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Genesis of the North Battleford Fluting Field, West-Central Saskatchewan

by

Nancy M. Grant ©

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

Department of Earth and Atmospheric Sciences

Edmonton, Alberta
Spring 1997

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled The Genesis of the North Battleford Fluting Field, West-Central Saskatchewan submitted by Nancy Margaret Grant in partial fulfillment of the requirements for the degree of Master of Science.

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Dr. Thian Yew Gan

Jan 6 1997

To my father Garry Grant (1932-1995) for picking up rocks with me when I was a child and clearing sections with me for my research.

Abstract

The North Battleford fluting field is located on the western edge of the Saskatchewan Plains in a large embayment in the Missouri Coteau. The distinct ridges and grooves of the fluting field begin at the upflow facing rim of the North Saskatchewan River valley and continue in a narrow zone 50 km toward the southeast, transverse to the direction of regional ice flow. Based on sedimentological and geomorphological observations, it is interpreted that the North Battleford fluting field has an erosional origin, and that the erosive agent was the large-scale, turbulent flow of subglacial meltwater. The regional-scale flood event also eroded a broad, almost featureless plain adjacent to the fluting field and discontinuous channels and hummocks at the northern wall of the embayment in the Missouri Coteau. Lobate gravel deposits and associated zones of intense scouring in central Saskatchewan were also produced by a subglacial sheet flow of meltwater. The smaller scale event occurred during the final deglaciation of the area as subglacial meltwater issued from the margin of the retreating ice sheet. Sheet flows of subglacial meltwater were a recurring and significant geomorphic agent in the evolution of the prairie landscape.

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Chapter 1

INTRODUCTION

Location of the Study Area

Saskatchewan is located within the Interior Plains of North America which extend westward from the Canadian Shield to the Rocky Mountains. Elevations range from 250 m above sea level in southern Manitoba to more than 1200 m above sea level on the plains near the Rocky Mountains. The generally gradual rise to the west is broken by pronounced escarpments or "prairie steps". These generally northwest-southeast trending escarpments are remnants of the preglacial land surface. The two most prominent are the Manitoba Escarpment, which rises 300 m above the Manitoba Plain in the east, separating it from the Saskatchewan Plain, and the Missouri Coteau which rises 100 m above the Saskatchewan Plain. The Alberta Plain extends from the Missouri Coteau to the Rocky Mountains in the west. The Saskatchewan Plain, which lies between 400 and 800 m a.s.l., has a drift blanket that varies in thickness between 30 and 120 m. Much of the region, however, has a drift blanket of 90 to 120 m in thickness, particularly in areas adjacent to the North Saskatchewan River (Klassen, 1989). The study area for this research lies on the western edge of the Saskatchewan Plain (Fig. 1-1). The study area encompasses a 200-kilometre zone trending northwest to southeast from the North Saskatchewan River at North Battleford to the Rural Municipality of Wolverine east of Saskatoon. The area is covered by National Topographic Series Maps 72 P/13 and P/14, and 73 A/3, A/4, B/2, B/5, B/6, B/7, B/12, B/13, C/9, C/16, F/1, and G/4, from approximately Latitude 53° 15'N Longitude 108° 30'W to Latitude 51° 45'N Longitude 105° 15'W.

Purpose of the Study

The primary objective of this research is to investigate the genesis of the fluting field in the North Battleford area of Saskatchewan. To achieve this, the specific objectives are:

1. To investigate the relationship between the morphology of the fluting field and the

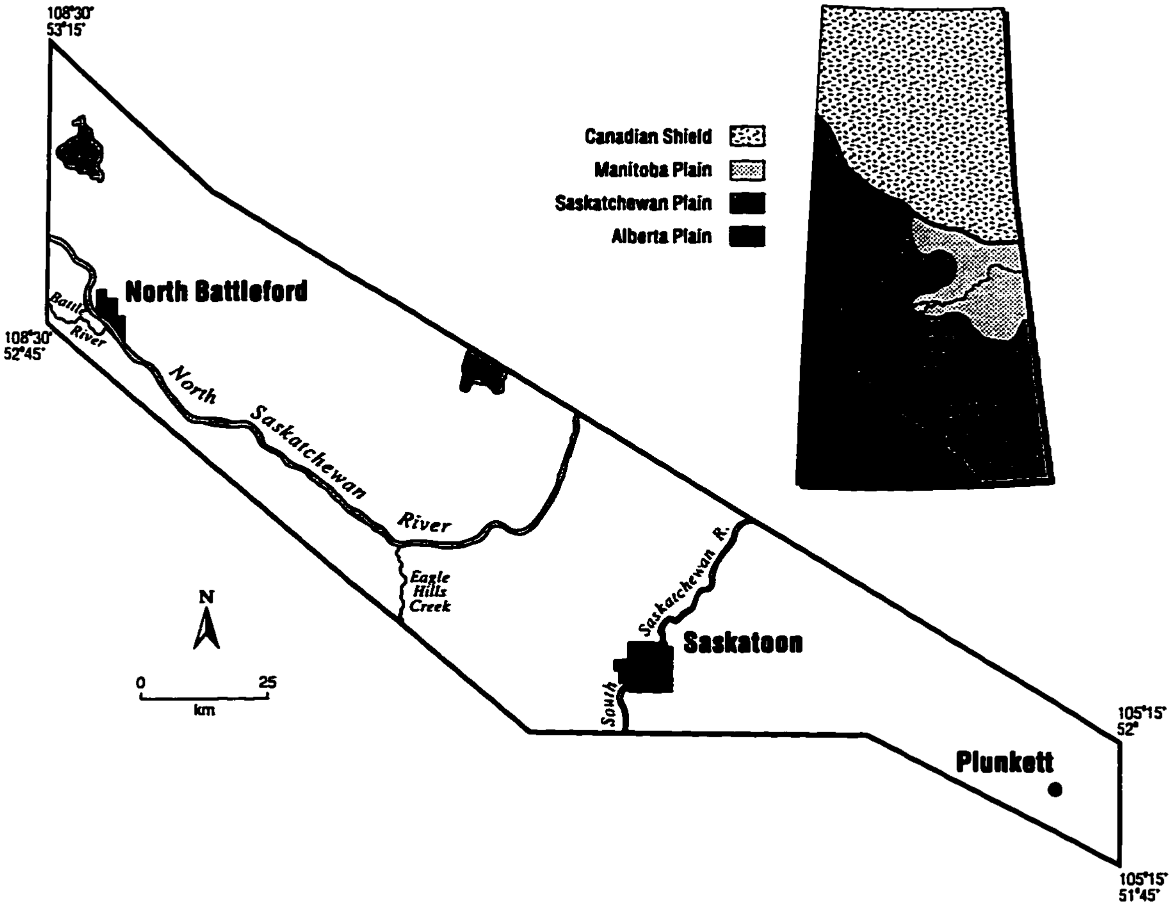

Figure 1-1. Location map of the study area.

internal structure of the fluting ridges.

2. To investigate the spatial and genetic relationship between the fluting field and other associated landforms.
3. To test the subglacial meltwater flood hypothesis as a significant geomorphic agent on the prairie landscape.

A secondary objective of this research is to investigate the origins of extensive gravel deposits in the southeast portion of the study area and to determine their relationship to the surrounding terrain.

Methodology

Field work

The investigation of the North Battleford fluting field is based primarily on the detailed inspection of aerial photography and the examination of field exposures and previously conducted well log and bore hole studies. Prior to the completion of field work during the summer of 1994, preliminary geomorphologic maps of the study area were produced using 1:80,000 stereoscopic aerial photography and 1:20,000 photomaps. The identification of landform suites and the associations between them were used to gain a regional scale perspective and to determine the areas of greatest geomorphic relevance for detailed field investigation. Field work consisted of extensive ground truthing for the production of geomorphological maps, the examination of available exposures in gravel pits, borrow pits, and ditches, the backhoe excavation of selected sites of particular interest, and the recording of surface materials. Where appropriate, sand and gravel deposits were collected for sieve analysis.

Laboratory analyses

Samples were collected from sand and gravel deposits for grain size analysis to aid in the interpretation of depositional environments (refer to the appendix for data). Samples with grain sizes greater than 4.0 mm were manually sieved twice to measure the weights of 6.1 mm and 25.0 mm grain sizes. The remaining measurements were obtained by mechanically sieving a subsample of approximately 300 g. The grain size intervals were chosen to separate the samples into the gravel, sand, and silt and clay groups as defined by the Wentworth Size Classes (Table 1-1). The weight percentages of each sample were subsequently used to construct cumulative curves. The grain size diameters (ϕ) of the sample at the weight percentages of 5, 16, 25, 50, 75, 84, and 95 from the cumulative curves were used to calculate the mean size (Mz), standard deviation (σ_I), skewness (Sk_I), and kurtosis (K_G) using the equations developed by Folk (1966):

$$M_z = \frac{\phi 16 + \phi 50 + \phi 84}{3}$$

$$\sigma_I = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

$$S_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

$$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

Geological Setting

Bedrock geology and physiography

The geological setting is characterized by flat-lying to nearly flat-lying Upper Cretaceous Lea Park, Belly River, and Bearpaw Formations (Whitaker and Pearson, 1972). The Lea Park Formation is predominantly composed of dark grey marine shales. The noncalcareous, montmorillonitic, heavily consolidated marine silts and clays become sandier toward the top of the unit. The overlying Belly River Formation consists of

Table 1-1. Grain size scale for sediments showing Wentworth size classes, equivalent phi and millimetre sizes. (Modified from Boggs, 1995.)

	Wentworth Size Class	Phi (ϕ)	Millimetres
GRAVEL	Boulder (-8 to -12 ϕ)	-12	4096
		-10	1024
		-8	256
	Cobble (-6 to -8 ϕ)	-6	64
		-4	16
	Pebble (-2 to -6 ϕ)	-2	4
		-1.75	3.36
	Granule	-1.5	2.83
		-1.25	2.38
		-1.0	2.00
SAND		-0.75	1.68
	Very coarse sand	-0.5	1.41
		-0.25	1.19
		0.0	1.00
		0.25	0.84
	Coarse sand	0.5	0.71
		0.75	0.59
		1.0	0.50
		1.25	0.42
	Medium sand	1.5	0.35
		1.75	0.30
		2.0	0.25
		2.25	0.210
	Fine sand	2.5	0.177
		2.75	0.149
		3.0	0.125
		3.25	0.105
	Very fine sand	3.5	0.088
		3.75	0.074
		4.0	0.0625
SILT AND CLAY		4.25	0.053
	Coarse silt	4.5	0.044
		4.75	0.037
		5.0	0.031
	Medium silt	6.0	0.0156
	Fine silt	7.0	0.0078
	Very fine silt	8.0	0.0039
	Clay	9.0	0.0020
		>10.0	>0.00098

marine shales, sandstones, and minor coal seams. The Bearpaw Formation is primarily dark grey, silty shale with layers of bentonite. The study area is located in a broad embayment in the Missouri Coteau eroded by water flowing through the preglacial Battleford Valley. Consequently the area is underlain primarily by the Lea Park Formation because other formations were removed prior to glaciation (Fig. 1-2). Thick drift overlies the Lea Park Formation in this area. The main portion of the study area near North Battleford is contained within an embayment in the Missouri Coteau and is bounded on the southwest by the Eagle Hills and on the northeast by the Thickwood Hills. These consist of higher elevation, gently rolling plains with rolling to hilly ridges rising from 60 to 150 m above the surrounding country. Acton et al. (1960) refer to the area between the Eagle and Thickwood Hills as the Saskatchewan River Plain. It is described as gently undulating to rolling terrain with glacial, lacustrine, alluvial and aeolian plains (Fig. 1-3).

Drainage system

The modern drainage system flows primarily toward the east, conforming to the general slope of the Interior Plains region. The North Saskatchewan River, with its headwaters in the Rocky Mountains, is the only major river that flows through the study area. It ultimately empties into Hudson Bay via Lake Winnipeg and the Nelson River. Tributaries are few in number, though the most significant are the Battle River and Eaglehill Creek (Fig. 1-3). In addition to the primary drainage system, numerous small streams empty into local depressions and lakes where most of the water is lost to evaporation. Many of the streams only contain flowing water in spring or during periods of unusually high precipitation (Mitchell et al., 1947).

The preglacial drainage system developed on a regional land surface that sloped to the northeast. Rivers with headwaters in the Rocky Mountains carried debris towards Hudson Bay and the Arctic and North Atlantic oceans. The Pliocene Epoch was primarily a period of erosion as rivers shifted laterally away from their coarse channel deposits and deepened their valleys in easily eroded bedrock (Klassen, 1989). The drainage system of the southern Interior Plains consisted of a series of major northeast to east trending, regularly

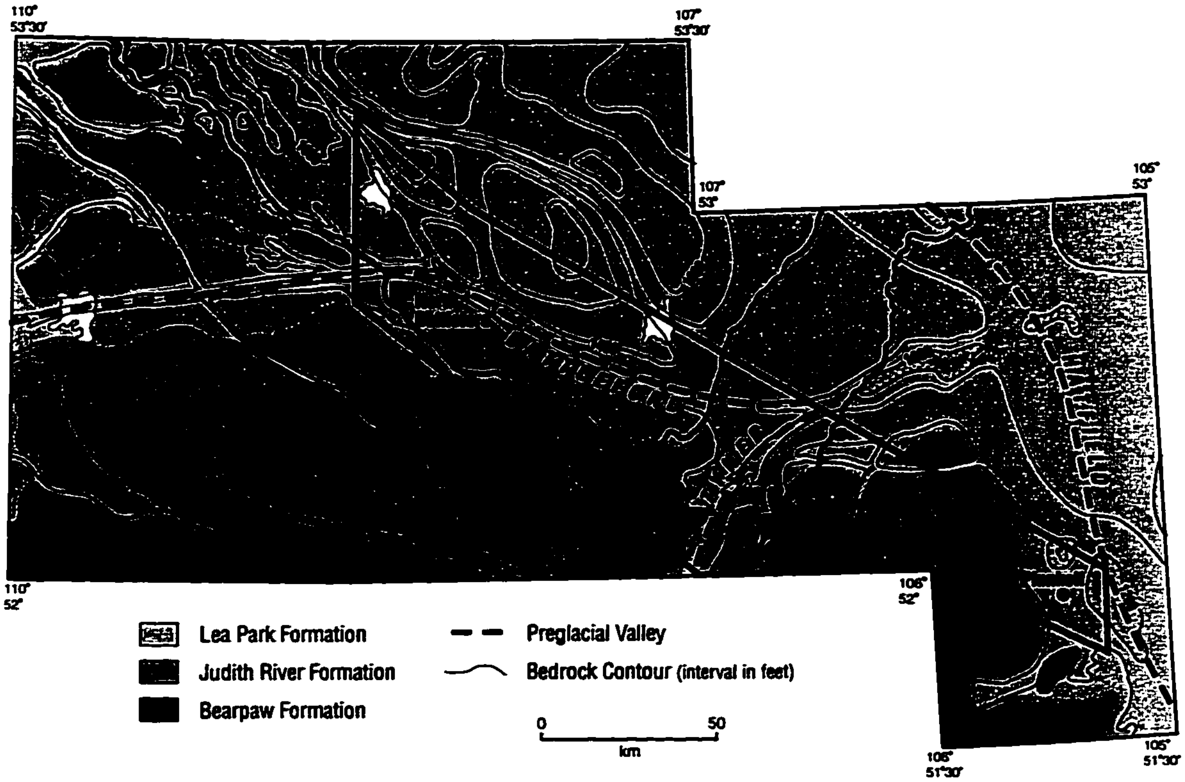

Figure 1-2. Geological map of the study area showing bedrock lithology, bedrock topography and preglacial valleys. Contour interval is 200 feet (61 m).

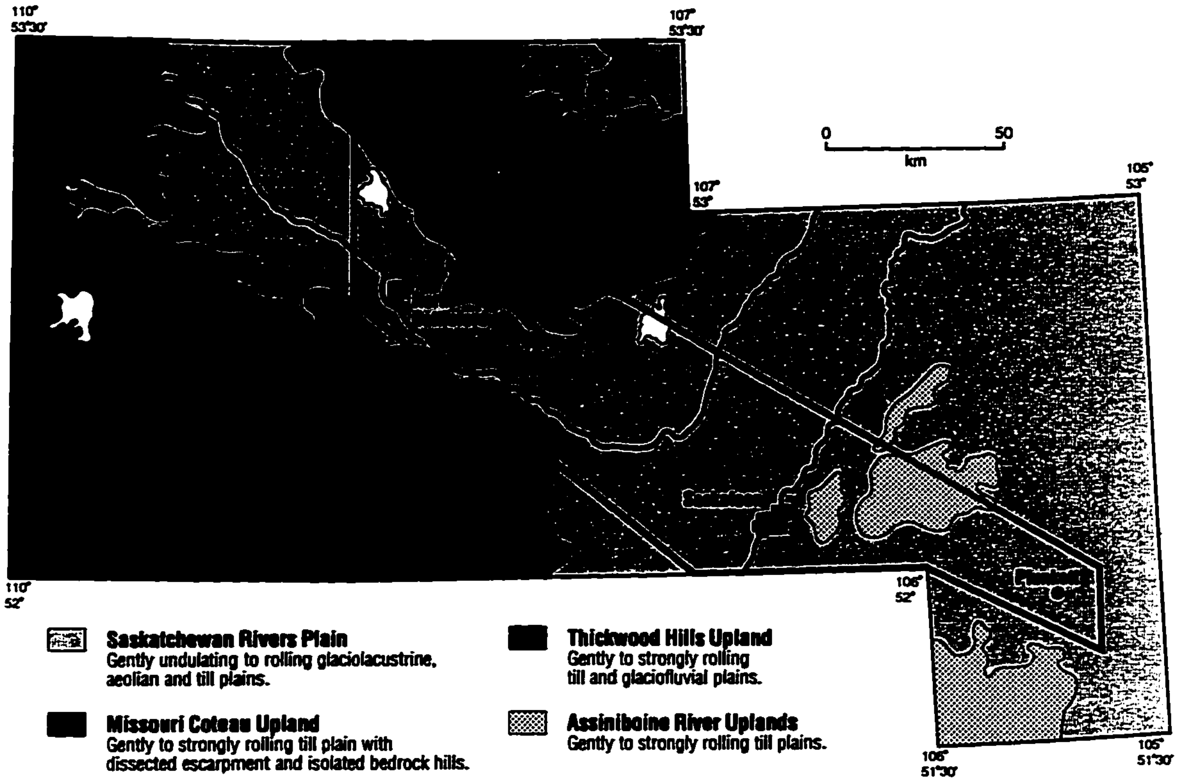

Figure 1-3. Physiography of the study area (modified from Acton et al., 1960).

spaced valleys which headed in the mountains and were separated by uplands capped with Tertiary sands and gravels (Fig. 1-2). Repeated episodes of glaciation resulted in the infilling of many of the existing valleys with till and other sediments and the creation of new basins by erosional processes associated with the overriding glacier. During interglacials, new valleys were cut across former uplands, glacially carved basins were occupied by lakes, and vast expanses of hummocky terrain developed unintegrated drainage systems. Some portions of the developing streams were reestablished in preglacial valleys while others flowed in new valleys that were created during glaciation (Klassen, 1989). The present drainage system, consequently, evolved in valleys that were used by rivers prior to glaciation, by meltwater that flowed under the glacier, by meltwater draining from retreating glaciers, by rivers that flowed during interglacials, and by rivers that have cut new valleys since the retreat of the last glacier to cover the area. The North Saskatchewan River and its main tributary, the Battle River, flow through segments of the preglacial Battleford Valley before it veers to the northeast (Christiansen, 1967).

Quaternary deposits

In all parts of the Saskatchewan Plains, most surficial materials date from the Quaternary Period. They were primarily deposited during episodes of Pleistocene glaciation near the limits of the ice where deposition dominated over erosion. Older drifts in Saskatchewan are preserved, though thick Late Wisconsin deposits comprise much of the surface. In the westernmost parts of the prairies, Late Wisconsin deposits are interpreted to directly overlie preglacial sands and gravels (Young et al., 1994). The distribution and character of these sediments are a reflection of bedrock topography and lithologies, patterns of ice flow, and the glacial processes that were active during the various phases of glaciation (Klassen, 1989).

Till is defined as sediment that has been transported and deposited by glacier ice with little or no fluvial sorting (Dreimanis and Lundqvist, 1984). Tills on the Saskatchewan Plains have a notably uniform composition due to their derivation mainly from the ubiquitous Cretaceous shale, siltstone and sandstone bedrock. Generally the tills of this region contain approximately equal amounts of clay, silt, and sand and only relatively minor amounts of coarser material. The predominance of fine grain sizes in the till indicates that erosion of the Interior Plains during glaciation was a very significant process. Most clasts in the till are resistant igneous and metamorphic rocks derived from the Precambrian Shield or carbonate rocks from the narrow band of Paleozoic rock that separates the Interior Plains from the Precambrian Shield. This relatively small, though significant, portion of the Quaternary deposits is locally important in determining the provenance of the deposits and patterns of ice flow (Klassen, 1989).

The commonly occurring glaciolacustrine deposits primarily consist of stratified to massive clay and silt. Sand and dropstones are a significant component in some areas, particularly where the glaciolacustrine deposits are associated with hummocky terrain (Klassen, 1989). Glaciolacustrine deposits are located in former basins of large glacial lakes and in numerous smaller basins. Beach ridges of sediment derived from the underlying till only formed along shorelines where large lakes were stable for long periods of time. In other lakes that did not achieve extended periods of stability or a large enough size, former margins are marked by wave eroded till. Glacial lakes formed with each advance and retreat of Pleistocene ice sheets as the regional drainage to the northeast was blocked (Klassen, 1989). Consequently, glacial lake sediments that were deposited with the final retreat of the Laurentide Ice Sheet are widespread over the surface of the Interior Plains. Older glacial lake sediments identified from boreholes constitute an important component of Quaternary valley fills and are commonly found as intertill sediments. Surficial geology maps (Campbell, 1987a, 1987b) provide information regarding Quaternary deposits throughout the study area (Fig. 1-4). Most of the surface materials are classified as either till or glaciolacustrine deposits. Glaciolacustrine deposits commonly occur as a thin veneer superimposed on or interspersed with till deposits.

