172	4
27	0	36
28	240	25
29	308	7
30	258	30
31	166	50
32	334	35
33	248	36
34	328	27
35	338	8
36	180	49
37	316	25
38	176	34
39	296	44
40	234	32
41	270	30
42	354	37
43	204	37
44	344	22
45	144	44
46	186	45
47	286	14
48	266	13
49	286	10
50	265	2
TOTALS		

--FLUTING2 SITE5

1	304	40
2	232	4
3	246	8
4	278	8
5	244	2
6	164	3
7	188	20
8	224	35
9	280	4
10	306	6
11	280	36
12	348	16
13	0	11
14	8	12
15	274	4
16	282	22
17	4	20
18	12	11
19	300	22
20	144	58
21	174	5
22	169	11
23	156	64
24	359	16
25	232	14
26	2	22
27	278	21
28	268	6
29	336	31
30	340	16
31	340	14
32	338	12
33	254	38
34	176	28
35	174	41
36	244	4
37	296	16
38	334	11
39	190	12
40	286	12
41	333	24
42	180	30
43	334	11
44	304	10
45	158	14
46	210	60
47	340	5
48	192	2
49	278	47
50	342	47
TOTALS		

--FLUTING2 SITE6

1	354	15
2	20	6
3	216	42
4	25	15
5	196	18
6	46	10
7	36	36
8	354	4
9	26	21
10	238	6
11	38	16
12	224	11
13	286	11
14	16	10
15	250	11
16	264	28
17	254	3
18	328	32
19	248	26
20	68	15
21	244	20
22	296	28
23	354	20
24	327	10
25	202	21
26	48	11
27	288	21
28	244	11
29	227	17
30	262	6
31	225	16
32	208	11
33	238	6
34	254	12
35	355	22
36	296	18
37	34	28
38	268	5
39	270	32
40	260	16
41	244	7
42	276	5
43	250	2
44	228	12
45	238	20
46	256	6
47	274	2
48	256	20
49	248	2
50	244	6
TOTALS		

--FLUTING2 SITE7

1	226	5
2	226	5
3	274	4
4	344	6
5	256	4
6	280	7
7	276	3
8	4	2
9	258	3
10	316	10
11	276	4
12	236	15
13	276	5
14	286	4
15	268	10
16	280	5
17	280	3
18	256	5
19	246	16
20	255	11
21	250	26
22	296	22
23	256	4
24	24	7
25	282	3
26	240	3
27	16	8
28	248	2
29	18	3
30	214	4
31	342	16
32	262	2
33	278	4
34	188	3
35	274	2
36	276	6
37	286	11
38	256	2
39	248	22
40	260	18
41	284	26
42	276	0
43	308	6
44	286	12
45	18	6
46	225	15
47	236	8
48	310	12
49	256	4
50	256	8
TOTALS		

--FLUTING2 SITE8

1	294	12
2	358	35
3	338	19
4	6	20
5	286	4
6	226	20
7	16	0
8	346	52
9	6	42
10	12	30
11	286	5
12	8	13
13	358	20
14	296	7
15	359	5
10	276	26
17	356	10
18	336	14
19	286	3
20	276	6
21	16	29
22	28	46
23	214	6
24	22	11
25	356	49
26	156	20
27	236	20
28	359	52
29	14	4
30	248	2
31	16	23
32	276	11
33	236	8
34	236	6
35	236	15
36	324	29
37	240	6
38	296	14
39	358	18
40	27	30
41	196	19
42	176	12
43	216	14
44	236	11
45	196	24
46	296	19
47	354	25
48	256	10
49	196	4
50	229	10
TOTALS		

--FLUTING3 1A

1	178	27
2	318	4
3	136	2
4	318	3
5	120	17
6	20	29
7	134	19
8	352	8
9	167	21
10	210	30
11	340	2
12	182	10
13	330	48
14	342	7
15	335	37
16	40	6
17	346	6
18	156	31
19	175	15
20	368	2
21	38	4
22	176	21
23	262	29
24	210	32
25	130	22
26	150	15
27	324	16
28	134	26
29	135	9
30	119	13
31	341	6
32	10	25
33	342	1
34	205	47
35	84	30
36	170	12
37	195	31
38	200	16
39	284	0
40	318	2
41	316	8
42	176	15
43	165	14
44	27	7
45	258	66
46	164	25
47	116	7
48	335	19
49	208	15
50	11	26
TOTALS		