Glaciofluvial deposits are also widespread in the Interior Plains. They consist of sands and gravels that are typically well sorted, moderately well washed and well stratified. Massive, slumped, or deformed deposits, however, are common. They are distinguishable from preglacial and interglacial deposits by their lithological composition. Glaciofluvial

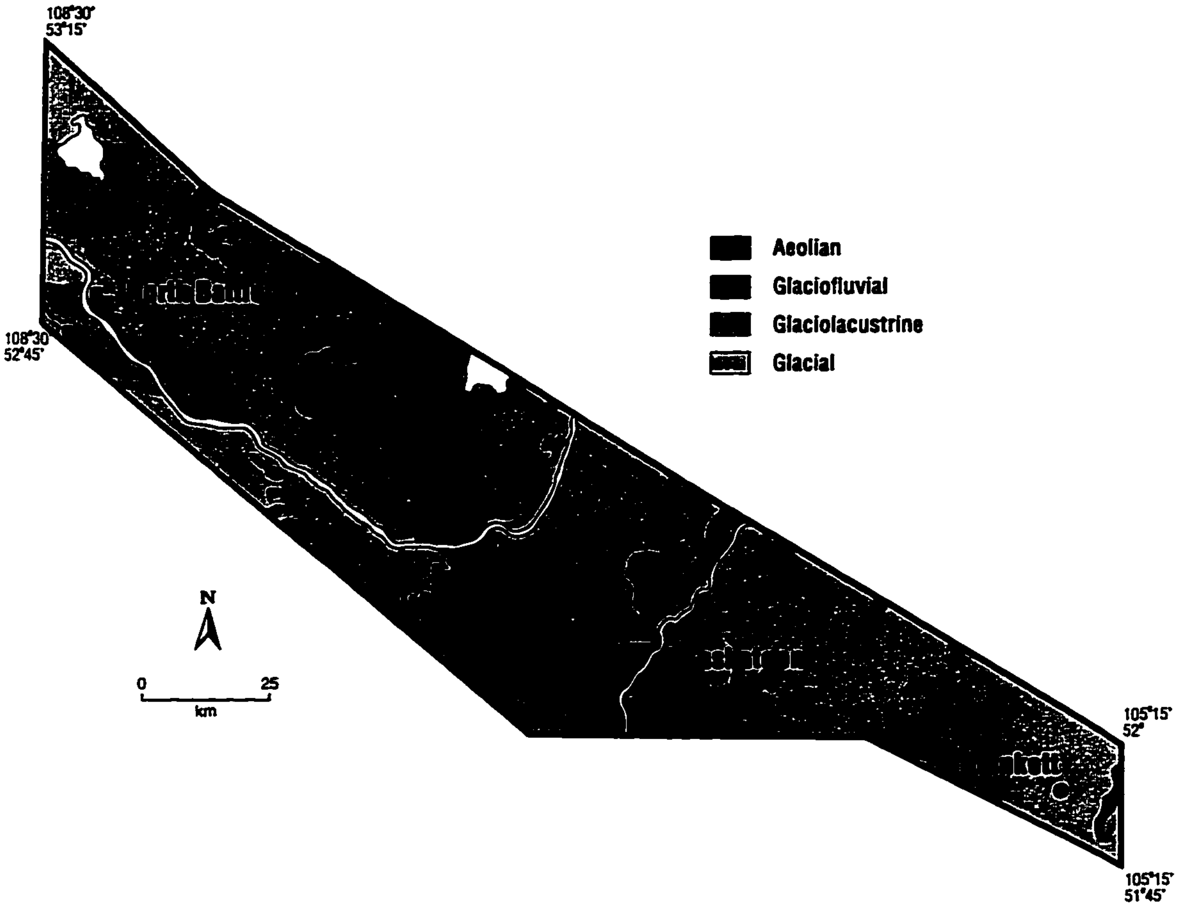

Figure 1-4. Surficial geology map of the study area.

deposits that were derived from till generally have a higher shale content than preglacial and interglacial deposits that were largely derived from sediment transported eastward from the Rocky Mountains. They are also more likely to show evidence of deformation (Klassen, 1989). Glaciofluvial deposits occur as distinct landforms including kames, eskers, deltas, fans, outwash trains, and kame and kettle complexes. Their development can, in most cases, be related to specific, well defined meltwater flow systems. Surficial geology maps (Campbell, 1987a, 1987b) of the study area indicate a relatively limited extent of disconnected glaciofluvial deposits in complexes of hummocky terrain where integrated drainage systems are not expected to form.

Nonglacial deposits are primarily attributed to processes active during the Holocene Epoch. They are most commonly found in valleys, in closed depressions that contain permanent or ephemeral lakes and ponds, and in areas where the vegetation cover and source of sediment supply are conducive to the formation of aeolian deposits. Holocene valley deposits in the study area are limited to small extents of alluvium and colluvium (Campbell, 1987a, 1987b). Gullied and slumped glacial deposits and alluvial plains and terraces can be identified in the modern valley of the North Saskatchewan River. Large and small depressions that originated with processes associated with glaciation occur throughout the study area and may or may not contain water. Jackfish, Scentgrass, Whitehill, and Radisson lakes are located in marginal areas of the study site and receive only locally derived water and sediment inputs. They contain thin lacustrine deposits and, in some areas, show minor development of organic deposits. Ephemeral lakes and sloughs are also abundant and frequently do not have sufficient water to completely fill their basins. Holocene sedimentation is very limited ensuring that the older Pleistocene deposits remain clearly discernible. Aeolian sediments composed of sand and silt cover a greater areal extent than any other Holocene deposits in the study area (Fig. 1-4). Sand and silt, originally deposited during the Pleistocene in association with deltas and other coarse glacial lake deposits, were subsequently reworked into dunes. The dunes became inactive with the establishment of a stabilizing vegetation cover.

Geomorphology

The regional geomorphology of the southern Interior Plains is largely a reflection of the underlying bedrock surface and the development of escarpments and scattered uplands. The smaller scale features superimposed on the underlying bedrock, on the other hand, that are found throughout the Prairie region, were predominantly formed by processes associated with glaciation. The Saskatchewan Plain is defined by the position of the Manitoba Escarpment in the east and the Missouri Coteau in the west and contains large areas of prominent uplands. The drift blanket covering the Saskatchewan Plain is generally much thicker than on the adjacent Alberta and Manitoba Plains (Klassen, 1989) giving features of the bedrock topography a more muted surface appearance (Fig. 1-5). Till deposits cover most of the study area in the form of morainal plains and hummocky moraines (Campbell, 1987a, 1987b) that may contain other important geomorphological features (Fig. 1-4).

Morainal plains may exhibit elements that are transverse or parallel to the inferred direction of ice flow or they may be low relief hummocky areas that have no evidence of directional elements. The topography is rolling to gently undulating with a relief of generally less than 10 metres. The ground moraine is traversed in some areas by small, shallow meltwater channels that carried flow toward the south or southeast. Other areas of morainal plains are characterized by a nonoriented topography of low relief hills and depressions or by more regularly patterned swell and swale topography. Of particular prominence are the linear and transverse elements. The portion of the study area contained in the embayment in the Missouri Coteau is notable for the well developed giant fluting field. The fluting field grades laterally into a zone of closely spaced transverse elements that is classified as washboard moraine on the surficial geology maps (Campbell, 1987a, 1987b). The sediments of the ground moraine are comprised primarily of till, though significant amounts of sand and gravel are associated with the giant fluting.

Higher relief hummocky moraine is better developed on the uplands that form the margins of the study area. Morainal hills, knolls, randomly oriented ridges and intervening

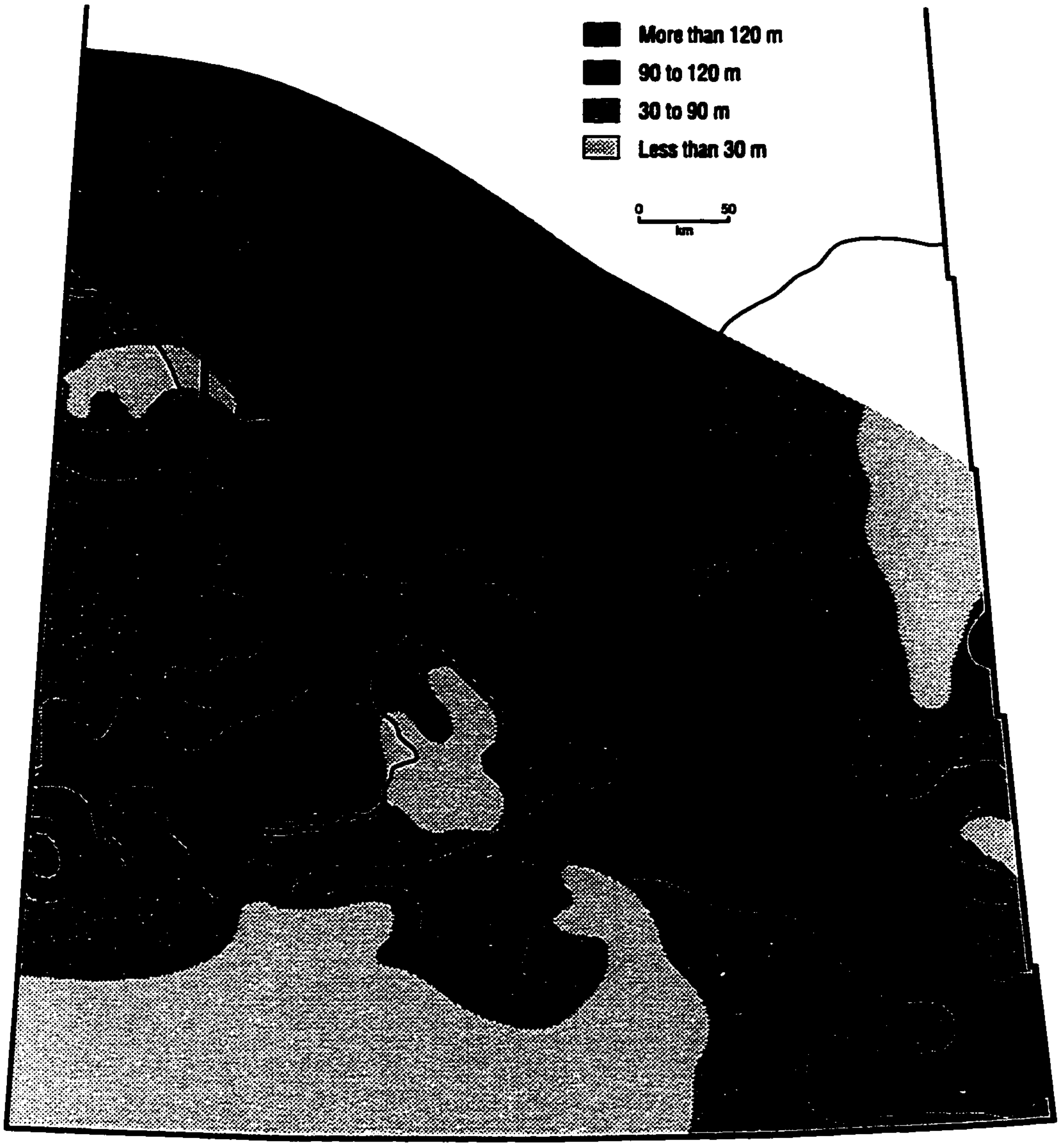

Figure 1-5. Drift thickness in southern Saskatchewan.
Modified from Klassen (1989).

depressions generally characterize high relief hummocky moraine. Surface patterns can range from regularly spaced knob and kettle topography to irregular hills and knolls with intervening depressions (Prest, 1968). Areas designated as hummocky moraine on surficial geology maps (Campbell, 1987a, 1987b) exhibit a broad scale lineation that trends from the northwest to the southeast. The high relief topography is created by a heavily eroded net of meltwater channels along the margins of the uplands that trend in a corresponding direction. Hummocky moraine is commonly composed of till that is similar to that of the adjacent ground moraine. Sand and gravel deposited or reworked by water, though, are significant components of some knolls and in places entire tracts of hummocky terrain are formed of glaciolacustrine silt and clay (Prest, 1968). The traditional explanation for morainal deposits is that they were largely shaped by various glacial processes during deglaciation as segments of the glacier margin stagnated. The thick deposits of drift in the area of the Missouri Coteau are attributed to the abundance of source material (Klassen, 1989). The Cretaceous bedrock of easily eroded shales in the escarpment face provided the flowing glaciers with abundant materials to form the very thick hummocky moraines in the area. The deposits may represent the accumulation of sediments during repeated episodes of glaciation (Klassen, 1989). Alternatively, Young et al. (1994) concluded that much of Alberta was only affected by a single, late Wisconsin ice sheet.

In the northwest portion of the study area, ground moraine and hummocky moraine are frequently overlain by lacustrine silts and clays. In some areas they form the dominant surface materials, while in others they exist in more integrated complexes with till deposits (Campbell, 1987a, 1987b). These deposits were laid down during the final retreat of the Laurentide Ice Sheet as a series of stages of glacial Lake Saskatchewan formed at the ice margin. Because this northwest extension of glacial Lake Saskatoon was relatively short-lived, the glaciolacustrine deposits are discontinuous and generally thin (Christiansen, 1979). The underlying geomorphic features that were formed while the land was still covered with ice remain as easily identifiable and significant elements of the landscape. The position of the main basin of glacial Lake Saskatchewan is marked by thicker, more extensive glaciolacustrine deposits. Their surface expression is the typical very flat, clay and silt deposits common to lake plains. Areas of hummocky and collapsed terrain, and deltaic and outwash deposits, however, are also in evidence (Campbell, 1987a, 1987b). Large areas of these coarser lake deposits were subsequently modified by aeolian processes. The eastern margin of the proglacial lake is marked as the predominantly flat lying lacustrine deposits grade into higher relief, undulating to rolling morainal deposits. The extreme southeast portion of the study area is characterized by extensive till and gravel deposits that are identified as hummocky moraine and ground moraine on surficial geology maps (Campbell, 1987a, 1987b). Elements that are transverse to the inferred direction of ice flow and meltwater channels comprise the primary geomorphic features in this area.

Glacial History

During periods of glaciation the Interior Plains were covered by continental ice sheets that consisted of a large complex of ice domes, divides, saddles, and lobes. The present understanding of the Laurentide Ice Sheet is based on the nature and distribution of sediments and landforms that result from glaciation. The complexity of the different factors that influenced the flow of ice and the lack of consensus regarding the geomorphic processes associated with continental ice sheets has resulted in conclusions that are frequently disjunct and contradictory. The difficulties that arise due to regional and local variations in physiography, climate and glacier bed conditions are compounded by the problems inherent in using flow features as indicators of ice movement. Patterns of glacier flow may or may not remain constant throughout a period of glaciation, flow features from earlier glaciations may be preserved despite subsequent glaciations, and material transported in one direction by early ice may be moved farther or in a different direction by later ice (Klassen, 1989).

Despite the difficulties, some general comments can be made regarding the style of retreat of late Wisconsin ice. The record of Pleistocene events in the Interior Plains region extends to the beginning of the Quaternary Period (Fulton et al., 1986) as continental ice sheets advanced several times from the Canadian Shield in the north and east across the region during the Pleistocene Epoch. The retreat of the Laurentide Ice Sheet likely began earliest in the west and south where large segments of the ice margin remained in contact with proglacial lakes for extended periods of time. Ice retreat was a dynamic process of repeated advances, development of lobes, shifting centres of flow and periodic surging, resulting in a complicated record of flow. In the Interior Plains the pattern of retreat of the downwasting ice was largely controlled by the bedrock topography. The chronology of glaciation in Saskatchewan (Christiansen, 1979; Clayton and Moran, 1982) has been interpreted from glacial deposits, landforms, drainage systems, glaciolacustrine stratigraphy, and radiocarbon dates. The series of ice marginal positions proposed by Christiansen (1965) are generalized and represent a stagnating zone of ice rather than a distinct ice front. Christiansen (1979) concluded that over time the glacier margin retreated at an ever increasing rate even though the volume of water released decreased with time. This suggests that much of the ice had melted before significant retreat of the ice occurred.

Christiansen (1979) describes a sequence of nine phases of advance, readvance, and retreat of the Laurentide Ice Sheet that comprises the deglaciation of southern Saskatchewan. Clayton and Moran (1982), in their chronology of Late Wisconsin glaciation in the Interior Plains, are largely in agreement with Christiansen (1979) in their configuration of the retreating ice sheet and the sequential development of glacial lakes and spillways. Discrepancy arises, however, in regard to the radiocarbon age of certain ice margin positions. The glacial maximum is placed in Montana and North Dakota at about 17 ka by Christiansen (1979) and at about 20 ka by Clayton and Moran (1982). The preglacial northeast drainage was disrupted by the overriding ice so that water drained through the Milk River system into the Missouri River. With deglaciation the prominent spillways that are common to the prairies began to form. The flow of meltwater eastward into glacial Lake Agassiz may have begun by 15.5 ka (Christiansen, 1979), but more likely did not occur until after 14 ka (Clayton and Moran, 1982). The ice front continued to retreat northward with its associated complex of rapidly changing proglacial lakes and

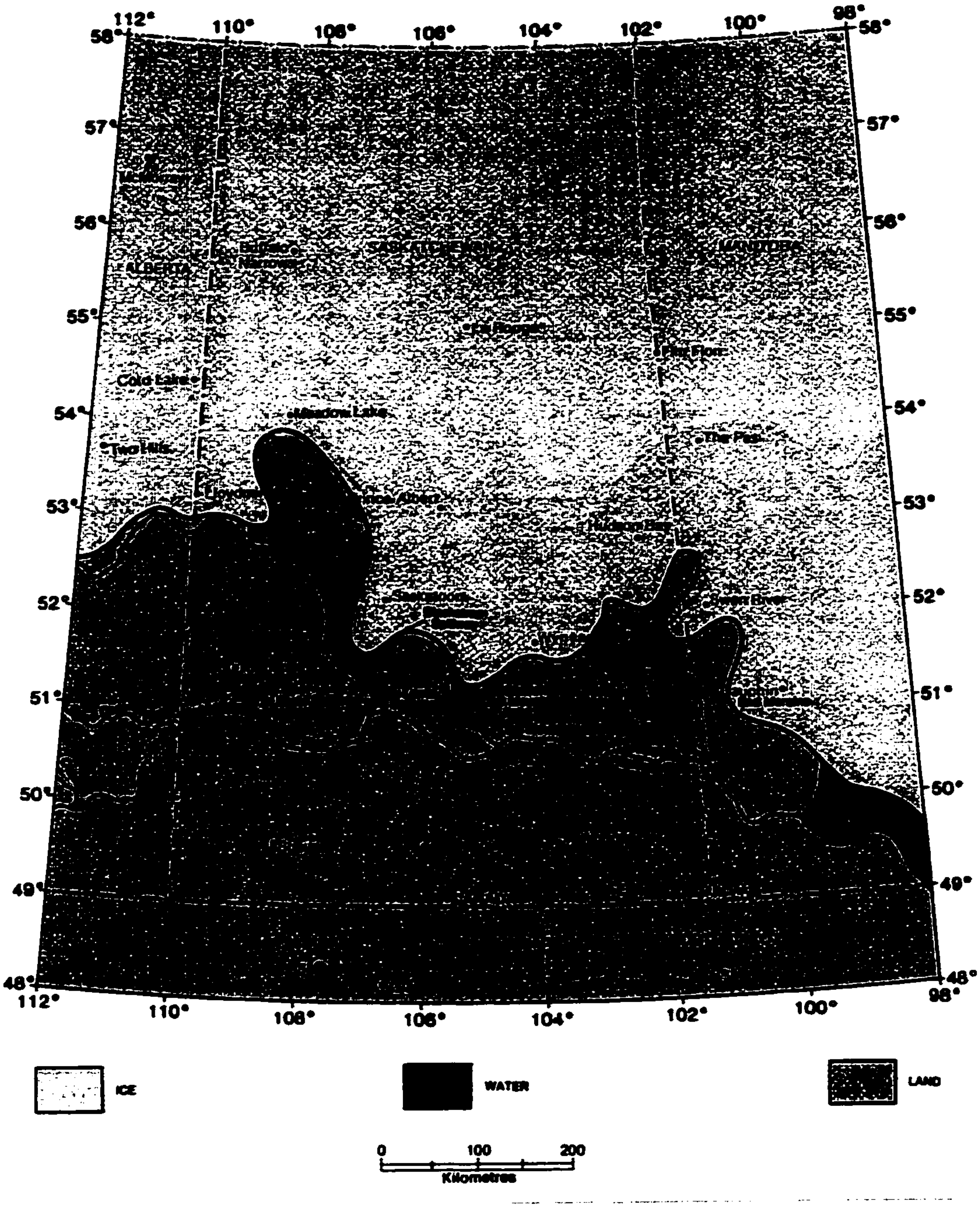

Figure 1-6a. Deglaciation of the northern portion of the study area (Christiansen, 1979).

spillways. By 12.5 ka (Christiansen, 1979) or 11.1 ka (Clayton and Moran, 1982) the area around North Battleford was ice-free as melting proceeded northwestward into the embayment of the Missouri Coteau (Fig. 1-6a). The uplands to the northeast and the southwest were free of ice while the intervening embayment still contained ice. The southeast portion of study area remained ice-covered. The northwestern reaches of glacial Lake Saskatchewan, fed by the ice marginal Battle Spillway, inundated the area. Sometime after 12 ka (Christiansen, 1979), glacial Lake Saskatchewan had retreated to the now ice-free Saskatoon area and was fed by the North Saskatchewan Spillway (Fig. 1-6b). With the final drainage of glacial Lake Saskatchewan all of the study area was free of ice and proglacial lakes and the modern North and South Saskatchewan Rivers were established as the main drainage system. Conditions similar to those of the present were established early in the Holocene. Immediately following deglaciation large expanses of unvegetated drift supplied ample sediment that led to the aggradation of streams and the development of terraces. Valleys that had carried glacial meltwater and those with gradients that were reduced by glacial isostatic adjustment experienced several brief episodes of downcutting and alluviation before the present drainage regimes were established.

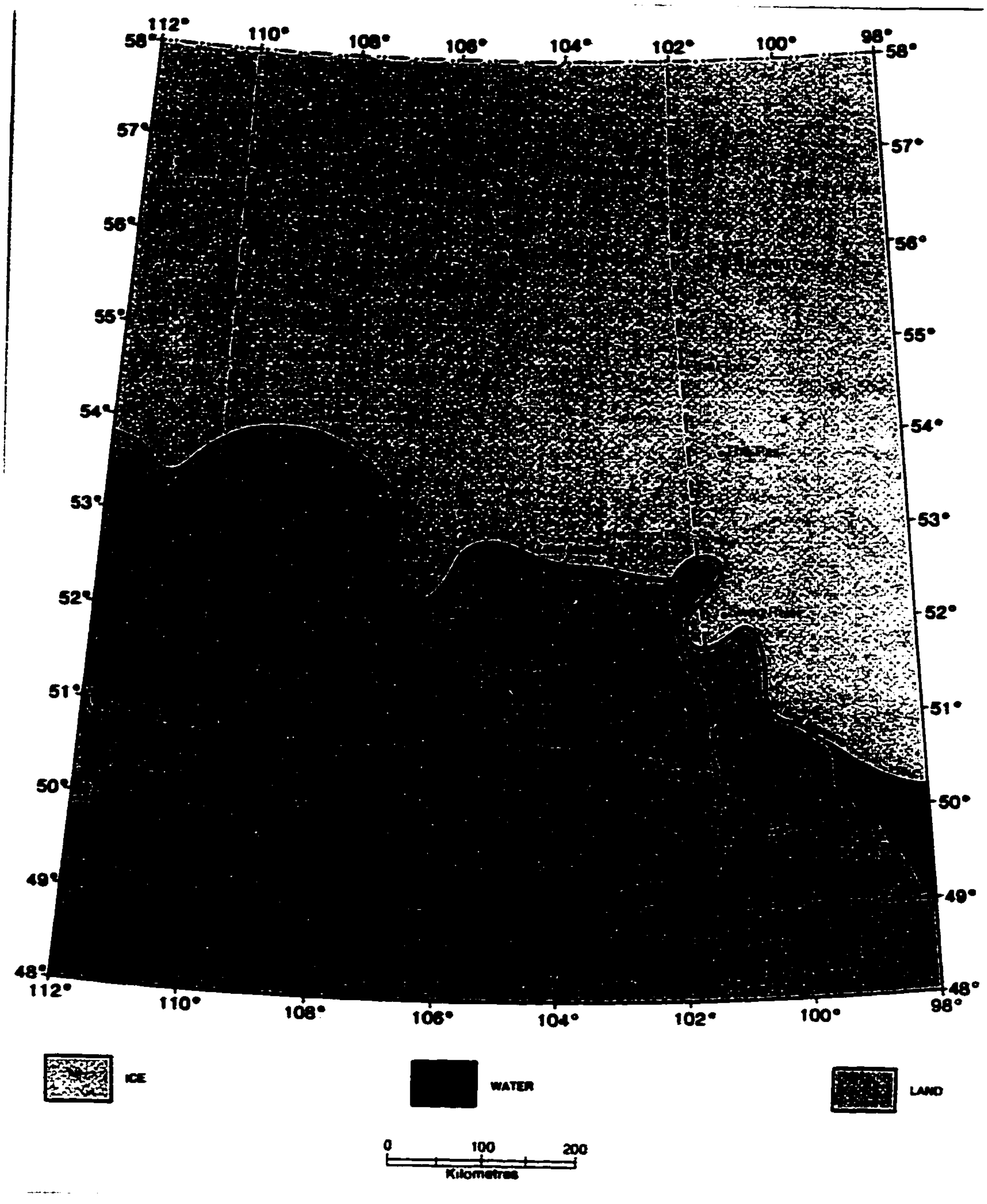

Figure 1-6b. Deglaciation of the southern portion of the study area (Christiansen, 1979).

Chapter 2

LITERATURE REVIEW

Introduction

Because a regional approach is taken in this thesis, it is necessary to consider all relevant aspects of the landscape to develop a meaningful understanding of its genesis. Therefore, the following comprehensive review of existing literature, that encompasses a variety of topics from different perspectives, is included. Regional work that includes the study area covers a wide range of literature ranging from a chronology of deglaciation in the region, to surface and subsurface geology, to interpretations of the development of specific features formed during glaciation. Because the North Battleford fluting field extends upstream into areas that have been investigated in Alberta, a brief review of this work is also included. More specifically, hypotheses of fluting formation are reviewed to facilitate the interpretation of the genesis of the North Battleford fluting field. Due to the abundance of published work regarding the formation of fluting, an exhaustive review is not feasible. Therefore, an overview of the main arguments that have been developed will be presented here. While much of the available literature suggests that fluting is a result of the direct action of overriding ice, more recent sources propose that catastrophically flowing subglacial meltwater played an integral role. Hummocky terrain is particularly well developed and widespread in the Interior Plains. Such terrain forms an important component of the landscape in the study area where it exists in close association with the fluting field. While numerous hypotheses have been developed to explain its diverse nature, distribution, and origin, it is the hypothesis of subglacial meltwater drainage that provides a possible unifying mechanism of landscape formation that may link various features in the study area. A review of the development of the subglacial meltwater theory, therefore, is also included.

Regional Literature

Christiansen (1979) developed a chronology of the Late Wisconsin deglaciation of southern Saskatchewan based on the distribution of surficial deposits and glacial landforms. Ridged moraine, ice thrust moraine, end moraine, ice-marginal channels and spillways, glacial lake basins and glacial fluting were identified and used to determine the configuration and position of the ice sheet during its final retreat. Deglaciation on the Interior Plains proceeded primarily by down-melting of marginal ice in a succession of nine phases (Christiansen, 1979). The absolute chronology was based on a limited number of radiocarbon dates obtained for a variety of organic materials. Phase 1, dated at 17 ka, began with the margin of the ice sheet at its maximum extent near the southern border of Saskatchewan. Other researchers are in close agreement with Christiansen (1979) regarding the position of the ice margin and the chronology, though there is discrepancy in the time of the maximum extent of the ice sheet and its initial retreat. Clayton and Moran (1982) placed the glacial maximum at 20 ka, where it remained until as late as 12 ka. The ages are based on the detailed analysis of only the most reliable radiocarbon dated wood samples. Klassen (1995) documented a sequence of retreat and advance phases in the Cypress Hills area in southwestern Saskatchewan between the time of its maximum extent at 18 ka to its last retreat from the region at about 13 ka. These are minimum ages based on the radiocarbon dates determined for postglacial sediments.

It was not until phase 5, dated at 12.5 ka (Christiansen, 1979, fig. 1-6a), that the North Battleford area became ice-free as the glacier continued to retreat to the northeast. Kehew and Teller (1994) alternatively suggest an ice margin in the same general area between 11 and 10 ka. During phase 5 (Christiansen, 1979), the uplands of the Missouri Coteau south of the study area were ice-free, while ice persisted in portions of the uplands to the north and northwest. Ice retreat generally proceeded toward the northeast, though Christiansen (1979) depicted a southeast trending lobe of ice northwest of the study area. It was not explicitly stated, but it is presumed that the position of the lobe was based on the presence of glacial fluting and ridged moraine in the North Battleford area. These types of landforms were used as interpretive tools in determining the direction of ice flow and the position of former ice margins, respectively. Glacial fluting on the Interior Plains was interpreted to have formed by erosional processes at the base of the moving glacier such that the trend of the ridges and grooves will be parallel to the direction of ice movement (Christiansen, 1979). Ridged moraine was described as minor, subparallel arcuate ridges with intervening swales of till. The orientation of the ridges was considered to be parallel to the position once occupied by the ice margin (Christiansen, 1979).

Phase 5 of the deglaciation of Saskatchewan (Christiansen, 1979) was also defined by the evolving system of glacial lakes and spillways that formed at the ice margin. A series of glacial lakes was created as meltwater was dammed at successively lower levels as the ice margin retreated. Christiansen (1979) deduced shifting lake levels from the position of strandlines, deltas, outlet spillways, and boundaries between lacustrine deposits and surrounding till. In addition to the developing extraglacial drainage system south of the ice margin, meltwater from the ice sheet flowed through the Battle Spillway and glacial Lake Saskatchewan to its eventual destination in glacial Lake Agassiz. Glacial Lake Saskatchewan was a long-lived lake that existed in various phases that were controlled by the position of the ice margin and local topography. Kehew and Teller (1994) also suggested that isostatic adjustment was a significant factor in the development of the ice-marginal environment. During phase 5, the Battle Spillway drained into a northern arm of the proglacial lake that extended into the main portion of study area. Meltwater did not flow through the North Saskatchewan Spillway until the ice retreated from the area to the northwest of the study area during phase 6 (Christiansen, 1979, fig. 1-6b). By the time of phase 6, the northern arm of glacial Lake Saskatchewan had drained leaving a smaller lake in the area of present-day Saskatoon and the establishment of the modern North Saskatchewan River in the North Battleford area. In addition, the Vermilion Spillway, west of the Alberta-Saskatchewan border, merged with the North Saskatchewan Spillway to connect glacial Lake Saskatchewan with the Bruderheim phase of glacial lake development in north-central Alberta (St. Onge, 1972).

The sediments deposited in Saskatchewan during episodes of Pleistocene glaciation have been described in detail by Christiansen (1968, 1992) and are attributed to multiple episodes of glaciation. Quaternary deposits are subdivided into groups and formations based primarily on data collected from boreholes (Table 2-1). The Saskatoon Group is correlated with the end of the Middle Pleistocene, the Late Pleistocene, and the Holocene. Sediments that are older than those of the Saskatoon Group are included in the Sutherland Group that extends from the Middle Pleistocene to the onset of glaciation in the Early Pleistocene. The Saskatoon Group is subdivided into the Floral and Battleford Formations. The oldest sediments are the proglacial and glacial sediments associated with the lower till of the Floral Formation. They are separated from the upper till of the Floral Formation by the Riddell Member (Christiansen, 1992). The Riddell Member consists of nonglacial sediments that are bounded above and below by proglacial sediments. It represents an ice-free period that is thought to correspond to the Sangamon Interglacial (SkwaraWoolf, 1981). The Battleford Formation is defined as the basal proglacial deposits and till that lie between the upper till of the Floral Formation and Holocene deposits (Christiansen, 1992). The till of the Battleford Formation is soft, massive, and unstained and is easily distinguishable from the hard, jointed, and often stained upper till of the underlying Floral Formation. The two tills were interpreted to be the result of two distinct glacial episodes based on the observation of unoxidized till of the Battleford Formation lying directly on oxidized till of the Floral Formation (Christiansen, 1992). The Battleford Formation is widespread throughout southern Saskatchewan and has at least two distinguishable units. The lower till unit is interpreted to have been deposited and consolidated under stagnant ice, while the upper till and clay unit was let down on top of the lower unit by ablation (Sauer and Christiansen, 1991). Holocene deposits are loosely defined as surficial stratified deposits and include deglacial lacustrine, outwash, and ice-contact sediments, as well as postglacial alluvium, colluvium, aeolian, and landslide deposits (Christiansen, 1992).

Surficial geology maps (Campbell, 1987a, 1987b) of the North Battleford (73C) and Saskatoon (73B) map areas depict a region comprised almost entirely of morainal and glaciolacustrine surface materials. The delineated elements of the land surface appear as a series of narrow and parallel northwest-southeast trending units that grade from one to the

Table 2-1
Stratigraphic Chart of Sediments, Saskatoon, Saskatchewan
(Modified from Cristiansen, 1992)

Time Units			Stratigraphic Units		
Quaternary	Holocene		Saskatoon Group	Surficial Stratified Deposits	
	Late Pleistocene	Late Wisconsin		Battleford Formation	
		Middle Wisconsin			
		Early Wisconsin		Floral Formation	Upper Till
		Sangamon			Riddell Member
	Early and Middle Pleistocene	Illinoian			Lower Till
		Pre-Illinoian	Sutherland Group	Warman Formation	
				Dundurn Formation	
				Mennon Formation	
Tertiary	Pliocene		Empress Group		

other in a northeast direction (Fig. 1-4). Nearest to the North Saskatchewan River, the surface materials are predominantly low relief morainal plains that are covered with a discontinuous blanket of glaciolacustrine sediments that vary in thickness. Glacial fluting, that is parallel to the trend of the landscape units, is depicted on the broad, gentle slope adjacent to the North Saskatchewan River. Parallel and adjacent to the fluting field, Campbell (1987a) defines a unit of morainal sediments that ranges from featureless plains to low relief, undulating hummocky terrain. A series of closely spaced, small ridges, oriented transverse to the direction of the fluting, is interpreted to be washboard moraine (Campbell, 1987a). The area of transverse elements is, in turn, bordered to the northeast by a second, smaller zone of fluted morainal plains. The northeastern margin of the study area is marked by the abrupt rise from the plains to the uplands of the Thickwood Hills. The surficial materials comprise a complex mixture of morainal, glaciolacustrine and glaciofluvial deposits. The morainal deposits are identified by Campbell (1987a) as low relief plains and high relief hummocky ablational and disintegration moraine. Extensive glaciolacustrine deposits grade from featureless lake plains in the southeast to kettled and deltaic glaciolacustrine and glaciofluvial deposits in the northwest. Modern deposits and geomorphic processes are indicated only in association with the North Saskatchewan River where the accumulation of alluvial materials has occurred, where the river bank has slumped, or where modern streams have developed.

Though no explanatory text accompanies the surficial geology maps, the terminology used to describe the landscape units and geomorphic features implies that specific formative processes associated with different phases of glaciation were active. Prest (1968) defines moraine as a till sheet that is thick enough to exhibit an uneven surface. The inferred deposition from active or stagnant glacial ice and the variety of forms that may be present provide the basis for further classification of different types of moraine. Morainal deposits that display longitudinal lineaments, such as glacial fluting, are generally interpreted to have been deposited by flowing ice (Prest, 1968) and are included in the general category of ice-flow features. The trend of the lineaments is generally assumed to be parallel to the direction of flow of the ice that is thought to have formed them.

Consequently, glacial fluting is used as an indicator of the direction of past ice flow. More recent ideas (Rains et al., 1993; Shaw et al., in preparation), however, suggest that the mechanisms responsible for the creation of glacial fluting may involve more complex subglacial processes that challenge the basic assumption that the linear features are, in all instances, indicative of ice-flow directions.

The washboard moraine indicated on the surficial geology maps (Campbell, 1987a) is alternatively named corrugated moraine by Prest (1968). Prest (1968) attributes the emplacement of the characteristic series of ridges to the subglacial pushing, thrusting, or squeezing of till and other surface materials in association with a fracture system or zone of weakness in an ice-marginal zone. The orientation of the ridges is inferred to be transverse to the direction of ice flow. The hummocky moraine identified by Campbell (1987a) is further described as ablational and chaotic disintegration moraine. According to Prest (1968), this type of moraine formed as dead ice disintegrated or stagnated in place letting down its contained debris onto the land surface. This is in contrast to basally deposited ground moraine. Glaciofluvial and glaciolacustrine deposits are generally interpreted to be associated with deglacial and proglacial processes (Klassen, 1989). Much of the study area has a blanket of fine-grained glaciolacustrine deposits that accumulated as meltwater ponded at the margin of the retreating glacier. Glaciofluvial and deltaic deposits mark areas where meltwater flowed from the glacier and from uplands into the proglacial lakes.

The surficial geology maps of the North Battleford (73C) and Saskatoon (73B) map areas (Campbell, 1987a, 1987b) show a landscape that was created by processes associated with the last episode of glaciation. The defined landscape units further suggest that the processes associated with deglaciation had the greatest impact on the present appearance of the land surface. Areas of glacial fluting are indicative of a subglacial environment associated with active ice, though it is difficult to assign a more specific phase of glaciation. It is implied, however, that areas described as washboard moraine formed during deglaciation at a time when a fractured and active ice front had retreated to the area. In accordance with the terminology used by Campbell (1987a), continued deglaciation resulted in the stagnation and disintegration of large portions of the ice margin and the consequent construction of zones of high relief, nonoriented hummocky moraine. Meltwater associated with ice retreat and stagnation modified the newly exposed landscape with the development of the large-scale Battle and North Saskatchewan Spillways and numerous smaller scale meltwater streams. The extensive glaciolacustrine deposits resulted as water ponded in glacial Lake Saskatchewan. The position of the ponded water and the meltwater channels was primarily controlled by the position of the ice front and significant topographic features such as the Missouri Coteau. Collapsed and pitted glaciofluvial and deltaic deposits formed where the initial deposits accumulated on stagnant ice that subsequently melted. Campbell (1987a, 1987b) showed that there has been minimal modification of the landscape subsequent to the final retreat of the last ice sheet. The evolution of the modern drainage system and the deposition of aeolian sediments represent only very minor changes.

Stauffer et al. (1990) specifically addressed the fluting in the North Battleford area in their study of ice-thrust features and landslides in the North Saskatchewan River valley. They identified a zone of fluting covering a distance of 300 km that they concluded was carved into till of the Floral Formation and subsequently mantled by a thin layer of till of the Battleford Formation and discontinuous glaciolacustrine sediments. In places, a poorly developed boulder pavement was observed at the base of what was interpreted to be the Battleford Formation. A small number of boulders exhibiting striations and chattermarks oriented in a northwest-southeast direction were also noted. The fluting was described as broad and shallow with roughly one metre of relief that was not apparent on the ground. Based on the identification of fluting that trends south and southwest on the uplands surrounding the study area and the fluting that trends southeast in the lowlands, Stauffer et al. (1990) concluded that the glacial ice that formed them flowed in a curving and streaming pattern. That is, the differently oriented fluting were interpreted to be coincident in time. Using hypotheses that attribute fluting formation to the direct action of glacial ice on the deformable underlying material (Boulton, 1987), Stauffer et al. (1990) further concluded that the fluting formed during the final stages of ice retreat. The authors referred to, but did not investigate, a series of ridges with several metres of relief that occur within the fluting field. The ridges, identified as crevasse filling, are oriented perpendicular to the southeast trending fluting.

Stauffer et al. (1990) proposed that the fluting formed as the direction of ice flow was controlled by the walls of the valley. For such control to be exerted, the ice could not have been thick enough to exceed the depth of the valley. It was suggested that during the generally southwest advance of the glacier a thin lobe of ice, referred to as the Battleford Lobe, was redirected toward the southeast so that it partially filled the river valley. Only when the ice sheet attained sufficient thickness could it have flowed toward the southwest over the top of the valley. During glacial retreat, as the ice thinned, the valley would again have controlled the direction of the flow toward the southeast. It was further speculated that even when the ice was at its maximum thickness and the direction of flow was generally toward the southwest, the ice in the valley bottom would still have been constrained by the valley walls such that it continued to flow to the southeast. Stauffer et al. (1990) considered the late glacial flow of the Battleford Lobe during ice retreat to be the formative agent of the fluting in the valley. Furthermore, the authors also concluded that shear stress under the Battleford Lobe was responsible for the creation of large-scale gouge zones and glacier thrusting. An area located on the south bank of the North Saskatchewan River near the downflow end of the southeast oriented fluting contains ice-thrust ridges that were investigated in detail. The nonarcuate surface expression of the ridges does not allow for a determination of the direction of ice flow. Subsurface analyses, however, showed deformation structures that are consistent with other indicators of the southeasterly flow of ice.

Gravenor and Meneley (1958) documented the existence of large fields of glacial fluting in northern and central Alberta. They noted that the fluting is aligned in two dominant trends with the majority of the features oriented to the south and southwest in accordance with the direction of the regional flow of ice. A smaller, though still significant, number are oriented toward the southeast. While the focus of the study was on fluting in the province of Alberta, the authors noted that the southeast trending Lac la

Biche fluting field near the Alberta-Saskatchewan border extends to a point almost 50 km southeast of North Battleford. Regional-scale analyses revealed that all the fluting fields are characterized by a preferred wavelength of 90 to 120 m between individual fluting ridges. In addition, all fluting fields, with the exception of the North Battleford area, have a secondary preferred wavelength of 180 to 210 m. Detailed till fabric studies that were conducted in the North Battleford fluting field showed a distinct change in clast orientation with depth in the fluting ridges. The authors concluded that the upper 3 m of till in the ridges was eroded from the adjacent grooves and transported obliquely over a short distance until it was deposited to form the ridge by ice advancing parallel to the trend of the fluting. Below 3 m, south and southwest oriented lineations were observed that were almost parallel to the trend of the fluting that is present north and south of the Lac la Biche and North Battleford areas. Based on the fabric analyses, Gravenor and Meneley (1958) speculated that the south and southwest oriented fluting developed during regional ice advance and the southeast oriented Lac la Biche fluting developed during deglaciation by a local readvance or possibly successive readvances of the ice. The formation of the differently oriented areas of fluting, therefore, was interpreted to have been separated by an unspecified period of time.

Jones (1982) conducted a more detailed investigation of the Lac la Biche fluting field in Alberta to determine the mechanisms involved in its formation. He described the fluting field as covering a distance of almost 390 km that extends nearly to North Battleford. In concurrence with Gravenor and Meneley (1958), Jones (1982) attributed the formation of the Lac la Biche fluting to a late phase resurgence of the retreating Laurentide ice sheet. The orientation of the fluting in a northwest to southeast direction transverse to the direction of the regional ice advance was interpreted to indicate that the Lac la Biche fluting field was formed during a late Wisconsin readvance. Furthermore, the narrowness of the field was interpreted to indicate constrictive forces were active at its margin. Jones (1982) speculated on the existence of large bodies of stagnant ice associated with the downwasting of the main Wisconsin ice that channelled the readvancing lobe in its path. Further evidence was gathered from the merging of the north to south oriented Cold Lake fluting with the Lac la Biche fluting. Based on the pattern of fluting, Jones (1982) suggested that two ice streams converged with the subsequent flow of the combined ice mass toward the southeast. Jones (1982) also noted the relationship between the fluting and other prominent features on the landscape. The Lac la Biche fluting field is bordered on the southwest and the northeast by deposits that are interpreted to be stagnation moraines and by large meltwater channels. Aeolian sand and sand wedges in the area were interpreted to indicate an extended period of arid periglacial conditions prior to the readvance of the Lac la Biche Lobe. The inferred presence of permafrost was thought to have promoted the widespread glaciotectonic activity that is also evident in the area.

Andriashek and Fenton (1989) provided an alternative reconstruction of events occurring during the final stages of glaciation in the Lac la Biche area of Alberta that they believed were associated with the development of the fluting fields. Based on extensive field studies, the authors concluded that during ice retreat the Late Wisconsin Laurentide Ice Sheet became differentiated into three distinct lobes. The highlands north of the study area may have contributed to the separation of the glacier into the southwestward flowing Primrose Lobe and the southward flowing Seibert Lobe. The southeast flowing Lac la Biche Lobe, on the other hand, was thought to have had its origins in southwestern Saskatchewan as southeasterly ice flow gradually extended up-glacier toward the northwest. The Primrose and Seibert Lobes were the first and second readvances to cross the study area. The Lac la Biche Lobe that advanced from the northwest was interpreted to have been confluent with the older Seibert Lobe. Though the Lac la Biche Lobe extended over a large area primarily as a thin ice cover, the fluting and large-scale glacial thrusting were attributed to a narrow, fast flowing, and highly erosive ice stream that extended at least as far as the Alberta-Saskatchewan border (Andriashek and Fenton, 1989). The authors concluded that the ice stream was restricted by the rise in regional topography to southwest and by stagnant ice of the Seibert Lobe to the northeast. The ice stream contained within the Lac la Biche Lobe was interpreted to have created an assemblage of features that grades laterally from well-developed fluting to fluting formed in rubble moraine to slightly streamlined rubble moraine to unmodified rubble.

Rains et al. (1993) hypothesized that much of the Alberta landscape was formed as catastrophic floods of subglacial meltwater flowed at various times and at various scales. Included in the many types of features that were believed to have been produced by these flood events are areas of large-scale fluting. The episodic nature of such flood events was hypothesized to have produced a complex landscape composed of similar elements that were created at different times. Based on the varying orientations of fluting fields, Rains et al. (1993) suggested that the Lac la Biche fluting field may have been truncated by the south and southwestward oriented Athabasca-Calling Lake fluting that formed during a catastrophic megaflood event that occurred near the time of the glacial maximum. Alternatively, Shaw et al. (in preparation) identified the Lac la Biche fluting field as a southeastward flowing diversion tract associated with the primarily southward flowing Livingstone Lake flood event that formed the Athabasca fluting field. In contrast to other researchers (Gravenor and Meneley, 1958; Jones, 1982; Andriashek and Fenton, 1989), the Lac la Biche fluting field was, therefore, interpreted to have formed some time near the glacial maximum (Rains et al., 1993; Shaw et al., in preparation), rather than during the final stages of glaciation.

Fluting

Fluting is commonly used as a descriptive term that refers to a specific type of streamlined features. Streamlined features range from small ridges that are only a few metres in height and width and less than a kilometre in length to large-scale systems of ridges and grooves that can have an overall relief of many metres and individual ridges and grooves of many kilometres in length. Large-scale fluting is associated with continental glaciation, while small-scale fluting is typically observed in front of modern retreating glaciers. Small-scale fluting has been extensively studied (Hoppe and Schytt, 1953; Baranowski, 1970; Paul and Evans, 1974; Boulton, 1976; Morris and Morland, 1976; Heikkinen and Tikkanen, 1979). The generally accepted explanation for its formation is the squeezing of unfrozen, water-soaked materials at the base of the glacier upward into cavities carved into the base of the ice. A simplified summary of the process of small-scale fluting formation is as follows. Cavities in the base of the ice are believed to be initiated as the glacier moves over an obstacle to flow such as a boulder, a block of frozen till, a bedrock knob, or any other resistant block at the base of the glacier. In response to differences in pressure in the vicinity of voids in the ice, pre-existing material will deform subglacially. Where pressure gradients are greater, erosional force is higher and material is forced away from the high pressure zones forming grooves. Where pressure is lower, accumulation of material will occur. By this mechanism, an obstacle to flow creates a low pressure zone that allows for the lodgement of till and other basal materials in the zone of reduced pressure on the distal side of the obstruction. The internal structure and till fabric of the fluting ridges are, therefore, expected to reflect the deformation inherent in their formation and the height of the fluting ridges is expected to be less than the height of the initiating obstacle. The primary factors in the formation of small-scale fluting are the differences in pressure beneath the ice as created by obstacles to flow and the resultant dynamics of ice and sediment movement.

Small-scale fluting that has been observed to form at the base of contemporary glaciers differs significantly from large-scale fluting that is associated with continental glaciation. Despite the similarities in form, it is not appropriate to use modern small-scale fluting as an analogue for determining the genesis of large-scale Pleistocene fluting. In the case of a continental ice sheet, it is unlikely that till and other basal material could be squeezed upward with sufficient pressure to create the large streamlined features common in previously glaciated landscapes or whether the cavities required for such infilling could be maintained at a sufficient height into a thick, flowing sheet of ice (Trenhaile, 1990). The flow dynamics in a continental ice sheet that produce large-scale fluting cannot be assumed to be analogous to the flow dynamics in either modern glaciers or a continental ice sheet that produce small-scale fluting. Furthermore, deformational hypotheses of fluting formation cannot explain the origin of fluting that has been identified in undeformed bedrock (Smith, 1948; Skoye and Eyton, 1992; Rains et al., 1993).