--FLUTING3 2A

1	333	30
2	337	29
3	323	20
4	352	28
5	147	8
6	152	23
7	142	4
8	251	31
9	304	25
10	320	14
11	282	2
12	290	39
13	116	1
14	305	44
15	140	17
16	158	44
17	126	3
18	125	6
19	342	11
20	324	28
21	336	11
22	327	34
23	175	14
24	138	2
25	298	40
26	75	22
27	316	14
28	326	64
29	349	21
30	335	14
31	156	11
32	114	6
33	299	28
34	301	24
35	315	16
36	326	37
37	322	24
38	131	4
39	304	45
40	322	14
41	326	5
42	295	24
43	296	29
44	310	20
45	305	33
46	320	17
47	346	22
48	117	14
49	302	13
50	154	14
TOTALS		

--FLUTING3 3A

1	192	22
2	311	1
3	191	27
4	168	18
5	192	30
6	197	12
7	229	29
8	268	12
9	183	44
10	338	28
11	262	42
12	210	50
13	198	37
14	94	20
15	189	26
16	140	55
17	184	26
18	15	17
19	187	40
20	192	32
21	194	41
22	220	42
23	166	29
24	41	6
25	182	25
26	74	1
27	191	9
28	278	37
29	171	19
30	185	30
31	60	30
32	181	50
33	195	35
34	252	13
35	191	50
36	338	20
37	191	8
38	190	17
39	146	19
40	208	26
41	193	31
42	101	37
43	101	10
44	195	54
45	161	38
46	357	15
47	336	23
48	220	36
49	332	23
50	2	40
TOTALS		

--FLUTING3 4A

1	282	28
2	193	22
3	145	32
4	342	17
5	165	4
6	284	25
7	197	45
8	104	20
9	248	33
10	163	13
11	13	60
12	156	3
13	194	21
14	307	65
15	191	7
16	358	30
17	295	11
18	324	1
19	196	14
20	197	40
21	331	14
22	318	10
23	90	17
24	220	42
25	247	12
26	320	6
27	275	17
28	304	1
29	137	5
30	284	10
31	277	10
32	225	63
33	325	1
34	260	21
35	41	10
36	100	21
37	227	15
38	334	14
39	299	40
40	320	5
41	177	24
42	123	20
43	273	21
44	199	30
45	273	3
46	155	9
47	315	12
48	129	14
49	195	28
50	173	12
TOTALS		

--FLUTING3 SITEA

1	336	40
2	304	56
3	260	26
4	4	36
5	258	49
6	278	4
7	240	16
8	250	6
9	344	34
10	308	17
11	240	28
12	350	9
13	316	4
14	326	42
15	336	48
16	322	49
17	8	28
18	233	5
19	348	26
20	344	45
21	350	26
22	267	22
23	280	26
24	280	5
25	314	48
26	194	53
27	264	13
28	298	17
29	308	12
30	240	13
31	238	48
32	2	26
33	347	16
34	318	11
35	234	43
36	306	63
37	300	58
38	236	37
39	334	32
40	334	7
41	318	38
42	278	8
43	206	16
44	358	32
45	357	6
46	270	63
47	350	36
48	340	58
49	338	22
50	316	14
TOTALS		

--FLUTING3 SITEB

1	226	38
2	278	6
3	182	5
4	296	2
5	336	32
6	6	10
7	256	9
8	278	2
9	276	12
10	22	16
11	356	56
12	304	5
13	346	35
14	314	7
15	320	24
16	304	22
17	218	15
18	330	26
19	240	42
20	340	11
21	256	15
22	356	46
23	320	13
24	276	44
25	248	6
26	352	6
27	188	34
28	334	42
29	2	45
30	324	22
31	345	28
32	300	14
33	258	15
34	336	22
35	316	18
36	216	20
37	246	22
38	280	10
39	316	6
40	308	8
41	320	28
42	216	48
43	34	6
44	328	41
45	358	8
46	296	2
47	320	42
48	286	18
49	236	4
50	298	30
TOTALS		

FLUTING3 SITEC

1	324	21
2	348	15
3	36	20
4	336	0
5	324	22
6	324	6
7	316	3
8	276	22
9	342	10
10	0	33
11	22	8
12	28	10
13	308	7
14	40	11
15	298	24
16	296	7
17	280	16
18	308	11
19	327	6
20	320	6
21	316	4
22	0	32
23	358	4
24	340	6
25	336	0
26	342	26
27	306	0
28	34	8
29	2	22
30	326	15
31	236	42
32	296	22
33	268	26
34	314	20
35	344	29
36	356	0
37	356	8
38	234	10
39	340	15
40	346	16
41	340	15
42	328	25
43	308	22
44	8	14
45	322	28
46	290	2
47	276	25
48	266	22
49	316	0
50	356	20
TOTALS		

--FLUTING3 SITED.

1	242	4
2	304	12
3	4	32
4	278	34
5	346	32
6	294	24
7	232	3
8	348	29
9	280	27
10	244	11
11	219	48
12	264	21
13	248	34
14	248	16
15	240	5
16	244	6
17	354	35
18	264	3
19	248	3
20	264	4
21	218	10
22	254	12
23	216	16
24	246	34
25	264	42
26	248	26
27	274	21
28	258	21
29	234	28
30	256	11
31	282	22
32	254	20
33	260	16
34	242	17
35	262	3
36	12	28
37	276	6
38	244	18
39	0	90
40	48	32
41	264	12
42	248	25
43	260	3
44	238	4
45	246	12
46	232	24
47	254	4
48	322	46
49	232	12
50	286	14
TOTALS		

--FLUTING3 SITEE

1	316	15
2	256	7
3	304	56
4	286	3
5	254	8
6	276	7
7	354	14
8	248	8
9	262	10
10	338	30
11	262	4
12	264	17
13	356	43
14	284	6
15	14	46
16	280	8
17	232	13
18	214	38
19	348	66
20	216	25
21	228	28
22	218	7
23	268	6
24	266	32
25	278	6
26	276	18
27	276	7
28	264	45
29	296	5
30	6	8
31	266	3
32	266	10
33	262	3
34	280	16
35	274	7
36	266	10
37	290	2
38	284	2
39	336	4
40	334	4
41	288	10
42	14	70
43	290	36
44	266	3
45	198	44
46	300	43
47	268	44
48	296	38
49	304	48
50	278	27
TOTALS		

--FLUTING3 SITEG

1	306	45
2	256	55
3	276	25
4	266	25
5	304	25
6	260	12
7	262	22
8	288	12
9	286	2
10	314	46
11	308	16
12	280	25
13	286	35
14	276	30
15	276	18
16	314	12
17	340	12
18	318	24
19	274	20
20	296	13
21	286	6
22	302	15
23	324	24
24	248	20
25	276	28
26	266	6
27	286	24
28	266	40
29	196	26
30	206	16
31	302	3
32	300	20
33	266	20
34	230	2
35	296	11
36	0	90
37	216	30
38	290	2
39	274	30
40	256	2
41	298	22
42	276	33
43	288	40
44	218	14
45	334	20
46	300	16
47	248	15
48	8	16
49	272	6
50	300	28
TOTALS		

--FLUTING3 SITEH

1	346	12
2	244	38
3	240	7
4	356	15
5	14	24
6	330	15
7	324	15
8	308	10
9	326	42
10	344	13
11	340	24
12	18	0
13	344	27
14	26	45
15	342	10
16	32	7
17	326	29
18	314	33
19	332	20
20	314	42
21	330	25
22	324	23
23	6	55
24	284	6
25	358	12
26	358	26
27	342	28
28	4	8
29	292	42
30	347	20
31	22	6
32	4	10
33	324	7
34	290	30
35	40	30
36	296	3
37	356	26
38	12	22
39	52	5
40	214	5
41	4	10
42	22	24
43	12	3
44	347	20
45	348	30
46	332	35
47	278	2
48	352	26
49	276	24
50	302	35
TOTALS		