Prest (1968) provided a basic definition for large-scale fluting that formed during continental glaciation. He also made the important observation that there appeared to be a spatial and genetic relationship between different types of streamlined features, including drumlins, drumlinoids, and fluting. The various types of features were differentiated on the basis of their dimensions and their morphology. Drumlins were described as elongate mounds and ridges of drift that range from 6 to over 30 m in length and 15 to 25 m in height. The characteristic morphology is a steep stoss end and a tapering off in both profile and plan toward the lee end. A wide variation in drumlin morphology, however, is common. Drumlins may be depositional or erosional and may occur singly or in fields. Drumlinoids are narrower and more elongate ridges that range from 3 to 30 m in height and have tapered stoss and lee ends. Generally, the stoss end is blunter than the lee end. Drumlinoids may be a few metres in length or they may extend for a few kilometres. They typically occur in groups that have a large areal extent and frequently grade into fluting. Prest (1968) defined fluting as narrow and shallow furrowing in drift with or without adjacent ridges, recognizing that the grooves were the primary form. The typically low local relief ranges from 1 to 10 m. The markedly elongate forms may extend from less than one kilometre to tens of kilometres in length. The closely spaced furrows are separated by ridges that have tops that are close to or at the same level as the surrounding ground surface. All three types of streamlined features are typically composed of till, though many types of materials are commonly identified. Prest (1968) suggested that the streamlined forms were created due to the direct action of glacial ice and that the differences between them were attributable to variable rates of ice flow and its consequent capacity to deposit and mould, or to scour and transport its basal load.

In this research the term fluting will be used to refer to an assemblage of large-scale, parallel grooves and ridges that was produced under a continental ice sheet. The specific processes involved in the origin of large-scale fluting are known with less certainty than their small-scale counterparts. Theories of fluting formation must account for their internal structure and sediments, their surface morphology, and their spatial distribution and location. Because fluting is a part of a larger group of streamlined features to which they appear to be genetically related, theories of formation should also be applicable to the genesis of drumlins and drumlinoids. The body of literature available regarding the genesis of subglacial streamlined features is too large to allow for an exhaustive review. Therefore, selected references have been chosen for review that illustrate the different types of hypotheses of fluting genesis that have been developed. The various ideas are not necessarily mutually exclusive and, indeed, are complementary in some respects. Fluting genesis has been attributed to the accretion of ridges (Evenson, 1971; Shaw and Freschauf, 1973; Aario, 1977; Nenonen, 1994), to deformational processes (Moran et al., 1980; Boulton, 1987; Menzies, 1987; Boyce and Eyles, 1991; Bluemle et al., 1993), to the preferential erosion of grooves by direct ice action (Smith, 1948; Lemke, 1958; Gravenor and Meneley, 1958; Aronow, 1959), and to erosion by subglacial meltwater (Shaw and Sharpe, 1987; Shaw, 1988; Tinkler and Stenson, 1992; Rains et al., 1993; Shaw et al., in preparation).

Accretionary hypotheses of fluting formation are based on the assumption that observed till fabrics developed in response to the processes involved in fluting formation and that those processes were associated with the direct action of overriding ice. Evenson (1971) concluded from till fabric analyses and the relationship between drumlins in a field that till was transported upward and laterally to the crests of the drumlins as ice flowed at the base of the glacier from areas of high pressure to areas of low pressure. Based primarily on till fabric evidence and comparison with features of similar form that were created by fluvial and aeolian processes, Shaw and Freschauf (1973) similarly suggested that fluting formed as basal till and ice became concentrated in linear belts along low pressure zones due to the convergence of secondary flows at the base of the ice during the transport of till. It was proposed that a secondary helicoidal flow which had a lateral component to the regional direction of ice flow, acted on a requisite evenly distributed thickness of till and ice along points of attachment and separation. Debris-charged basal ice would then move toward separation points and clean, upper ice would replace debris-charged ice in areas around points of attachment. Troughs were expected to form where material was removed from points of attachment as the eroded material became incorporated into the ice along points of separation. In this accretionary hypothesis, Shaw and Freschauf (1973) suggested that the resultant bands of debris-rich ice and clean ice would ultimately be left on the landscape as an alternating series of upstanding ridges and intervening grooves as long as the banding was maintained during deposition. The smooth, streamlined form of the fluting was thought to develop due to differential rates of stagnation as clean ice continued to shear past stagnant debris-rich ice.

Aario (1977) hypothesized a higher ice flow velocity in areas where troughs were created in conjunction with a spiral flow along the sides of the ridges. He noted, however, that it was not clear if the spiral flow was a response to or a cause of the trough and ridge topography and that the squeezing of basal material into tunnels near an ice margin as a possible cause fluting could not be discounted. Nenonen (1994) developed a depositional hypothesis of drumlin formation that associates the variability in drumlins to variability in the velocity of the overriding ice, the thickness of the till beds, irregularities in the gradient of underlying bedrock, erosive capability of the moving ice, and drumlin location under ice. The formation of drumlins was attributed to rapid and strong ice flow on a bedrock surface such that the deposition of till around and on the distal sides of rock or till cores occurred during late phases of glaciation. Variations in the direction of orientation of till fabrics in the drumlins were interpreted to be indicators of rapid changes in ice flow direction that occurred during the period of drumlin formation. The obstacles to flow were hypothesized to be irregularities in the bedrock substrate in the case of rock cored drumlins. Till cores, on the other hand, were postulated to have originated either as features that were produced during previous episodes of glaciation or as deformed basal material produced by the overriding ice.

Deformational processes at the base of the ice induced by shear stresses has also been investigated as the primary formative mechanism in the creation of subglacial streamlined features. Boulton (1987) considered the deformation of sediments under a modern glacier in the creation of fluting, drumlins, and rogens to develop an explanation for the formation of Pleistocene features of similar form. A glacier model was described in which the primary strain regime was one of longitudinal extension superimposed on simple shear, that caused net erosion of a sediment bed. This regime gave way to longitudinal compression in the marginal zone of the glacier, resulting in net deposition. Basal sediments, that were also identified within drumlins, were divided into structural horizons based on their response to stress (Boulton, 1987). An upper horizon with a non-linear viscous response to stress and a very high strain rate was termed deformation till. A middle horizon that had an elastic or plastic response and low strain rates was underlain by a lower rigid horizon. Modelling was used to demonstrate that streamlined, drumlin-like forms resulted due to the deformation of an inhomogeneous sediment bed that contained zones of stiffer material.

Modern streamlined features that were exposed in front of retreating glaciers were believed to have formed rapidly at the ice margin and were interpreted to have orientations that were a reflection of the local ice flow directions. Pleistocene drumlins and other forms were also interpreted to have resulted from the interaction between glacier and the sediments on its bed such that the subglacial sediments were deformed by processes such as folding, plucking and shearing (Boulton, 1987). Variations in the resultant morphology of the streamlined forms and the pattern created by groups of features were attributed to differences in the viscosity of the sediment horizons and the dynamics of ice flow. Using the results of modelling experiments and modern, subglacially produced streamlined features as analogues, Boulton (1987) concluded that the genesis of the morphology and pattern of both modern and Pleistocene forms could be explained using the deformation theory.

Boulton (1987) further described conditions under which streamlined features were expected to form. Drumlinoid formation could be initiated on the proximal side of a laterally extensive bedrock step where drift was differentiated into discrete ridges as gaps in the scarp create low pressure zones in the lee of inter-gap knobs or on the distal side of bedrock knobs as flow was enhanced around the flanks of the obstacle. In addition, drift patches moving over bedrock could be retarded by crags, creating low pressure zones that were subsequently filled with debris. The drift could remain attached to the initiating obstacle creating crag and tail forms or the tail could detach from the crag in response to continued ice movement. Finally, drumlins could be initiated by stiff sediment obstacles that formed either deforming or rigid cores.

Menzies (1987) identified certain drumlins as part of a larger subglacial bedform continuum of forms in which their genesis was influenced by ice basal stresses, thermal conditions and mechanical reactions of the interface boundaries, pore-water content and pressure, bed morphology, the presence of pre-existing bedforms or other obstructions, and areal and temporal changes of other transient dynamic interface conditions. The deformation of subglacial sediments to produce drumlin forms was concluded to result when an active interface boundary existed between upper, mobile sedimentary units and lower, immobile units. Menzies (1987) hypothesized that once certain glaciological and mechanical conditions were reached, a triggering instability would change the stress field beyond a critical point such that a new stress field was created that would transform the interfacial geometry and allow for the formation of drumlins. It was further postulated that the instability could spread according to the local conditions of stress and interface geometry so that groups of forms or a continuum of forms were produced. In contrast to Boulton (1987), Menzies (1987) warned against using modern glaciological and glacial sedimentological data as analogues for Quaternary landforms.

Boyce and Eyles (1991) recognized from extensive subsurface data from a large drumlin field, that some drumlins composed of unlithified material were formed by the subglacial erosion of preexisting sediments. The interpreted erosive agent was deforming subglacial sediment flowing under conditions of low effective stress as till streams between cores of more resistant basal material. Stable cores of coarse-grained proglacial, fluvial sediments that were better drained and more resistant to deformation were hypothesized to have been shaped and maintained on the landscape by swales from which resistant, pervasively-deforming sediment was removed as streams of till. The thick deposits of till in the swales were interpreted to represent a period of deposition subsequent to the selective erosion of the swales. Systematic spatial variations in the drumlin forms within the drumlin field were interpreted to be a function of time. Widely spaced, spindle-shaped drumlins were thought to result in up-glacier areas where the duration of the deforming bed conditions was longest. In down-ice areas, a decreased amount of time available for streamlining resulted in drumlins that were ovoid and more closely spaced. Larger features were also thought to form where thicker initial sediments were available for excavation by the deforming till streams.

Moran et al. (1980) developed a model of glaciation that addressed the apparent genetic relationship between glacially thrust terrain and glacially streamlined terrain premised on the deformation of substrate materials by overriding ice. They suggested that where an advancing ice sheet flowed over areas that did not allow for the free drainage of subglacial water, elevated pore-pressure in the frozen-bed zone facilitated shear failure within the substrate. Blocks from the substrate were subsequently transported by the ice for variable distances and with varying degrees of deformation depending on the local conditions. Moran et al. (1980) further hypothesized that blocks that were deposited far enough from the glacier margin so that they were overridden by sliding ice in the thawed-bed zone, were subjected to erosional and depositional smoothing. Purely erosional processes were postulated for forms that contain fluvial or lacustrine sediments with little deformation of the internal sedimentary structures. Most streamlined forms, however, were observed to contain other types of sediment that were frequently deformed and were consequently thought to have formed as the glacial-thrust blocks forced the ice into deforming flow patterns. The process described involved the convergence of ice around the thrust block so that debris was deposited in the basal zone of the glacier in the form of a lee-side tail. Moran et al, (1980) also suggested that debris may have been deposited in the lee of thrust blocks by the upward injection of thawed, saturated and highly plastic substrate materials into the low pressure zone created in the lee of the obstruction. Regardless of the process of deposition of debris, continued movement of the glacier subsequently streamlined the forms. In summary, the formation of the streamlined and thrust terrain was primarily related to non-steady-state conditions characteristic of the advancing margin of the glacier or the down-glacier movement of the boundary between frozen-bed and thawed-bed zones.

Bluemle et al. (1993) similarly concluded that the conditions that caused the glacier to form large ice thrust masses also contributed to the formation of large scale fluting and that the primary factors involved were high pore-water pressures in interbedded permeable and impermeable materials beneath a thin, swiftly flowing glacier, and the presence of areas of frozen ground near the margin of the glacier. Fluting ridges were hypothesized to have formed as constructional features with the glacial and hydraulic transport of sediments from immediately adjacent areas. Long, narrow depressions formed along the sides of the ridges as materials in a frozen or semi-fluid state were thought to have been forced by squeezing and injecting into the ridge. The very large fluting ridges were believed to have been initiated in a subglacial cavity as the glacier overrode ice-thrust blocks. The cavity, in such conditions, would become a zone of low pressure which caused the adjacent glacial ice to converge. Consequent elevated pore-water pressures in the immediate subglacial area and associated shear strength reduction were expected to induce sediment transport into the basal cavity as the moving glacier continued to equalize the pressure differential produced by the obstruction. It was further hypothesized that as pore-water dissipated and sediments became over-consolidated, the shear strength of the deformed material would increase sufficiently to maintain a continued obstacle to flow. Bluemle et al. (1993) concluded that to maintain a cavity that remained open long enough for the very large fluting ridges to form required a thin, surging glacier margin so that the pressure of the overriding ice did not cause ice flow to infill the cavity.

The preferential erosion of grooves by direct glacial action in combination with ice moulding has also been suggested for the formation of fluting. Lemke (1958) and Gravenor (1953) drew the common conclusion that large-scale streamlined features were formed as basal materials were shaped and moulded into grooves and ridges by overriding glacier ice. Gravenor and Meneley (1958) further suggested that grooves were eroded in response to alternating, parallel, high and low pressure zones that existed at the base of the ice. In this hypothesis, material was eroded from below high pressure zones and subsequently incorporated into the ice so that it moved downstream in a curved path toward low pressure zones on the sides and tops of the fluting ridges. Smith (1948) emphasized the development of grooves as the primary form in an area of bedrock fluting. The origin of the grooves was attributed to some unspecified flow dynamic in the glacier ice such that the conditions of erosion were steady for a long period of time. Plucking and abrasion by the direct action of ice were postulated as the principal mechanisms responsible for the removal of vast amounts of material in the creation of the grooves. It was also noted that there was a downflow transition from the large-scale grooves to drumlinoid features, suggesting a related process of formation. Smith (1948) also observed that the orientation of the grooves and drumlinoids bore little relationship to either topography or bedrock structure and, therefore, interpreted them as a reliable indicator of former ice flow direction. Aronow (1959) similarly concluded that erosion must be considered as a significant factor in the development of large-scale fluting and other streamlined forms. Without offering specific suggestions, Aronow (1959) emphasized that the variations in the morphology, internal structure and composition, and location of streamlined forms must be accounted for by considering the characteristics of the formative medium, which he assumed to be ice.

Most hypotheses of fluting formation have assumed the direct action of overriding ice in the modification of basal sediments. Departing from these ideas is the hypothesis that processes associated with the catastrophic flow of subglacial meltwater may have been the primary formative mechanism. Rains et al. (1993) used the presence of large-scale fluting as supportive evidence for hypothesized megaflood flow paths in Alberta. Sheet-flood paths were, in part, inferred from the long-axial trends of the fluting ridges. Support for the subglacial meltwater genesis of streamlined forms was drawn from earlier work showing that enormous, turbulent, subglacial water flows could account for a variety of erosional bedforms, including glacial fluting (Shaw and Sharpe, 1987; Shaw, 1988; Shaw et al., 1989; Shaw and Gilbert, 1990). Shaw et al. (in preparation) used detailed morphological and sedimentological evidence to suggest that catastrophic flows of subglacial meltwater were the most likely eroding agent of the wide variety of forms and sediments encountered in a fluting field. They identified erosional troughs with concave cross-profiles that they interpreted to be primary erosional features. Spindle shaped depressions, at a wide range of scales, and muschelbruchen and sichelwannen were also identified and were concluded to be comparable to similar forms that had been previously attributed to meltwater erosion (Shaw, 1988; Kor et al., 1991). The truncation of sedimentary sequences within the fluting ridges, including undisturbed melt-out till, lodgement till with intratill meltwater deposits, and highly deformed diapiric mélange with lateral debris flow and meltwater deposits, and a gravel lag at the truncation surface were also used to support the conclusion that the fluting field had a glaciofluvial origin.

The pattern and location of the fluting field was also consistent with the subglacial meltwater hypothesis (Shaw et al., in preparation). In common with other comparable features, the fluting field began at the rim of a steep valley slope that faced into the formative flow. Numerical and experimental modelling of flow conditions at upflow-facing steps showed that vortices are generated upstream from the step and that high velocity streaks are formed at the step as the vortices were carried over the rim (Shaw et al., in preparation). If the streaks were held in place by defects in the rim, fluting develops that has exactly the same form and topographic location as the fluting field under investigation. Tinkler and Stenson (1992) described similar conditions of fluting formation that was initiated as subglacial meltwater flowed over a bedrock escarpment. The landscape was shaped by erosional longitudinal furrows and remnant ridges that formed at the rim of an escarpment that faced into the direction of the formative flow. Tinkler and Stenson (1992) concluded that as meltwater was confined under the ice sheet, it flowed against the escarpment until it was forced up and over. Structural irregularities of the bedrock in the escarpment face caused the lateral adjustment of the meltwater flow around bedrock highs and lows. The consequent development of vortices in a flow containing high amounts of abrasive sediment was then responsible for the erosion and smoothing of the furrows. Downflow from the escarpment, the fluting ridges were tapered and more subdued and were interpreted to indicate a dissipating and spreading flow. The loss of relief in the downflow direction was due to the rising floors of the furrows rather than a lowering of the ridges, again indicating a dissipation of energy and a reduced erosive capability. As with other erosional hypotheses of fluting formation, the removal of vast amounts of material was noted (Tinkler and Stenson, 1992). Determining the preglacial landscape, however, was problematic because it was impossible to know how much material originally existed and to know how much of the removal of material could be attributed to the meltwater flow event.

The scale of the hypothesized meltwater event proposed by Shaw et al. (in preparation) requires that the formation of the fluting be placed in a regional perspective that can genetically relate various elements of the landscape. Shaw et al. (in preparation), therefore, proposed a model of subglacial landscape evolution that involved long episodes of glacial erosion, transport, and deposition interrupted by episodic large flows of channelized meltwater as well as large-scale, catastrophic sheet flooding. Thick accumulations of glacigenic sedimentary sequences were thought to have been deposited for thousands of years as the ice sheet gradually reached it maximum extent. In addition to the deposition of till, the subglacial environment was believed to be characterized by periodic, short lived, glaciofluvial events as meltwater drained in conduits and sheet flows. Shaw et al. (in preparation) concluded that these events yielded the boulder pavements and intratill sorted and mélange beds that were observed in the fluting ridges. Larger scale glaciofluvial events ensued that excavated deep tunnel channels. It was these tunnel channels that, in some instances, were believed to have provided the initiating topographic conditions of an upflow-facing step for fluting formation. In addition, the high pressure gradients due to the high meltwater discharges were expected to have had the effect of lifting the ice from its bed and promoting the diapiric extrusion of sediment into low pressure cavities. The mélange and graded sediments thus produced were, therefore, also considered to be independent of the fluting forming process. The final hypothesized event that shaped the landscape was a vast, anabranching, catastrophic sheet flood that swept across the tunnel channels and other subglacial sediments and features at some time near the glacial maximum (Rains et al, 1993). Rains et al. (1993) concluded that the effects of the flood were primarily erosional as glacigenic sediment and bedrock were scoured, leaving, as one type of erosional feature, the spindle shaped troughs and residual ridges of the Athabasca fluting field.

Morainal and Hummocky Deposits

Prest (1968) defined glacial drift as those materials which are deposited as a result of glaciation. Till is that portion which is deposited directly by ice. Where the till is thin, it is referred to as a till sheet. Where it is thick enough to exhibit an uneven surface, Prest (1968) proposed the use of the term moraine. By this definition, morainal materials can be laid down by active or stagnant ice. Moraines are further classified on the basis of the presence or absence of elements that are transverse or parallel to the inferred direction of ice flow. Non-oriented moraines are those deposits which contain no such elements and are considered to have been created by the uncontrolled deposition of material. Non-oriented moraines were further designated as high or low relief. Prest (1968) concluded that moraines formed from a combination of the processes involved in glacier stagnation, glacier ablation, and large-scale basal deposition.

Gravenor and Kupsch (1959) distinguished between terrain that was left by a rapidly retreating ice margin and terrain that resulted from ice disintegration. Ground moraine that characteristically has a relief of less than 10 m is the most widespread morainal deposit on the prairies and was interpreted by Gravenor and Kupsch (1959) to have been left as a glacier retreats at a fast rate so that no separate blocks of ice are left on the landscape. Ice disintegration, on the other hand, refers to the breaking up into numerous small blocks of a stagnant and wasting glacier. Gravenor and Kupsch (1959) attribute the genesis of numerous features to the process of ice disintegration. They are interpreted to vary in form and composition depending on the amount of debris carried by the ice, the position of debris on or in the ice, and the amount of meltwater present. Furthermore, ice disintegration features were presumed to exist in a well-preserved state due to their creation during a late phase of glacial deposition. Disintegration of the glacier may be uncontrolled (the forces breaking up the ice are equal in all directions) or controlled (the ice separates along lines of weakness). Round, oval, and polygonal features with a general lack of linear elements are attributed to uncontrolled disintegration, while features that exhibit linear or lobate landforms are attributed to controlled disintegration. Gradations in form between controlled and uncontrolled features, however, are frequently found. Gravenor and Kupsch (1959) attribute low relief hummocky ground moraine to deposition directly from basal ice that had become inactive during the recession of the glacier, though

Prest (1968) suggested that ablation and the letting-down of material onto the land surface also likely played an important, though secondary, role.

The low relief hummocky terrain of the Interior Plains frequently includes elevated areas referred to as prairies mounds (Gravenor, 1955; Bik, 1969), plains plateaux (Stalker, 1969), and ice-contact rings and ridges (Parizek, 1969). These are complex and enigmatic features that have been variously attributed to deposition by ice with the sliding of ablational or englacial debris and melting of buried ice, the squeezing of till into holes associated with systems of crevasses in the ice, and periglacial phenomena. These processes are not mutually exclusive and debate has centred around the nature and relative importance of the processes involved.

Gravenor (1955) described the widespread occurrence of circular mounds approximately 90 m in diameter and 4.5 m high with a central depression 0.9 to 1.2 m lower than the outer rim. The mounds investigated were generally composed of clayey till comparable to the till of the surrounding area, though some contained masses of contorted and slumped stratified silts and clays that were not found in the adjacent sediments. Gravenor (1955) attributed the origin of these features to deposition from stagnating ice under conditions of slow melting and downslope retreat of the glacier. The process involved pits in the ice surface that filled with unsorted material that was subsequently let down onto the land surface once the ice had completely melted. The formation and configuration of the pits on the ice was believed to be controlled by differential ablation created by the uneven distribution of debris on the ice. In addition, it was speculated that the collapse of caves within the ice that developed by the enlargement of crevasses located beneath the water table and the concurrent rapid solution of areas in the ice with lesser amounts of debris also contributed to the formation of pits. Ice retreat in a downslope direction was a required condition to maintain a sufficiently high water table to promote the formation of caves and to inhibit the role of meltwater action in the deposition of sediments. To summarize Gravenor's (1955) conclusions, an even, pitted ice surface was characterized by the infilling of the pits due to the washing of material or mass wasting. The resulting mixture of sediments was expected to include both sorted and unsorted material that acted as an insulating cover over a core of ice. The maintenance of the unsorted nature of most prairies mounds required slow melting. The central depression characteristic of many mounds was believed to form with the final melting of the ice core. This ablational let-down hypothesis was expanded upon by Gravenor and Kupsch (1959) to include the basal squeezing of debris into subglacial cavities as a complementary process in the origin of prairie mounds and a wider variety of ice disintegration features.

Stalker (1960) described a range of low relief, stagnant ice features that he attributed to the ice-pressing of drift into basal cavities during the retreat of the glacier. Among these are the prairie mounds of Gravenor (1955) which were one element of his more broadly defined elevated plains plateaus. Stalker (1960) described plains plateaus that range from less than 15 m to more than 180 in diameter and from 1.5 m to 9 m or more in height. The more commonly occurring dimensions of about 90 m in diameter and 1.5 to 4.5 m high, however, were in accordance with the observations of Gravenor (1955). Stalker (1960) described an ideal form consisting of a flat-topped plateau. While this type was common, in many instances there were landforms characterized by central depressions that ranged from 0.6 to 1.5 m deep. In general, the central depressions described contained fluvially deposited sand, silt, and clay, though features with no central filling were identified. In such cases, the depression was observed to reach the general level of the ground outside the plateau leaving a form that consisted only of a rim ridge. Plateau fields typically contain up to several hundred individual forms that Stalker (1960) observed to be commonly arranged in a distinct linear pattern. In contrast, Gravenor (1955) interpreted the mound pattern to be apparent only.

Stalker (1960) concluded that the forms were created by a process he described as ice-pressing. With deglaciation, holes were believed to exist at the base of the ice that were infilled with saturated, highly plastic subglacial material in response to the weight of the overlying ice. The regional downslope retreat of the glacier and the consequent higher water table ensured an abundance of saturated material. The creation of the holes in the ice was attributed to water seepage along crevasses and joints between crevasses. Once an opening in the ice was initiated, it could be enlarged by calving. Stalker (1960) further reasoned that the preservation of the holes required thin, stagnant ice that inhibited the infilling of the hole by the plastic flow of ice. With the creation of holes at the base of the ice, till and other basal material was squeezed upward and outward into the opening so that the features were either built from below or by accretion as material was draped over the surface of the form. The displaced material left depressions that Stalker (1960) referred to as kettles once the ice was completely melted.

While Stalker (1960) did not discount the ablational let-down hypothesis that required deposition from the ice surface (Gravenor, 1955; Gravenor and Kupsch, 1959), he favoured an explanation that supported the primary importance of the intrusion of plastic basal till into subglacial cavities in stagnant ice. Hoppe (1952) reached similar conclusions based on till fabric studies of low relief hummocky terrain. He concluded that in a subglacial environment, the basal till initially moved toward a cavity with a slight upward flow that successively transformed itself into a horizontal flow and ended with a slight downward movement. The regular orientation of the till fabric was interpreted to indicate that ice-pressing rather than slumping was instrumental in the formation of mounds.

Bik (1969) proposed a periglacial origin for prairie mounds, in which a subaquatic or subaerial formative environment was favoured over subglacial or supraglacial conditions based on the observation that, in some mounds, lacustrine deposits are overlain by till. To address the shortcomings of earlier periglacial hypotheses of mound formation involving the growth and subsequent decay of ice wedge polygons, Bik (1969) compared their genesis to that of collapsed pingos. Pingos are ice-cored hills that form where water can circulate below the permafrost or through unfrozen areas within the permafrost. Open-system pingos form where water rises to the surface and freezes, forcing up the overlying sediments. Closed-system pingos form due to the entrapment of groundwater following the drainage of a water body as the freezing plane shifts downward into the ground. Again, the trapped water freezes causing the overlying sediments to heave upward. As the resultant ice core begins to melt, the pingos develop a summit crater. Final melting of the ice core leaves shallow, rimmed depressions on the land surface. If the mounds found in the southern Interior Plains formed by a similar process, a fossil permafrost layer must be assumed. According to Bik (1969), the location, pattern, and distribution of mounds were controlled by the former position of proglacial lake shore zones. Mounds developed where permafrost was partially thawed below the shore zones prior to the lowering of the water level and subsequent reestablishment of permafrost in the drained area. The combination of collapsed pingo formation and the subsurface displacement of plastic material resulted in mounds consisting of till and proglacial lacustrine deposits. Bik's (1969) explanation, in summary, is premised on the deformation of preexisting material, rather than the concurrent deposition and deformation of mound sediment.

Parizek (1969) studied what he termed, "ice-contact rings and ridges" in the southern Interior Plains. These comparatively minor, though widespread, landforms are associated with hummocky and transitional ground moraine and were interpreted to have formed as an end product as debris-rich ice thinned and stagnated. Accordingly, they could form in glaciolacustrine, glaciofluvial, ablational, or supraglacial environments. Rimmed kettles, a term borrowed from Christiansen (1956), are features that are equivalent to the prairie mounds of Gravenor (1955) and the closed disintegration ridges of Gravenor and Kupsch (1959). Parizek (1969) described them as low relief features that are nearly circular in plan view with, in most cases, a round or irregularly shaped central depression. A range of forms, though, were identified that tended to grade one into the other. Their formation was attributed to the sliding or flowing of supraglacial till or lake sediments into a sinkhole in the stagnant ice. A subsequent inversion of topography resulted due to the insulating effect of the drift in the bottom of the sinkhole. Mass movement of this drift away from the centre of the original sinkhole and down the sides of the buried ice core, and the final the melting of the ice core, were hypothesized to leave a rimmed kettle form on the landscape (Parizek, 1969). The processes of collapse, letdown and inversion were believed to account for the topographic form and contorted bedding, the lack of uniformity in observed till fabrics, and the association with other related dead-ice landforms. In contrast to Stalker (1960), Parizek (1969) concluded that there was no evidence to support the process of ice pressing as the dominant formative mechanism of these features.

Areas of ground moraine may also contain oriented lineations. The lineations may be in the form of ridges or depressions, that are oriented transverse to the inferred direction of regional ice movement. Corrugated ground moraine (Prest, 1968) is commonly found in the Interior Plains and refers to low relief patterns of irregular-branching transverse ridges. Individual ridges range from short to elongate in form with an irregular, wavy outline and are generally spaced between 80 and 275 m. Corrugation ridges are invariably discontinuous and vary in height and width (though they are generally less than 10 metres in height) in contrast to the uniformity that is typically observed in other types of ridges (Prest, 1968). The composite pattern is often accentuated by water filled depressions and frequently forms a broad arcuate system that is interpreted to outline the positions of former glacier lobes. The ridges are most often composed of till, though stratified material or slabs of bedrock may be found locally. The emplacement of the ridges has been attributed to the pushing, thrusting, or squeezing of subglacial sediments in association with a fracture system near the ice-marginal zone (Prest, 1968). Gravenor and Kupsch (1959) concluded that corrugated ground moraine formed as the glacier disintegrated along thrust planes. They described the ridges as disintegration features that exhibit inherited flow control and were consequently interpreted to be parallel to the former ice margin. Their discontinuity was interpreted as a function of the narrowness of the thrust planes, in contrast to the more open nature of crevasse systems. The well-preserved condition of corrugation ridges was thought to indicate the subsequent stagnation of local ice. In some locations the transverse ridges were observed to merge with longitudinal ridges, suggesting that these elements were formed by a common genetic process (Gravenor and Kupsch, 1959). Prest (1968) hypothesized that either moulding during the active flow of ice or the squeezing of material into fractures in the base of the ice as it stagnated were the primary processes involved.

Linear, ice-block ridges (Prest, 1968), plains ridges (Stalker, 1960), and linear disintegration ridges (Gravenor and Kupsch, 1959) all refer to small, elongate, steep-sided ridges that formed transverse to the inferred direction of ice-flow. Again stagnant ice conditions were generally considered to be a prerequisite for their formation (Prest, 1968). Most of these ridges described were composed of till, though some contained varying amounts of sand and gravel suggesting an ice-contact environment of deposition (Gravenor and Kupsch, 1959). The ridges are generally less than 8 m high and 300 m long and typically have semi-oval profiles. They were thought to have developed by the emplacement of till into fracture systems, either by squeezing from beneath the ice (Stalker, 1960) or from the slumping of debris from the ice surface (Gravenor, 1955).

Stalker (1960) described minor ridges that he interpreted to have formed in crevasses that were positioned between active and dead ice. The formative mechanism involved was the squeezing of basal till into the crevasse from both sides. Disintegration along crevasses typically resulted in features that have two or three dominant trends (Gravenor and Kupsch, 1959). This characteristic was used to distinguish these ridges from corrugation ridges that may have a similar appearance. Their genesis, however, was attributed to the deposition of material in continuous open crevasses rather than the squeezing of material along thrust planes (Gravenor and Kupsch, 1959; Stalker, 1960).

Non-oriented high relief moraine was described by Prest (1968) as a constructional feature with a hummocky and pitted surface expression that is characterized by the absence of linear elements. The origin of hummocky terrain has generally been associated with the disintegration of stagnant ice (Gravenor and Kupsch, 1959; Stalker, 1960). Gravenor and Kupsch (1959) defined hummocky disintegration moraine as broad tracts of rough morainal deposits with an irregular outline and no pronounced elongation or linear arrangement of knolls or depressions. Local relief was typically observed to be 6 to 18 m and, in extreme cases, up to 60 m. Knobs occurred as isolated mounds, as clusters, or as a series of forms joined by ridges and were typically composed of till, though some contained crudely stratified drift overlain by a layer of loosely washed drift. Circular undrained depressions were observed at the summit of and between many knobs, though irregular hollows were more common. The resulting characteristic "knob and kettle" topography (Gravenor and Kupsch, 1959) was best developed over preglacial uplands, though a more subdued form was identified on preglacial lowlands. The formation of hummocky, knob and kettle topography was considered to be the end product of various processes associated with the disintegration of ice (Gravenor and Kupsch, 1959). Ice disintegration features were distinguished from true end moraines with aligned knobs and depressions, by the absence of discernible trends, an overall broad, round form, and indistinct borders grading almost imperceptibly into surrounding low relief basally deposited ground moraine.

As with low relief ground moraine, hummocky terrain generally contains a range of several distinct elements. Gravenor and Kupsch (1959) described the ice disintegration process as the mechanism by which many prairie landscapes features, including moraine plateaus, linear and closed ridges, and ice-walled channels, were produced. They considered the variation in form to depend on factors such as the amount of debris carried by the ice, the position of the debris on or in the ice, and the amount of meltwater produced. In addition, they suggested the generally well preserved state of the features indicated that there was little geomorphic activity subsequent to their formation and, therefore, it was concluded that many of these features should be assigned to a late phase of glacial deposition.

The let-down of supraglacial and englacial drift due to ablation and the ice-pressing of subglacial material were considered to be the most significant formative mechanisms (Gravenor and Kupsch, 1959). With ablation, debris in the ice was expected to accumulate gradually on the glacier surface. As melting continued, the surface debris was let down onto basal ice deposits as it fell into crevasses, subglacial channels and irregularly shaped hollows. The landforms produced were thought to reflect the original irregular distribution of debris on the ice as it was arranged into ridges, knolls and depressions. Ablational material was expected to be loose, non-compact, non-fissile and rich in gravel and larger stones. Forms that contained stratified drift were explained as having developed in an environment with a greater degree of meltwater action accompanying ablation. Forms that were composed of very compact till were hypothesized to have been created by thrust planes in the ice or the squeezing of sediments into crevasses (Gravenor and Kupsch, 1959).

Hummocky terrain ranges from highly pitted and hummocky, to areas that contain broad, elevated, flat-topped moraine plateaus (Stalker, 1960). These features are similar to plains plateaus in their composition and general form and are attributed to a common mechanism of formation. The moraine plateaus of Gravenor and Kupsch (1959) included all circular to irregularly shaped, flat areas within hummocky moraines that are at the same elevation or slightly higher than the surrounding knobs. Rim ridges in various stages of development were observed, though it was noted that these ridges were not a ubiquitous feature of moraine plateaus. Stalker (1960), on the other hand, used the term moraine plateau to refer to those features that occurred in hummocky moraine that tended toward a plateau form and that had till rim ridges that rise up to 6 m above a flat central depression filled with water-laid sediments. Moraine plateaus were easily identified as the only level portions of otherwise rough knob and kettle topography. The plateaus were observed to rise steeply from 6 to 15 m above the surrounding kettles. Stalker (1960) interpreted the rim ridges as being formed by ice-pressing as saturated clay-rich till was squeezed into spaces between ice-blocks and crevasses in the ice.

Parizek (1969) discussed what he termed rim-ringed moraine-lake plateaus. The flat surfaces of the moraine-lake plateaus were concluded to be related to the initial configuration of the subglacial land surface, the processes associated with deglaciation, the occurrence of lake sediments that fill depressions, and the inversion of topography in conjunction with flowing and ponded meltwater. In agreement with earlier ideas (Gravenor, 1955; Gravenor and Kupsch, 1959), Parizek (1969) suggested that an insulating cover of debris facilitates differential melting of the ice. Parizek (1969) further hypothesized that melting was accentuated along joints and cracks above till or bedrock highs where the ice was expected to be thinner and that the consequent supraglacial depressions promoted the development of lakes on top of the ice. With downwasting of the ice, the till or bedrock highs appeared as nunataks. As meltwater was ponded above the highs, superglacial debris slumped from the surrounding ice into the depressions. These materials then contributed to the sediments of the plateau surface. Rim rings and terrace rings were interpreted to develop at successively lower levels as remnant blocks of ice progressively wasted in place. Rings that were composed of till were thought to indicate a lack of subsequent sorting. Those that were composed of till, sand, gravel, silt, and clay, conversely, indicated fluvial and lacustrine processes were involved in their formation. Common breaches in the rim rings were interpreted to have been caused by the flow of meltwater at various points and at various times. Supraglacial till and ablational debris were then inverted from their initial positions on and within the stagnant ice adjacent to the plateau as the remnant ice blocks finally melted away, leaving a knob and kettle topography with ponds and sloughs forming in the dead-ice hollows. Parizek (1969) favoured the process of ablation and the letting-down of debris onto the land surface over the ice-pressing hypothesis (Stalker, 1960) as the primary mode of formation of these features.

An alternative interpretation for the formation of certain belts of hummocky terrain containing zones of moraine plateaus was proposed by Rains et al. (1993). Two major subglacial flood paths were hypothesized in Alberta that represent the large-scale, catastrophic, north to south, flow of melt water at some time near the Late Wisconsin glacial maximum (Shaw et al., 1996). It was suggested that overspill diversion of the flow event from the main flood paths created interference zones of shallower water where they converged. In these areas it was reasoned that belts of hummocky terrain with a strong preferred orientation were moulded out of the initial subglacial sediment. Individual hummocks in the path of the hypothesized flood were observed to contain a diverse assemblage of sediments including primary till, reworked till, debris flows, rhythmically bedded sands, silts, and clays, glaciofluvial sand and gravel, glaciotectonically thrust bedrock and undisturbed bedrock (Munro et al, 1996). In some cases, the sedimentary units were traced laterally for many kilometres throughout hummocky and non-hummocky zones. The hummock form was interpreted to be erosional and, therefore, unrelated to the primary genesis of the sediment (Shaw et al., 1996). Commonly occurring boulder lags and crescentic scours over many hummock surfaces, drumlinized hummocks, and a position downflow of other features that were interpreted to have formed by meltwater erosion lend additional support to the glaciofluvial origin for hummocky terrain (Munro et al., 1996). Hummocky terrain was postulated to have formed as the longitudinal vortices that were responsible for the erosion of bedrock were dampened and complicated in the interference zones causing less efficient erosion. The resulting nets of erosional troughs and residuals may have been subsequently modified by ice pressing as debris was pressed into cavities eroded into the underside of the floating ice sheet by the flow of meltwater (Rains et al., 1993). Support for the subglacial meltwater hypothesis as the formative mechanism for hummocky terrain was drawn from the distinctive linear patterns of hummocks and associated depressions and beaded spatial relationships within plateau zones that were consistent with the inferred direction of the interference vortices. Further evidence was found in the superimposition of eskers on hummocks that support the conclusion that the hummocky terrain was formed subglacially. It was further proposed (Rains et al, 1993; Munro et al., 1996; Shaw et al., 1996) that the plateaus represent remnants of a preflood, subglacial surface composed of glacial, glaciofluvial and glaciolacustrine sediments. The moraine plateaus were interpreted as pinning points that remained in contact with the Laurentide ice sheet base as differential meltwater scour occurred around them. Hummocky areas that do not contain moraine plateaus were believed to indicate zones where the initial surface was removed by relatively effective meltwater sheet flow erosion. The well-preserved state of the hummocky belts was also thought to indicate the lack of subsequent large-scale geomorphic activity (Rains et al., 1993). This would be expected due to the postulated creation of thin, clean ice after a significant meltwater erosional event. Stagnant ice conditions during deglaciation were considered to be responsible for the superimposition of only minor erosional and depositional features.

Gravenor and Kupsch (1959) also identified erosional features that commonly occur in high relief hummocky terrain. Ice-walled channels that were often observed to be filled with till and were recognizable by a chain of depressions in the valley bottom typically occurred where local relief was high and the drift blanket was thick. These types of channels were easily distinguishable from the broad, open channels that were associated with areas of thin, low relief ground moraine. The ice-walled channels were characterized by a complex pattern of parallel and intersecting elements and were frequently noted to be associated with esker systems. Furthermore, in some areas major channels appeared to be roughly parallel to the inferred direction of ice movement, while in other areas directional control by ice position was not obvious. Gravenor and Kupsch (1959) speculated that the channels may have had polygenetic origins in glacial erosion, subglacial meltwater erosion, and proglacial, ice-contact fluvial erosion.

Parizek (1969) identified three types of meltwater channels. Channels that formed prior to being overridden and partially infilled by glacial ice were thought to arise where they were positioned at the margin of an active glacier. Channels that were eroded into lodgement till were interpreted to have formed in an ice-walled environment. Segments of these channels were thought to have been used by subglacial meltwater and subsequently partially filled by ablational debris prior to ice retreat. The third type of channel was that which formed in conjunction with ice walls, but no ice roof. Again, these channels contained ablational debris deposited before complete ice retreat. All three forms were interpreted by Parizek (1969) to have developed in stagnant ice conditions that promoted the let-down of supraglacial and englacial debris parallel to the meltwater channels. The association of ridges on the rims of the channels with circular disintegration ridges was used as evidence to suggest a common ablational origin.

Hypotheses concerning the origins of hummocky terrain have traditionally stressed the importance of processes associated with ice stagnation in the final stages of glaciation. Low relief ground moraine, high relief hummocky moraine and their numerous associated features were generally considered to reflect deglaciation by stagnation of portions of the ice margin. Prest (1968) and Klassen (1989) noted that hummocky terrain is uniquely well developed in the southwestern part of the Interior Plains of Canada. Prest (1968) attributed this to the accumulation of thick deposits of clay-rich till that was susceptible to slumping, sliding and squeezing. The prevalence of these deposits was concluded to be a function of the manner of ice retreat as controlled by local and regional topography. Klassen (1989) attributed the distribution of the thick drift deposits to the position of the escarpments that provided an abundant supply of shale bedrock for the construction of thick hummocky deposits. Disagreement, however, arises in regard to the specific glacial processes involved. Glacier ablation and large-scale basal deposition, while not mutually exclusive, are advanced as the predominant formative mechanisms. Departing radically from these traditional explanations is the subglacial meltwater hypothesis that places an emphasis on regional scale associations that include a consideration of the possible genetic relationship between various types of features.

Catastrophic Drainage of Subglacial Meltwater

Glaciofluvial hypotheses have been formulated to explain the formation of both depositional and erosional drumlins (Shaw, 1983; Shaw and Kvill, 1984; Shaw and Sharpe, 1987). Evidence in support of these hypotheses was gathered from the drumlin forms themselves and their similarity with other known fluvial forms, from geomorphological interpretations of the relationship between individual drumlins and between drumlins and other associated features, and from the sedimentological character of the drumlin sediments. The formation of depositional drumlins has been attributed by many researchers to shear stresses applied directly by ice that mould sediments at or near the glacier-bed interface (Menzies, 1979; Menzies and Rose, 1987). Alternatively, fluvial hypotheses have been proposed that advocate subglacial flood events as an essential component of drumlin formation. In the cavity-fill hypothesis of drumlin formation, Shaw (1983) and Shaw and Kvill (1984) suggested that the drumlin forms were related to the direct action of subglacial meltwater. Cavities that were initially eroded into the overlying ice by deep, broad sheet flows of meltwater were subsequently infilled with sediment during the declining flow. Shoemaker (1995) demonstrated that the initial cavities could have formed by corrasion from suspended sediment as vortices in a turbulent sheet of water attached to the ice roof and that the location of drumlins and their varying dimensions could be explained by variations in the velocity of the flow. The drumlin form that resulted from the infilling of cavities in the ice roof bear a striking resemblance to imagined infills of other forms eroded by turbulent flows.

The varied forms observed in depositional drumlins depart radically from the classical drumlin form of a blunt-nosed, half-ellipsoid shape with a long axis parallel to the inferred direction of ice movement. Shaw (1983) described three major forms of depositional drumlins in the drumlin field on the Athabasca Plains in northern Saskatchewan. Spindle forms are long, narrow features that are pointed at both ends and are generally symmetrical about their dividing plane. Parabolic forms are pointed at their stoss end and broaden in a downflow direction. They may be symmetric or asymmetric and commonly have superimposed minor ridges and furrows. Transverse asymmetrical forms have long axes that are not parallel to the direction of the formative flow and are highly asymmetric. These forms may also exhibit minor, superimposed ridges and troughs. The first line of evidence examined in the development of the cavity fill hypothesis was the observed similarity between these drumlin forms and other erosional marks (Shaw, 1983; Shaw et al., 1989). Spindle forms have analogs in erosional flute marks formed in a variety of materials by a variety of erosional mechanisms. Primary flute forms originate by erosion. Turbidite sole marks, though, appear as positive forms on the underside of turbidite beds because the erosional flutes are infilled by the waning stages of the flow that created them. Similarly, parabolic and transverse asymmetrical drumlin forms also have counterparts in a variety of erosional marks. The marks, though, are produced by more complex, separated turbulent flows.

In addition to the form analogy of individual drumlin types, patterns of erosional marks were also observed that have recognizable corresponding patterns in drumlin fields (Shaw, 1983; Shaw et al., 1989). The clustering into conjugate patterns and en echelon arrangements of forms were observed in many types of erosional marks at a variety of scales, as well as in drumlin fields. Furthermore, the different drumlin forms were reported to occur in clustered heterogenous assemblages in a manner that is also mirrored by other types of erosional marks. In different areas parabolic or transverse asymmetric forms dominated in number, while spindle forms were of secondary importance. The demonstrated form and pattern analogy between cavity fill depositional drumlins and other erosional marks formed in a range of materials by differing mechanisms was used to suggest that the drumlins were created by turbulent sheet flows of subglacial meltwater.

This conclusion was supported by the observations of Allen (1971) that differing physical and chemical mechanisms can produce erosional marks that are indistinguishable one from another. The common controlling factor for this form similarity is that the eroding mechanisms are characterized by separated fluid flows.

Shaw and Kvill (1984) and Shaw et al. (1989) examined the internal composition and structure of drumlins in the Livingstone Lake area of northern Saskatchewan. The drumlins were predominantly composed of waterlaid gravels and sands. The gravels were typically matrix supported, unstratified, poorly sorted and contained mainly angular clasts of local provenance. In accordance with observations of similar gravels, it was concluded that the drumlin sediment was rapidly deposited from suspension in hyperconcentrated flows. Conditions of high discharge and catastrophic flooding accounted for the sorting style characterized by the dispersion of pebbles, cobbles, and boulders in a sorted matrix, the lack of flow stratification, and the poorly defined bedding. A subglacial environment consisting of cavities in the ice where sudden flow expansion caused the rapid loss of velocity and transporting capacity accounted for the deposition of the material as discrete features. Shaw et al. (1989) concluded that a large scale, catastrophic flood lifted the ice from its bed. Cavities were eroded upward into ice that had been depleted of debris and boulders were plucked from the underlying bedrock. Once formed, the cavities acted as very effective sediment traps resulting in the short-distance transport of the predominantly local and angular clasts and other material. Evidence for the proposed sheet flow of meltwater was also found in the interdrumlin areas which were marked with numerous signs of fluvial erosion. Smoothly sculpted exposures of bedrock, scalloped erosional forms, concave distal slopes, and sichelwannen were interpreted as indicators of erosion by running water rather than glacial ice. The superimposition of glacial striations on these fluvially created forms indicated that they developed subglacially.

The structure of the sediments corresponded to the surface form of the drumlin and the general attitude of bedding indicated the drumlins increased in size by accretion. The bedding attitude corresponded to the external form of the drumlin though the land surface slope was generally steeper than the bedding dip. This was consistent with accretion in a cavity because the beds were draped over one another so that the maximum deposition was near the axis. As expected, the beds dipped outwards from the axis. The margins of the drumlins were former ice contact slopes. As sediment was banked against the cavity wall, beds developed so that their dips were lower than that of the drumlin slope. Sharpe (1987) noted the interbedded nature of many drumlin sediments. He concluded that the process by which they were deposited was an integral part of the drumlin building process and that the stratified material did not exist prior to drumlin construction. Mélange diamictons were also present, though of lesser importance. Their inclusion in the drumlin sediments was attributed to local failure, mass movement and subsequent resedimentation. The general lack of deformation of the drumlin sediments was considered to negate hypotheses that advocate the streamlining of preexisting materials by high basal stress conditions (Sharpe, 1987). Alternatively, an explanation that accounted for the accumulation of sediments in place beneath a melting ice sheet by mechanisms that involve the flow of subglacial water was favoured.

The strong similarity in form and pattern was extended to discussions of drumlins formed by erosion. The meltwater erosion of a substrate, whether it consisted of bedrock or unlithified surficial materials, was responsible for drumlins that were interpreted to be scour remnant ridges (Shaw and Sharpe, 1987). Horseshoe vortices that resulted from flow separation in turbulent fluids were shown to erode a characteristic form over a wide range of scales. By comparing erosional drumlins with small and medium scale subglacial fluvial forms, the drumlins were hypothesized to have been created by horseshoe vortices contained in sheets of meltwater. The resultant drumlins were characterized by a crescentic scour upstream of the ridges and lateral furrows on either side. Because this type of drumlin consisted of preexisting material, the composition and internal structure had little bearing on their genesis. Internal deformation was only expected where intense pressure gradients caused by the overlying ice produced structures such as diapirs and clastic dikes subsequent to the formation of the drumlin ridge (Shaw et al., 1989).

Similar to the development of the cavity fill hypothesis for depositional drumlins, the form of erosional drumlins was compared to smaller scale remnant ridges that were known to have formed in bedrock by the erosive action of subglacial meltwater (Shaw and Sharpe, 1987). Rat tails are commonly occurring, small-scale features that formed by fluvial erosion in a subglacial environment as a remnant ridge behind an obstacle. Preferential erosion occurred to create a crescentic scour upstream of the obstacle and paired, parallel furrows on either side of the medial ridge. The smooth and polished furrows become wider and shallower downflow leaving a medial ridge with a tapered and lower lee end. It has been demonstrated that rat tails are fluvially formed as horseshoe vortices develop in response to contact of the flow with an obstacle (Shaw and Sharpe, 1987). Shaw et al. (1989) identified features with a similar form but at a variety of scales that were also interpreted to have developed in response to horseshoe vortex action. These scour remnant ridges had a broad, convex proximal end and flanks that either converged to form a tapered tail or remained straight to form a remnant ridge of uniform width for its entire length. Finally, large-scale erosional drumlins were observed to characteristically have upstream crescentic scours, relatively flat crests that are accordant in height where they occur in groups, and adjacent furrows eroded into bedrock. As with the smaller scale features, the ridges were interpreted to be remnant forms left upstanding subsequent to the erosion of the furrows. The presence of identical morphological features despite the differences in scale was used as evidence to suggest that the features had horseshoe vortices in a turbulent flow of water as the common formative agent (Shaw and Sharpe, 1987). Evidence of glacial abrasion that occurred subsequent to the formation of the fluvially produced forms indicated that the meltwater erosion also occurred subglacially (Sharpe and Shaw, 1989). Furthermore, the formation of these types of marks, regardless of their scale, required that the forms be submerged in the formative flow. For features as large as drumlins therefore, a large-scale sheet of turbulent, subglacial meltwater was postulated to have contained the necessary vortices for their formation (Shaw and Sharpe, 1987). The widespread occurrence of these and other types of meltwater forms in glaciated areas was believed to indicate that subglacial sheet floods were a common and recurring event.

A significant aspect of the glaciofluvial hypotheses for the genesis of drumlins is the association of the drumlins with other features on the landscape. Shaw (1983) noted the close relationship between the drumlins of the Livingstone Lake drumlins in northern Saskatchewan and tunnel valleys, eskers, and large crescentic scours. Large eskers of tens of kilometres in length climb over drumlins in places indicating that they formed subglacially under hydrostatic pressure subsequent to the formation of the drumlins. Eskers were also found in large, sinuous channels of a fluvial origin that truncated some drumlins. The channels, therefore, are younger than the drumlins and older than the eskers. Since the drumlins and eskers formed subglacially, it follows that the channels formed subglacially as well. Drumlins that appear to be incompletely formed in their distal portion commonly give way to esker complexes. Crescentic scours are common features and are interpreted as sichelwannen that form at the leading edge of an obstacle submerged in a flow. The association between these features supports the suggestion that the drumlins were also formed by the subglacial erosion of meltwater. This argument was further strengthened by noting the relationship between the anabranched patterns of channels formed in the unglaciated Channeled Scabland of Washington State and the occurrence of fields of oriented, residual hills that have a shape comparable to some types of subglacially formed drumlins. Similarly, assemblages of erosional residuals created by the catastrophic drainage of proglacial lakes and consequent anabranched channels in the Interior Plains are very similar to observed assemblages of drumlin shapes (Shaw et al., 1989). Such channels result from high flood discharges where a single channel cannot accommodate the flow. Eskers and tunnel channels also exhibit anabranched patterns that are related to extreme discharges that can only be sustained for short periods of time, indicating that major floods also occurred beneath the ice.

The glaciofluvial hypotheses for the origin of erosional and depositional drumlins have in common a requirement for deep, broad subglacial sheet flows of meltwater. For the Livingstone Lake flood event (Shaw, 1983) that was believed to have formed the drumlins of the Athabasca Plains in northern Saskatchewan a flow that was at least the size of the 150 km wide field and at least as deep as the several tens of metres high drumlins was required. The velocity of the flow was estimated to range from 2 to 10 m/s based on the minimum velocity required to transport the boulders associated with the drumlins (Shaw et al., 1989). Estimated flow discharges were in turn calculated to range from 0.6 x 10^7 to 6 x 10^7 m^3/s and were interpreted to have flowed for a period ranging from 16 to 162 days. The estimated total discharge calculated to be 84.1 x 10^3 km^3 was subsequently revised, however, to be at least an order of magnitude smaller (Shoemaker, 1995). These values are comparable to those calculated for the glacial Lake Missoula flood events that created the Channelled Scablands of Washington State (Baker, 1978) and for the development of the tunnel valleys on the Scotian Shelf (Boyd et al., 1988). Floods of this magnitude would require the storage of meltwater in large reservoirs that may have existed subglacially, englacially, or supraglacially (Shaw et al., 1989; Shaw, 1996). While the existence of such reservoirs has not been definitively demonstrated, their development and catastrophic drainage has been shown to be theoretically possible (Shoemaker, 1991, 1992, 1995).

Floods of the magnitude determined for the formation of the Livingstone Lake drumlin field would necessarily have implications for the development of large tracts of the landscape. Kor et al. (1991) developed a regional scale view for the formation of sculpted erosional forms in a 70-kilometre wide area in southern Ontario. The area is characterized by an almost complete absence of lag deposits and a wide variety of sculpted bedrock forms that range in size from less than 1 metre to greater than 10 kilometres. The erosional forms were observed to exist in a systematic arrangement interpreted to indicate the geometry of the formative flow and its interaction with the bed topography. Kor et al. (1991) concluded that coherent flow structures in the formative flow interacted with the bed to produce a hierarchy of forms at different scales. The inferred aspects of flow scale, vorticity, separation, convergence, funnelling, strength, and direction were interpreted to indicate subglacial meltwater erosion rather than glacial erosion as the formative agent. The hypothesized meltwater event responsible for the erosion of the bedrock and the removal of material was at least 70 kilometres wide and had a discharge on the order of 10^7 m^3/s.

Shaw and Gilbert (1990) recognized that individual drumlin fields must have formed in response to a single event if a coherent regional flow pattern could be demonstrated. This coherence of flow argument was extended from groups of drumlins to groups of drumlin fields. The alignment of drumlins fields in southern Ontario and New York State was used to infer two major subglacial flood events. The earlier Algonquin flood event flowed over the highlands of central Ontario and southward through the uplands of New York. The subsequent Ontarian event flowed southeastward along the Lake Ontario and Lake Erie basins. To be considered a valid hypothesis, however, the proposed flood events must be shown to explain other landforms that are associated with the drumlins and the flood paths.

Regional scale studies of bedrock erosional forms (Shaw and Sharpe, 1987; Shaw, 1988; Sharpe and Shaw, 1989; Kor et al., 1990) support the hypothesized Algonquin and Ontarian flood events. In the Wilton Creek area of southern Ontario, large and small scale flutings and other erosional forms contained within a broad valley cut into bedrock (Shaw, 1988) were interpreted to represent the interaction of complex vortices in a turbulent flow of meltwater and the land surface. The bedrock flutings formed as regional, subglacial meltwater flows were confined between high ground and the overlying ice. Intense scouring and fluting occurred as flows accelerated and vortices were elongated. The vortices either wrapped around or created obstacles to flow and eroded the troughs that define the upstanding ridge. The superimposition of glacial striations exhibiting a deviation in orientation from the flutings on the water sculpted forms indicated water erosion occurred beneath the ice. For this erosion to occur, the glacier must have separated from the bed over a broad area by the flow of meltwater. Similarly, in southern Quebec the association of ice abraded and fluvially eroded forms (Sharpe and Shaw, 1989) suggested that the glacier was repeatedly lifted from its bed by episodic meltwater floods.

Tunnel channels have been demonstrated to be genetically related to drumlins (Shaw, 1983; Shaw et al., 1989). Tunnel channels containing flow indicators that are opposite to the regional slope, undulating long profiles and deep scour pools, eskers, drumlins, and gravel dunes suggest that the valleys formed subglacially and that they carried the total discharge during the rising and falling stages of the flood events. Subglacial sheet flows that were not contained within the tunnel channels lifted the ice from its bed to form flutings in interfluve areas (Shaw, 1988). These channels and other erosional features appear to be an integral part of landscapes that were periodically submerged by large-scale catastrophic flows of subglacial meltwater and lend support to the hypothesized existence of major subglacial floods that affected large portions of glaciated areas.

The Livingstone Lake flood that created the Athabasca Plains drumlin field in northern Saskatchewan was determined to have been of very large, catastrophic proportions (Shaw, 1983, Shaw and Kvill, 1984). Whether the total flow volume was 8.4×10^4 km^3 as initially calculated by Shaw et al. (1989) or at least a full magnitude smaller as reevaluated by Shoemaker (1995), the flood event would necessarily have left evidence of its passage outside of the drumlin field. Rains et al. (1993) described a coherent regional pattern of landforms and suites of landforms in Alberta. Downflow from the Livingstone Lake drumlin field, giant fluting and drumlins were observed throughout the province that were used with other associated features to reconstruct two major flow paths. Crosscut fluting fields indicate that subglacial flood events occurred at different times and at different scales. Belts of hummocky terrain that contain small areas of moraine plateaus were interpreted to represent zones of less efficient fluvial erosion as the overspill of meltwater from the main flow paths created interference zones of thinner water where they converged. Moraine plateaus composed of glacial, glaciofluvial and glaciolacustrine deposits were interpreted to be remnants of the preflood subglacial surface (Shaw et al., 1996). In contrast to the thick drift deposits of the high relief hummocky terrain, the flood paths are characterized by extensive tracts of scoured bedrock which later developed solonetzic soils. The scarcity of glacigenic deposits and the presence of flutings and remnant ridges, meltwater scour forms, and anabranching channels with elongate residuals all indicate intense subglacial fluvial erosion (Sjogren and Rains, 1995). Rains et al. (1993) also argue that the largely glaciofluvial landscape created beneath the ice was not significantly altered during deglaciation. Floods of the magnitude suggested would leave a low-gradient, debris free ice sheet that would not promote intense geomorphic activity.

Chapter 3

GEOMORPHOLOGY OF THE NORTH BATTLEFORD FLUTING FIELD

Introduction

The North Battleford fluting field is located in the northwest portion of the study area. The distinct parallel ridges and grooves of the fluting field trend from the northwest to the southeast in a large embayment in the Missouri Coteau. The fluting field begins abruptly at the northwest facing rim of the North Saskatchewan River valley and grades gradually into hummocky terrain at its distal end. The southwest margin of the fluting field is sharply demarcated by the river and the abrupt rise of the Missouri Coteau. The less distinct northeast margin of the fluting field, on the other hand, contains other features that are associated with the processes that formed the fluting. Consequently, the fluting field and its associated features define a natural geomorphological unit that comprises the main focus of this study. The geomorphological characteristics of the fluting field provide information regarding the relationship between its various elements as well as its process of formation.

Geomorphological Description

The North Battleford giant fluting field is located on the western edge of the Saskatchewan Plains in a large, preglacially carved embayment in the Missouri Coteau. The modern North Saskatchewan and Battle Rivers that once served as glacial meltwater channels and spillways, currently flow through the embayment forming the primary drainage system in the area (Fig. 1-3). In the North Battleford area, the North Saskatchewan River flows predominantly in a southeasterly direction. The only significant variation in its course occurs immediately west of North Battleford, where an 8 km long reach of the river flows southward before resuming its southeasterly flow. In addition, a slight shift in flow to a more easterly direction occurs for an 11 km long reach beginning 25 km southeast of North Battleford. The Battle River flows from the west to join the

North Saskatchewan River 4 km downflow from North Battleford. The main portion of the fluting field extends from the rim of the North Saskatchewan River valley west of North Battleford to approximately 60 km downstream where the valley makes a broad turn to join the South Saskatchewan River. The fluting field occupies a narrow zone that is bounded on the south by the North Saskatchewan River and the Eagle Hills that rise steeply 150 m above the lower land surface. The northern boundary is marked by the Thickwood Hills that rise more gently to an elevation 100 m above the Saskatchewan River Plains. The upland areas at the margins of the study area are a part of the Missouri Coteau which separates the Saskatchewan Plain from the Alberta plain.

The surficial material in the North Battleford area is predominantly till that overlies bedrock of the Cretaceous Lea Park Formation. Significant, though less continuous, deposits of glaciofluvial and glaciolacustrine material are also associated with the major geomorphic features (Fig. 1-5). While the North Battleford fluting field can be considered as a discrete entity, it is important that it be placed in a broader spatial context with other similar features. Gravenor and Meneley (1958) described the North Battleford fluting field as an extension of the Lac la Biche-Vermilion fluting field located to the northwest in Alberta. Isolated and less distinct fluting ridges and grooves can be identified beyond the northwestern limit of the North Battleford fluting field. The North Battleford fluting also has an orientation that is closely aligned with fluting to the southeast near Regina, Saskatchewan (Prest et al., 1967) and in North Dakota (Lemke, 1958; Bluemle, 1993).

Ridges in the North Battleford fluting field are characterized by their large length-to-width ratios, low relief, and adjacent grooves (Fig. 3-1). In general, the fluting ridges range in length from 0.5 to 4.5 km, with an average length of 2.5 km. Three ridges, however, are notable for their extreme lengths. Two measure 8.5 km long, while the third is 7 km long. The fluting ridges exhibit minimal variation in widths that range from less than 0.5 km to approximately 1 km. They typically have rounded to nearly flat-topped crests that rise 10 m or less above the grooves that border most ridges on one or both sides. Portions of some of the grooves contain shallow, spindle-shaped, water-filled depressions that are generally 0.2 to 0.4 km wide and 1 to 2 km long, though the largest is

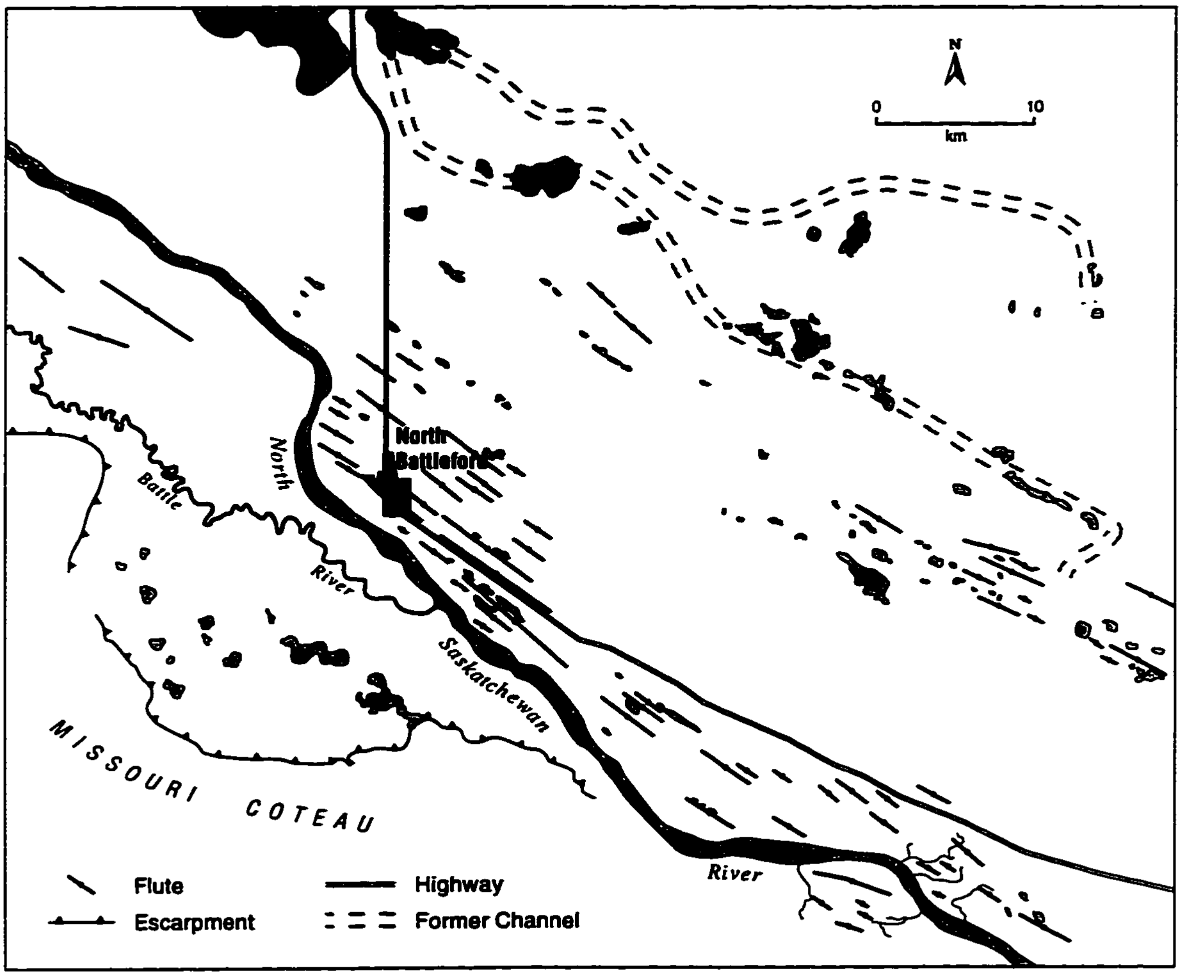

Figure 3.1. Geomorphological map of the North Battleford fluting field and associated features.

3.5 km long. The best developed fluting, including the three ridges with the extreme lengths, are those that formed in the drift on the broad, sloping approach to the northern bank of the North Saskatchewan River. The land surface slopes gently toward the river from an elevation of 560 m to 470 m at the river's edge. The fluting is very uniform and has a regular spacing of 0.7 to 0.8 km as defined by the distance between the lowest points in adjacent grooves. When viewed on aerial photographs (Fig. 3-2), the fluting is most easily identified by the linear, water-filled depressions of the grooves. Similarly, because the features are very large and have an extremely subtle surface expression, it is the position of the ponded water that provides the easiest method for recognizing the fluting on the ground. The fluting is particularly notable for its straightness and parallelism. Without exception the ridges trend S50°E to S60°E with negligible variation along their lengths. All of the fluting ridges are asymmetric in cross profile with a steeper, shorter side on the northeast and a gentler, longer side on the southwest (Fig. 3-3). The fluting ridges located near the base of the slope are somewhat narrower and more likely to be discontinuous in their length than those near the top of the slope. While most of the fluting ridges appear as discrete forms, a rudimentary en echelon pattern can be recognized in some features. In general, the fluting ridges are very uniform along their length with only minor superimposed lineations and localized gullying due to post-glacial stream development. Many of these streams have segments that flow in a direction opposite to the regional slope as they curve around the stoss ends of flutings (Fig. 3-1), indicating that the grooves decrease in depth in a downflow direction.

Near the village of Denholm, 25 km southeast of North Battleford, a small portion of the terrain abruptly takes on a more scoured appearance (Fig. 3-1). The fluting ridges generally have higher relief, sharper crests, deeper grooves (Fig. 3-4), and are less regular in longitudinal profile. Very subtle, low-relief lineations that have the same orientation as the flutings are evident on aerial photographs. The lineations occur on some of the fluting ridges, though they are more numerous in the intervening grooves. One small fluting ridge exhibits a slight curvature at its stoss end. The grooves and the flanks of the fluting ridges reveal evidence of erosion that contributes to their rough appearance. One low relief

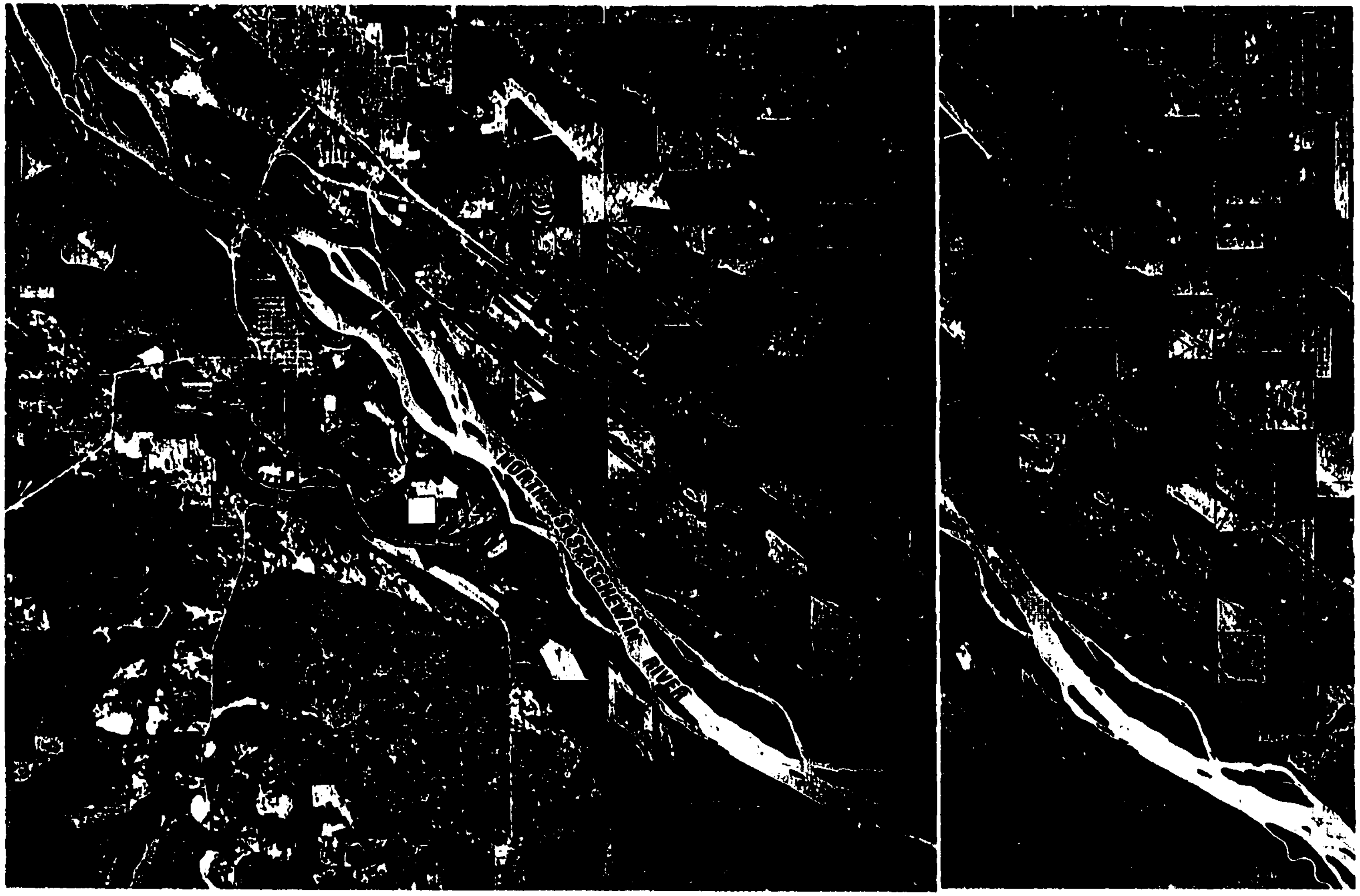

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Figure 3-2. Stereo aerial photographs of well-developed fluting in the vicintiy of North Battleford. Long, parallel ridges are separated by grooves that frequently contain water filled depressions.

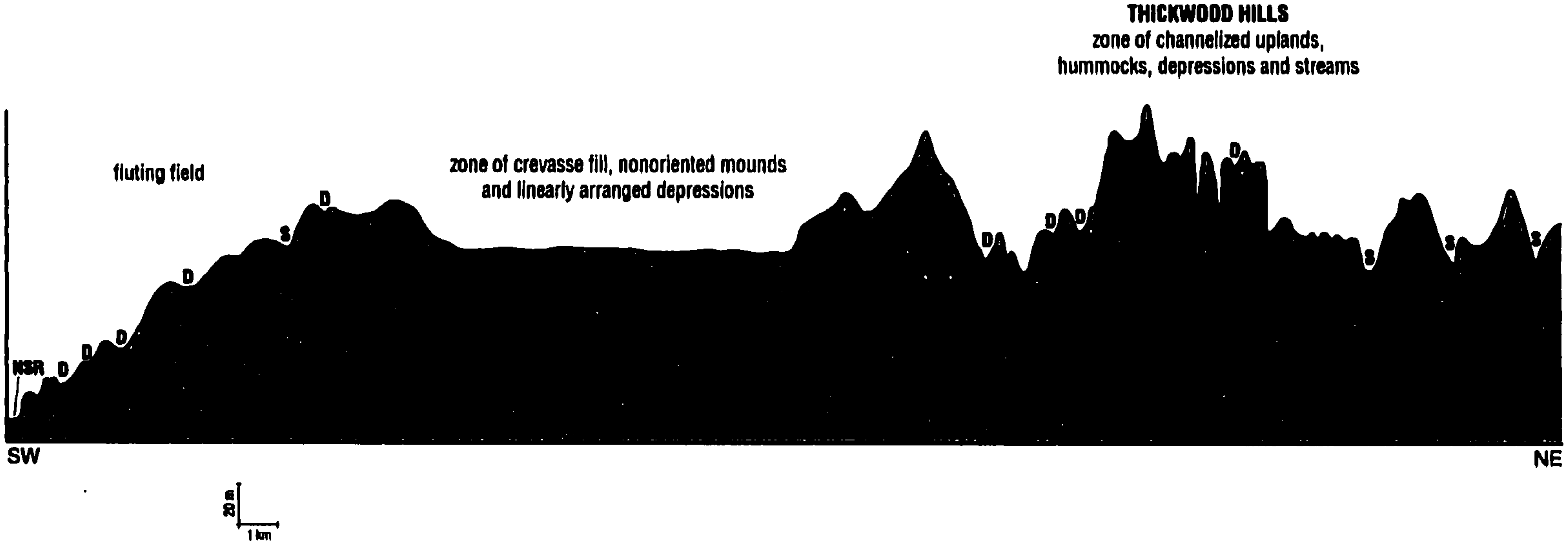

Figure 3-3. Cross-section of the North Battleford fluting field and associated features from the North Saskatchewan River (NSR) to the Thickwood Hills of the Missouri Coteau. The cross-section is perpendicular to the longitudinal axes of the fluting ridges. The fluting ridges are separated by waterfilled depressions (D) or streams (S). The margin of the Thickwood Hills is marked by broad channels that contain smaller waterfilled depressions and streams.

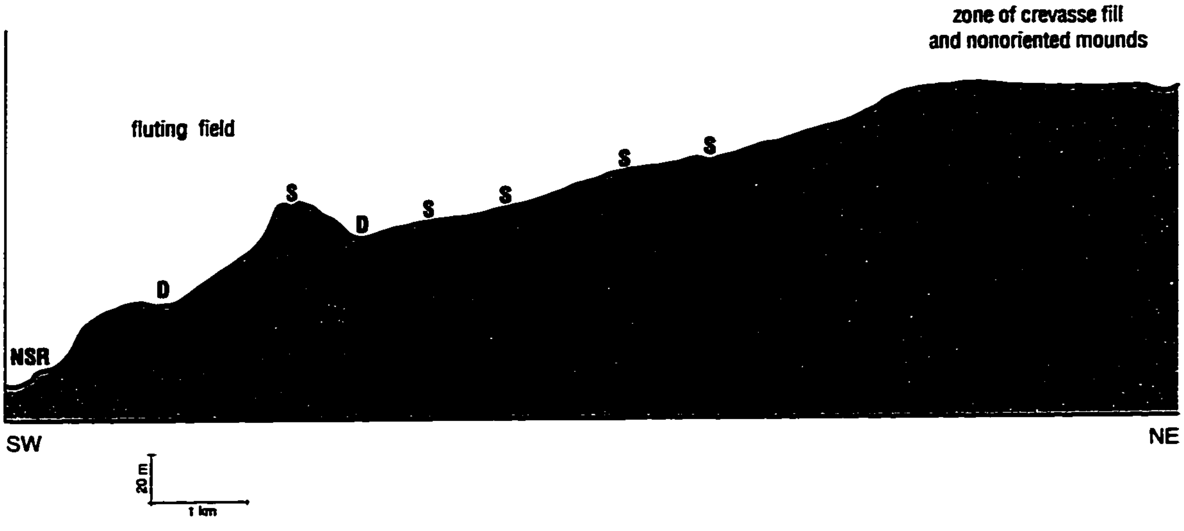

Figure 3-4. Cross-section of the fluting field in the vicinity of Denholm, 25 km southeast of North Battleford. Waterfilled depressions (D) and streams (S) are associated with sharp-crested, irregular fluting ridges.

fluting is unique in its appearance due a surface pattern that resembles ripples arranged transverse to the long axis of the ridges. Downflow, the fluting field quickly reverts to the more characteristic uniform features that are found upflow. The ridges and grooves, though, are of much lower relief and would be difficult to recognize as fluting if they were not associated with the easily identifiable features to the northwest. In this area, the fluting field occupies an increasingly narrow band between the North Saskatchewan River and the hummocky terrain located to the northeast. In the extreme downflow areas of the fluting field, the fluting is cross cut by an area of randomly distributed, circular depressions that is typical of low relief hummocky terrain.

South of Denholm, the North Saskatchewan River shifts its course slightly to the east (Fig. 3-1). The fluting ridges, that trend in a southeast direction, are truncated at their stoss ends or along portions of their flanks due to the development of the modern river valley. On the south side of the river, in a small area confined by the river bank and the steep face of the Missouri Coteau, is a set of small conjugate flutings that are heavily eroded along their flanks (Fig. 3-5). The upflow ends of some of the fluting ridges are obscured by Holocene slumping of the river valley wall. The fluting is also dissected by post-glacial streams that curve around the stoss ends of the ridges in a direction that is opposite to the regional slope. Associated with this area of fluting, are broad ridges that have tapering stoss and lee ends. They have the same orientation toward the southeast but are characterized by a pronounced "rippled" pattern that is created by series of superimposed, linear transverse forms that have boulders inset into their steep upflow sides (Fig. 3-6). Located between the ridges are broad channels that contain circular depressions, erosional remnants, and underfit streams.

Other variations in the character of the ridges and grooves are observable near the margins of the fluting field. Fluting located northwest of North Battleford is unique in the extreme narrowness of the fluting ridges and its striking appearance on aerial photographs (Fig. 3-7). The fluting trends S55°E for a distance of 10 km from the river's edge, though it is only near the river that the fluting is well defined. The very straight and parallel fluting ridges are contained in an area 1.6 km wide. They have lengths ranging from 3 to 4 km

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Figure 3-5. Stereo aerial photographs of the continuation of the fluting field on the south side of the North Saskatchewan River. Broad ridges (R) with a "rippled" pattern of boulders are associated with fluting ridges.

Figure 3-6. Transverse ridges with angular inset boulders on their stoss sides are superimposed on large northwest-southeast trending ridges. The ridges are located in an area bounded on the south by the Missouri Coteau and on the north by the North Saskatchewan River and are associated with the distal end of the North Battleford fluting field. The formative flow was from left to right.

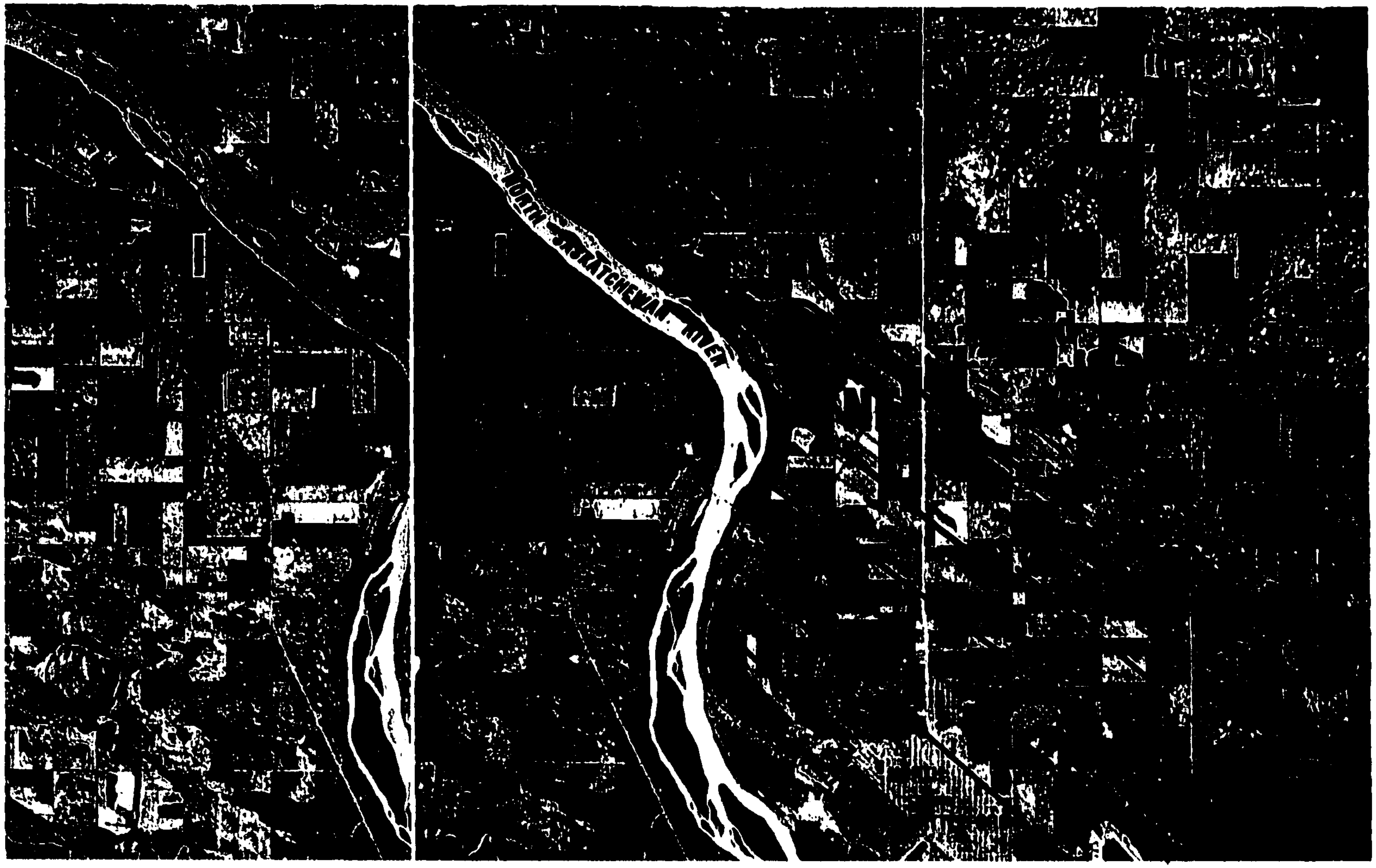

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Figure 3-7. Stereo aerial photographs of a portion of the North Battleford fluting field and associated features. Fluting ridges range from broad, widely spaced features to narrow, closely spaced features (NF). To the northeast the fluting field grades into a low relief plain (LRT) characterized by crevasse fills (CF), non-oriented mounds (m) and linearly arranged waterfilled depressions (d).

and an average wavelength of 0.26 km. Clearly defined grooves occur between the crests and, in some locations, contain small water-filled depressions. The ridges are generally accordant in height and have crests that range from rounded to sharp. One notable exception is a very narrow and very sharply crested ridge that is of lower relief than surrounding ridges. Its associated grooves are also broader, giving the impression that the grooves would have merged had the formative mechanism continued. It also reinforces the overall impression that the grooves, rather than the ridges, are the primary forms of the landscape. The well-defined ridges and troughs quickly grade into lower relief, ill-defined features in the downflow direction before merging into the well-developed large flutings near the river valley. On aerial photographs, the area has an overall appearance of having had a rake dragged over it. On the ground, however, it is very difficult to distinguish individual ridges or crests due to their extremely low relief and the irregular shrub vegetation cover (Fig. 3-8).

A transition in the nature of the fluting field also occurs laterally as the exceptionally narrow features give way to broader and more widely space fluting to the south (Fig. 3-7). A set of more subtly defined fluting ridges occurs that have individual widths of 0.4 to 0.6 km wide and an average wavelength of 1 km. The ridges have the characteristic asymmetric cross profile of the well-defined fluting with a shorter northeastern flank and a longer southwestern flank. The modern North Saskatchewan River has truncated this portion of the fluting field so that the stoss ends of some of the fluting ridges have been removed. Other ridges have clearly visible, intact stoss ends that begin less than 0.5 km from the valley wall. There is a marked consistency in the height and orientation of the ridges. They are very subtle features that rise approximately 10 m above the intervening grooves and trend S55°E. On the ground, a series of gentle undulations can be easily recognized that marks the positions of the fluting ridges (Fig. 3-9). Similar to the narrow fluting ridges to the north, there is one crest, truncated at its leading end, that is narrower, sharper, and lower than the others. It is flanked on both sides by broad depressions that give it the appearance that the two grooves would have coalesced to form a single broader groove had the formative process continued. In contrast to fluting ridges in the rest of the

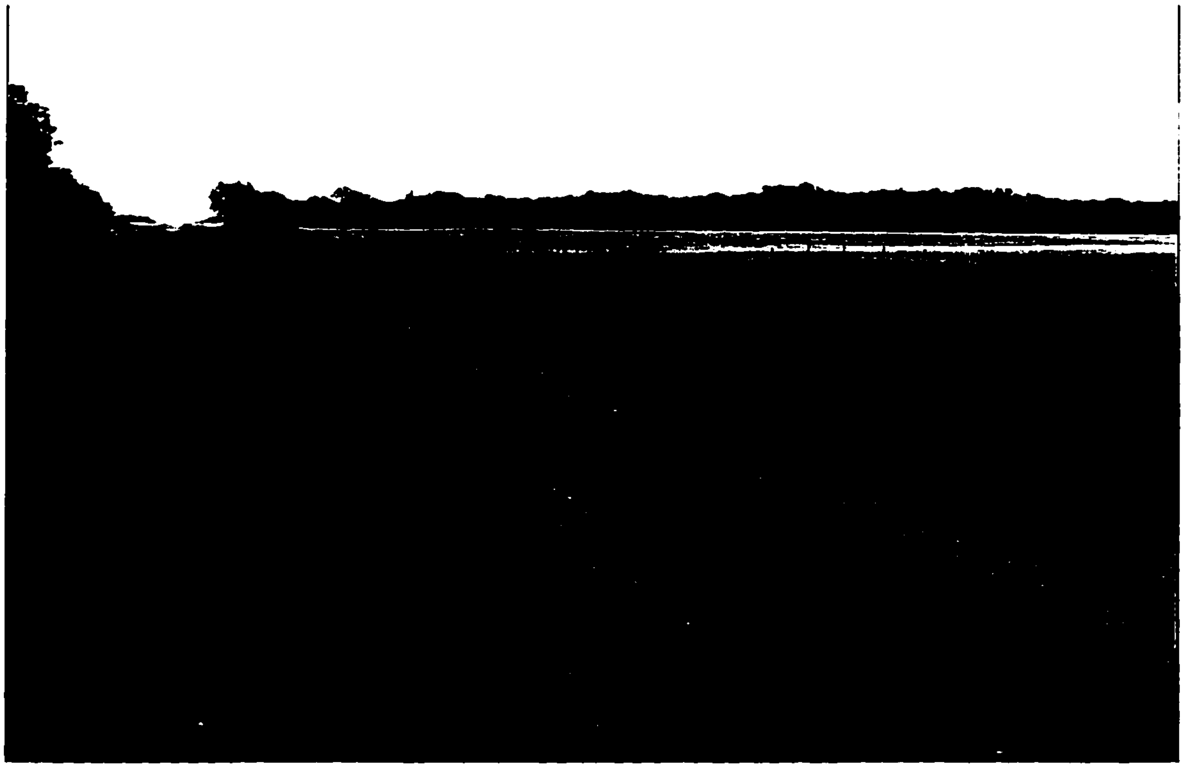

Figure 3-8. Narrow, closely-spaced fluting ridges and grooves beginning at the west-facing rim of the North Saskatchewan River have a very subtle surface expression on that is most easily discerned where the undulations are accentuated by fence lines. The direction of the formative flow was from the northwest (bottom left corner) to southeast (upper right corner).

Figure 3-9. The fluting field begins at the west-facing rim of the North Saskatchewan River on the right side of the photograph. The photograph was taken from the crest of a fluting ridge looking south toward the adjacent groove and the next fluting ridge. The distance between the crests of the ridges is 0.5 km and the difference in elevation between the crest of the ridges and the bottom the groove is approximately 10 m.

field, these ridges do not show the same marked uniformity along their longitudinal axes. Superimposed lineations oriented parallel to the long axis of the fluting ridges are common and are easily viewed on aerial photographs (Fig. 3-7), though they are too subtle to be easily distinguished on the ground. In addition, the fluting ridges in this area exhibit low points on their crests that correspond to low points in the intervening grooves, identifiable by the presence of small, water-filled, spindle-shaped depressions. Furthermore, the low points in adjacent grooves are perfectly arranged in a line that is perpendicular to the orientation of the flutings. A topographic map of the region reveals that the entire area near the southward flowing segment of the North Saskatchewan river is contained within a broad, very shallow, irregularly shaped hollow that rises 20 metres from its lowest point to its perimeter. The irregularities along the margin of the hollow are coincident with the position of the well-defined portions of the flutings.

Located downflow and immediately east of North Battleford, is a cluster of closely-spaced fluting ridges. In contrast to the smooth, uniform surface texture that is characteristic of most fluting in the area, this portion has a rough appearance (Fig. 3-10). The fluting is easily identifiable on aerial photographs by its shrub and pasture vegetation cover that is in sharp contrast with the surrounding cultivated land (Fig. 3-7). The fluting is also distinct in that it exhibits a strong conjugate pattern. The stoss ends of two fluting ridges merge into one larger fluting ridge with a resulting slight curvature at its upflow end. The two largest ridges in the cluster are separated by a smaller and narrower ridge that is located in a shallow groove. While the ridges have the typical asymmetric cross profile and rounded crests, the southwestern flank of the southernmost fluting is highly eroded and falls away steeply from the top of the ridge. The natural steepness of the flank is accentuated by the removal of aggregate resources from various sites along its length. The distinct appearance of this fluting, however, does not suggest a distinct formative mechanism. The northernmost ridge has the typical smooth appearance at its stoss end, while its lee end takes on the ragged appearance of the other ridges in the cluster. This suggests that the fluting was formed by a common process and that the differences in appearance must be attributed to some other cause.

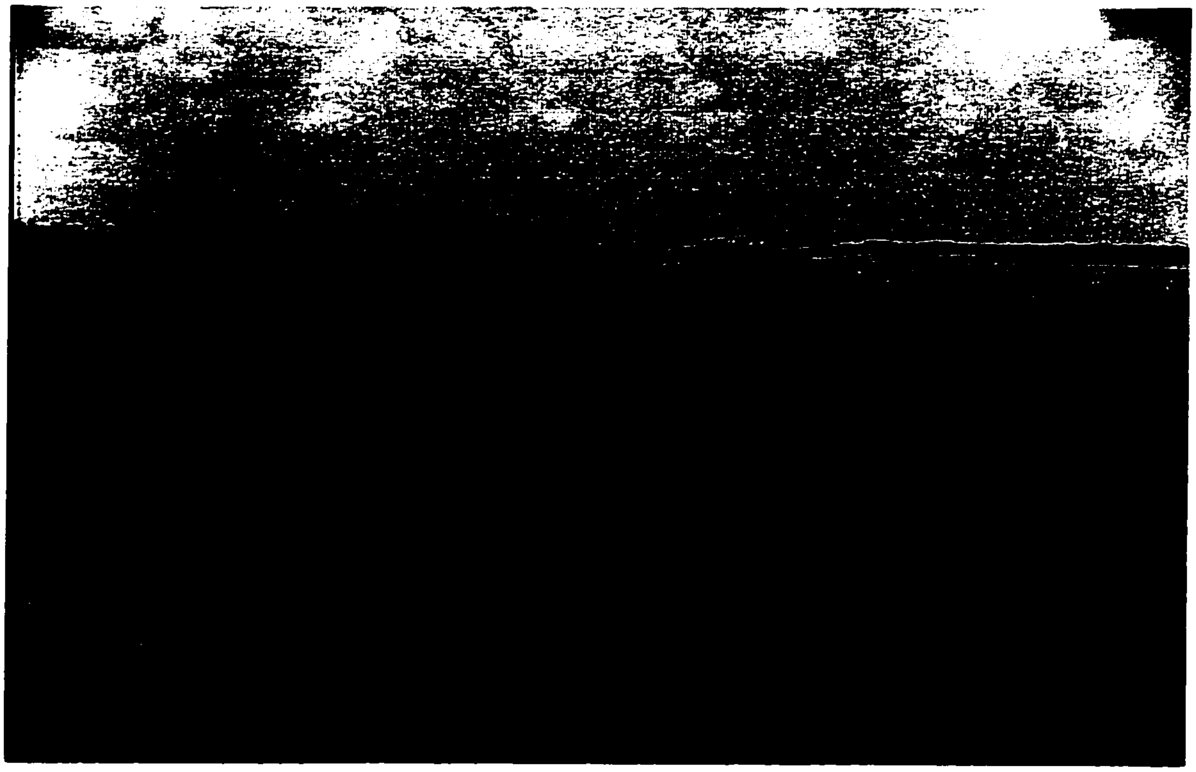

Figure 3-10. Fluting ridge and groove 9 km downflow from the west-facing rim of the North Saskatchewan River. The excavation is 100 m from the crest of the ridge on its northeast flank.

Interpretation

The geomorphological characteristics of the North Battleford fluting field illustrate many important aspects of the landscape that provide insights into its genesis. One of the most obvious large-scale features of the fluting field is its position in a large embayment in the Missouri Coteau. This position gives the impression that the configuration of the embayment exerted a broad-scale topographic influence on the formation of the fluting. The presence of fluting in highly varied topographic conditions throughout the Interior Plains (Gravenor and Meneley, 1958), however, shows that topography may be an influencing but not a controlling factor in the formation of fluting. In the North Battleford area, it is necessary to consider the role of the embayment in the Missouri Coteau in the development of the regional preglacial, glacial, and postglacial drainage system.

The embayment was initially carved by east trending rivers that developed as part of the Tertiary preglacial drainage system (Klassen, 1989). Christiansen (1967) identified the buried preglacial Battleford Valley that flowed eastward through the embayment from its headwaters in the Rocky Mountains. With repeated episodes of glaciation, proglacial spillways carried meltwater away from the ice margin. During the last episode of deglaciation in central Saskatchewan, meltwater flowed through the Battle and North Saskatchewan Spillways in the embayment as the glacier receded (Christiansen, 1979). These former spillways are presently occupied by the modern North Saskatchewan and Battle rivers. It is likely that similar spillways formed during earlier episodes of glaciation as well. It is reasonable to hypothesize that meltwater may also have flowed in subglacial tunnel channels in the embayment. Over time and in widely varying flow conditions, the presence of the embayment likely provided a topographically controlled preferred route for the regional-scale flow of water.

Stauffer et al. (1990) suggest a similar topographic control by the embayment in the Missouri Coteau on the regional flow of ice during the last episode of glaciation in their interpretation of the North Battleford fluting field. Based on the orientation of various fluting fields over a wider region, they concluded that a curving, streaming flow of ice developed as thin marginal ice moving generally toward the southwest was funnelled into the embayment forced to flow toward the southeast. The authors also postulated that during the time of the glacial maximum, a basal ice stream continued to flow southeastward through the embayment even though the general direction of movement of the overlying ice was to the southwest.

Stauffer et al. (1990) considered the relationship between the North Battleford fluting field and other fluting fields in the region. Their interpretation of the genesis of the North Battleford fluting field is, in part, premised on the postulated genetic relationship between the northwest-southeast oriented fluting in the North Battleford area and adjacent north-south oriented fluting. The assumption is made that the differently oriented fluting fields were formed at the same time by the same process and that the variation in direction reflects rapidly changing flow dynamics in the overriding ice. In contrast, other researchers (Gravenor and Meneley, 1958; Jones, 1982; Andriashek and Fenton, 1989) made the observation that the North Battleford fluting field is related to the Lac la Biche fluting field approximately 50 km to the northwest. These fluting fields have a common northwest to southeast orientation that is transverse to the direction of regional ice movement. In addition, the formative flow appears to have followed a preferred path through the embayment in the Missouri Coteau in the North Battleford area. The implication of the observed relationship between the North Battleford fluting field and similar features to the northwest is that the same formative process was active over a large region. In addition to large, distinct fluting fields, the formative flow also produced small isolated fluting ridges and grooves in the area that separates the main fields. The fluting forming process, therefore, operated with greater intensity at certain points along the flow path. Jones (1982) and Andriashek and Fenton (1989) hypothesized that the Lac la Biche fluting field was formed during a late phase of glaciation by a southeastward flowing lobe of ice. Jones (1982) concluded that a resurgence of the retreating Laurentide ice sheet was channeled toward the southeast by large bodies of stagnant ice, while Andriashek and Fenton (1989) concluded that the retreating ice margin separated into a series of discrete lobes. In both cases, the assumption was made that the fluting was formed by the direct action of overriding ice, thus necessitating explanations for the development of ice that flowed in a direction transverse to the general direction of ice movement.

A prominent feature of the North Battleford fluting field is its position in relation to the upflow facing rim of the North Saskatchewan River valley. The proximal end of the fluting field is very sharply defined at the rim of the valley in a manner that has been observed in other areas of fluting (Smith, 1948; Shaw, 1988; Tinkler and Stenson, 1991; Shaw et al., in preparation). Tinkler and Stenson (1991) and Shaw et al. (in preparation) described conditions of fluting formation that are controlled by the sheet flow of turbulent subglacial meltwater over a steep, upflow-facing step. These same conditions are met in the North Battleford area where the North Saskatchewan River flows from north to south. Shaw et al. (in preparation) described fluvial modelling experiments in which high velocity streaks were generated by vortices in the flow as they were carried over an upflow facing step (Pollard et al., 1996). Fluting-like forms resulted if the streaks were held in place by defects in the rim of the step. Tinkler and Stenson (1991) consider the formation of bedrock fluting at the rim of an escarpment. As water was forced up and over the escarpment rim, vortices developed in the flow that eroded concave grooves that left ridges as residual forms. The formation of bedrock fluting (Shaw, 1988; Tinkler and Stenson, 1991) and fluting (Shaw et al., in preparation) by this mechanism requires a large-scale, turbulent sheet flow of subglacial meltwater and the consequent separation of the glacier from its bed. The flow of meltwater as the formative mechanism for the fluting removes the requirement for southeast flowing ice (Jones, 1982; Andriashek and Fenton, 1989; Stauffer et al., 1990) and it does not restrict the time of formation of the fluting to a late stage of glaciation. Shaw et al. (in preparation) relate Lac la Biche fluting formation to the Livingstone Lake megaflood event which was concluded to have occurred near the time of the Late Wisconsin glacial maximum (Rains et al., 1993).

The regional-scale characteristics of the North Battleford fluting field that provide evidence for its glaciofluvial origin need to be mirrored in the smaller scale aspects of the fluting field itself. The ridges of the North Battleford fluting field are remarkably consistent in their form and orientation suggesting that all areas of the fluting field were formed at the same time by the same event. The ridges are very straight and groups of fluting ridges are generally accordant in height. Subglacial meltwater erosion has been shown to produce troughs with concave cross-profiles and spindle-shaped depressions (Shaw, 1988; Kor et al., 1991) that are comparable to the grooves in the North Battleford fluting field. Superimposed grooves on some fluting ridges and smaller scale, closely spaced fluting indicate that the formation of the grooves occurred at different scales. This is also characteristic of subglacial meltwater erosion (Shaw and Sharpe, 1987; Shaw 1988; Tinkler and Stenson, 1991).

The geomorphological characteristics of the fluting field also show that the grooves, rather than the ridges, are the primary form and that ridges are defined by adjacent grooves. While most fluting ridges are broad with rounded or flat crests, a small number of narrow, sharp-crested ridges also occur. They are bounded by large grooves that formed with the erosion of the intervening ridges. It is likely that had the erosive event continued, these ridges would have been completely removed as the grooves coalesced. Throughout the fluting field, the grooves gradually become shallower in a downflow direction until they merge with the surrounding landscape. In some cases, the deepest part of the groove wraps around the stoss end of ridges. The clearest examples of these are in fluting ridges that have stoss ends accentuated by post-glacial stream development. Streams that carry water into the North Saskatchewan River curve around fluting ridges in a direction that is opposite the regional slope. Tinkler and Stenson (1991) made similar observations in bedrock fluting and interpreted the longitudinal change as indicating a dissipation and spreading of the formative flow with a consequent reduced capacity for erosion. On a larger scale, the most prominent fluting in the North Battleford area developed at the proximal end of the fluting field where vortices in the formative flow were set up at the rim of the river valley. At the distal portion of the fluting field the grooves and ridges are smaller and more subdued, again indicating a dissipating, less erosive flow with increased distance from the valley rim.

The geomorphological evidence from the North Battleford area shows that the fluting field was created by a regional-scale process that acted with varying intensity along its flow path. The relationship between the sharply defined proximal end of the fluting field and the rim of the North Saskatchewan River valley is one that can be observed in other areas of large-scale fluting (Smith, 1948; Shaw, 1988; Tinkler and Stenson, 1991; Shaw et al., in preparation). Combined with observations of smaller scale features within the fluting field, the geomorphological evidence suggests that the fluting was formed by the preferential erosion of the grooves and that the erosive agent was the subglacial sheet flow of meltwater. To gain further insights into the origin of the North Battleford fluting field it is necessary to consider its sedimentary character. If the process of fluting formation is erosional, it is expected that the morphology of the ridges and grooves is independent of the sediments in the ridges and grooves.

Chapter 4

SEDIMENTOLOGY OF THE NORTH BATTLEFORD FLUTING FIELD

Introduction

Most sediment exposures in the North Battleford fluting field are located in active gravel and borrow pits in fluting ridges. I investigated these sites by logging the available sections and collecting samples where appropriate. Due to the orientation of the pits along the east-west and north-south road system, the exposures are close to, though not precisely normal or parallel to the longitudinal axes of the fluting ridges. Where data are available, the information gathered from the logging of exposures is augmented by maps and grain size analyses completed by the Saskatchewan Department of Highways and Transportation. Bore hole and well drilling data from the Saskatchewan Research Council provide valuable subsurface information that could not otherwise be obtained. The location of exposures and other sediment information are shown in Figure 4-1. By using these different sources of information, sedimentological data are available from most regions of the study area, providing a broad overview of the types of sediments that occur. The documented variation in the sediments allows for an interpretation of the genesis of the fluting field based on the relationship between the sedimentary characteristics of the fluting and its surface morphology.

Sediment Description

Exposure NB-01

Exposure NB-01 (NW24-44-17-W3) is located in a gravel pit 6 km northwest of North Battleford (Fig. 4-1) in a fluting ridge that is one in a series of low, broad ridges beginning at the rim of the North Saskatchewan River valley (Fig. 3-7 and 3-9). The west-facing exposure is situated 25 m downflow from the stoss end of a prominent fluting ridge and is approximately transverse to its longitudinal axis. The exposure cuts across the crest of the ridge and a portion of the gently sloping southwestern flank. The dominant sediment type

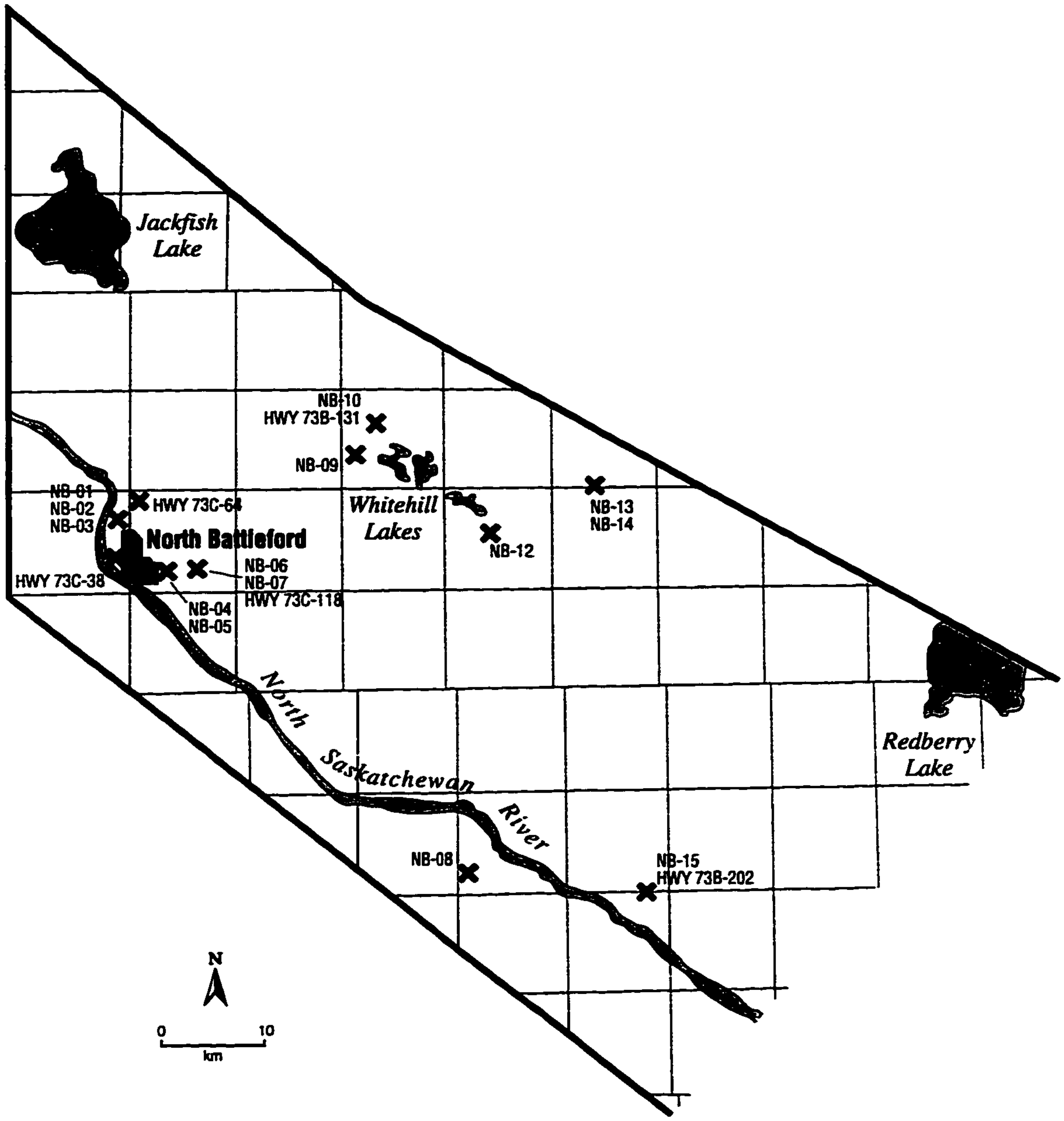

Figure 4-1. Location of study sites.

in the 3.5 m deep exposure is a mélange of unlithified clasts and ribbons of medium sand embedded in highly compacted diamicton that has a variable sand content (Figs. 4-2 and 4-3). The sand ribbons are generally horizontal, though some variation in dip is evident, including one sand clast with a nearly vertical long axis. The longitudinal extent of the sand ribbons is unknown. The sand bodies are more abundant near the base of the exposure and occur in conjunction with sand stringers that display differing degrees of mixing with diamicton (Fig. 4-4). The diamicton contains abundant, generally angular to sub-angular, pebbles of mainly crystalline rock, though fewer numbers of quartzitic and carbonate clasts are also present. Clast fabrics have a moderately strong preferred orientation with S_1 values of 0.594 and 0.604. The samples also showed a preferred dip of the clast long axes in an up-glacier direction. The preferred orientations of the fabrics (A=196.2° and 181.2°) are not parallel to the fluting ridges suggesting that the formation of the fluting is related to processes that are different from those that resulted in the deposition of the sediments.

A prominent and continuous boulder pavement of faceted, crystalline and carbonate rocks is located at the top of the diamicton. The boulder pavement is generally one clast thick as it defines a plane that arcs gently downward in close approximation of the morphology of the southwest flank of the fluting ridge (Fig. 4-2). The boulder pavement is overlain by 1 m of medium to coarse bedded sand that dips 10° in a direction perpendicular to the long axis of the fluting ridge. About 5 m south of the exposure the sand unit has a thickness of more than 3 m with no evidence of an underlying boulder pavement. The sand contains small and infrequent till balls and cobbles and pebbles. At the site of the exposure, the surface material is completely removed due to previous excavation of the pit. At nearby sites, however, the sand is capped by 0.5 m of multimodal gravel that contains material ranging from sand to cobbles and scattered boulders. The surface gravel is slightly imbricated, indicating a north to south palaeoflow that is approximately transverse to the long axis of the fluting ridge. The undisturbed stoss end of the fluting ridge is paved with a dense cover of boulders (Fig. 4-5).

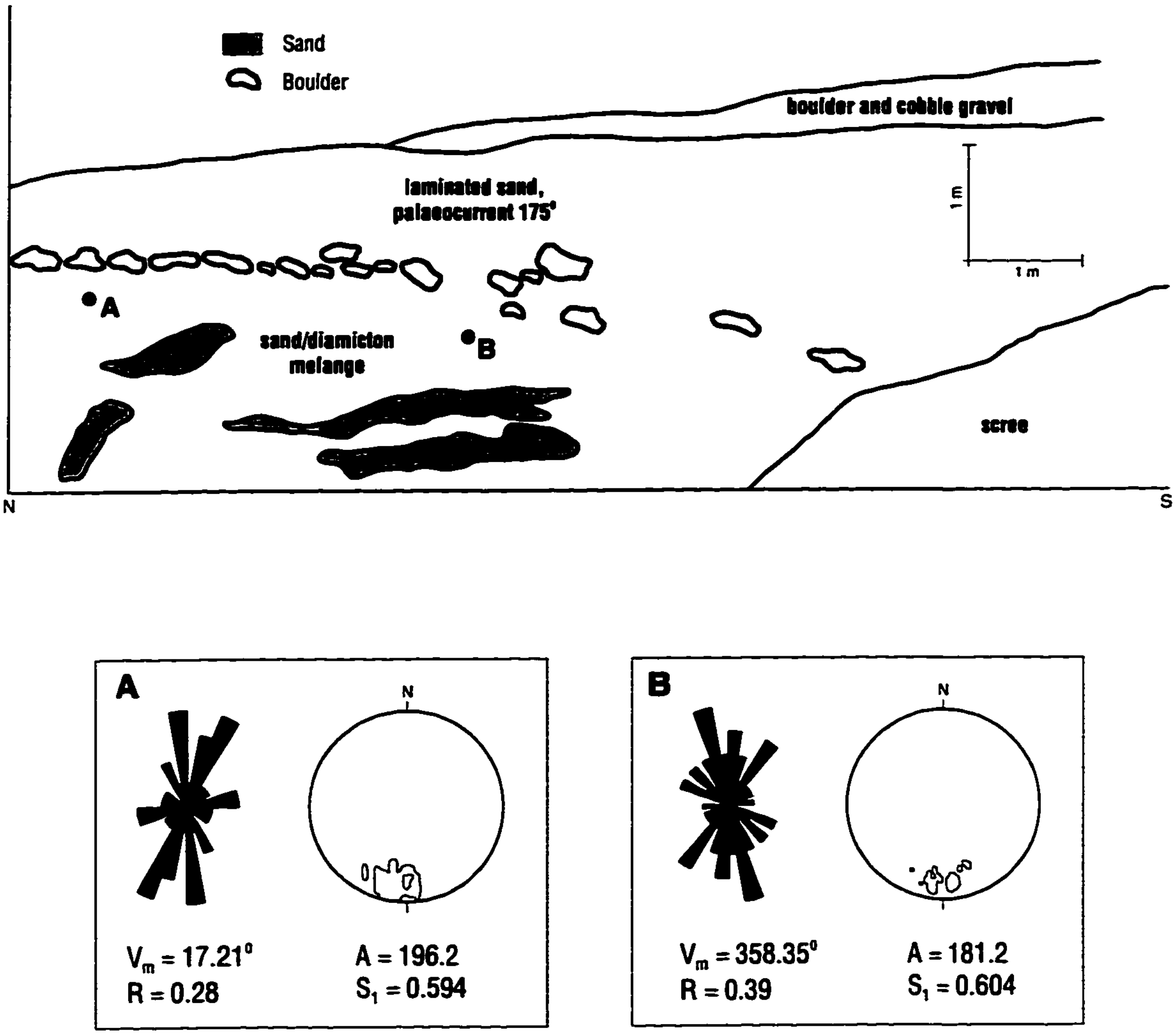

Figure 4-2. Exposure NB-01 (NW24-44-17-W3), sedimentary sequence and clast fabrics. V_m=2-D rose diagram vector mean, R=normalized 2-D vector strength, A=azimuth of the principal eigenvector, S_1=principal eigenvalue. Contour interval=1σ.

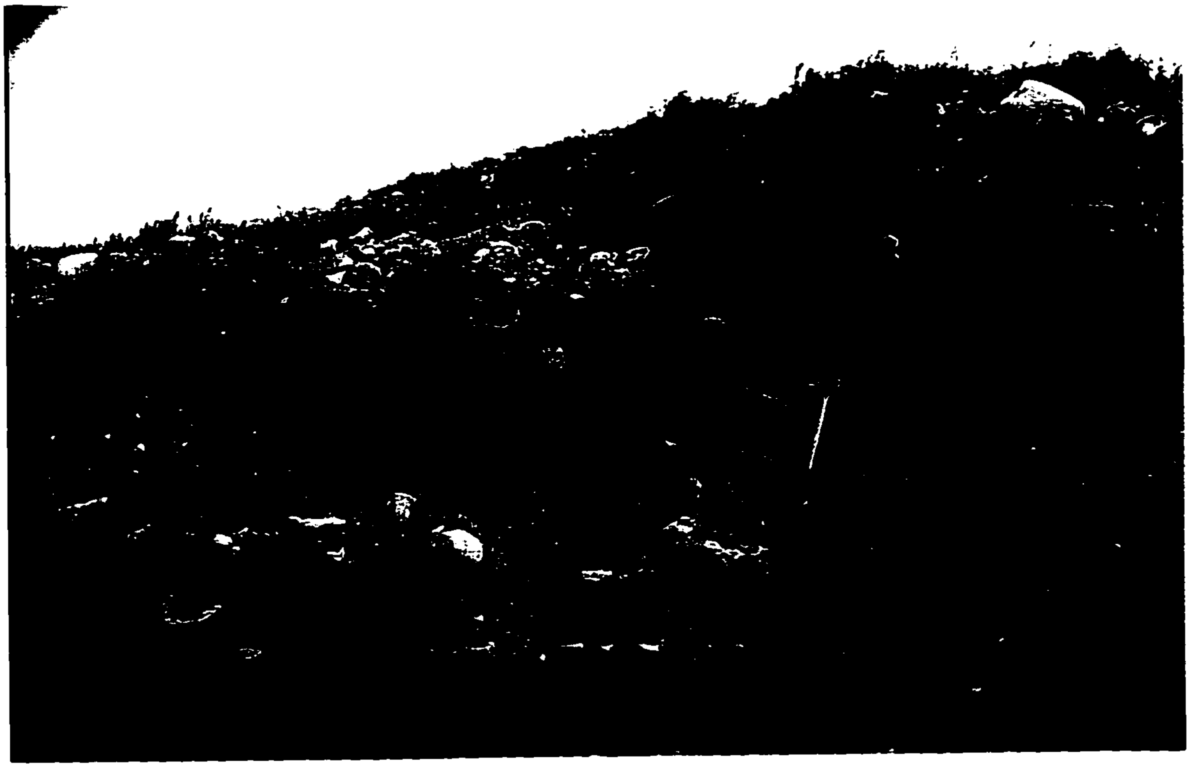

Figure 4-3. Exposure NB-01 is located near the crest of a fluting ridge at the rim of the North Saskatchewan River valley and is approximately transverse to the longitudinal axis of the ridge. The flow direction that formed the fluting was toward the southeast (into the photograph). Disturbed coarse gravel at the surface and a unit of plane-bedded sand overlie a boulder pavement and a lower unit of mélange.

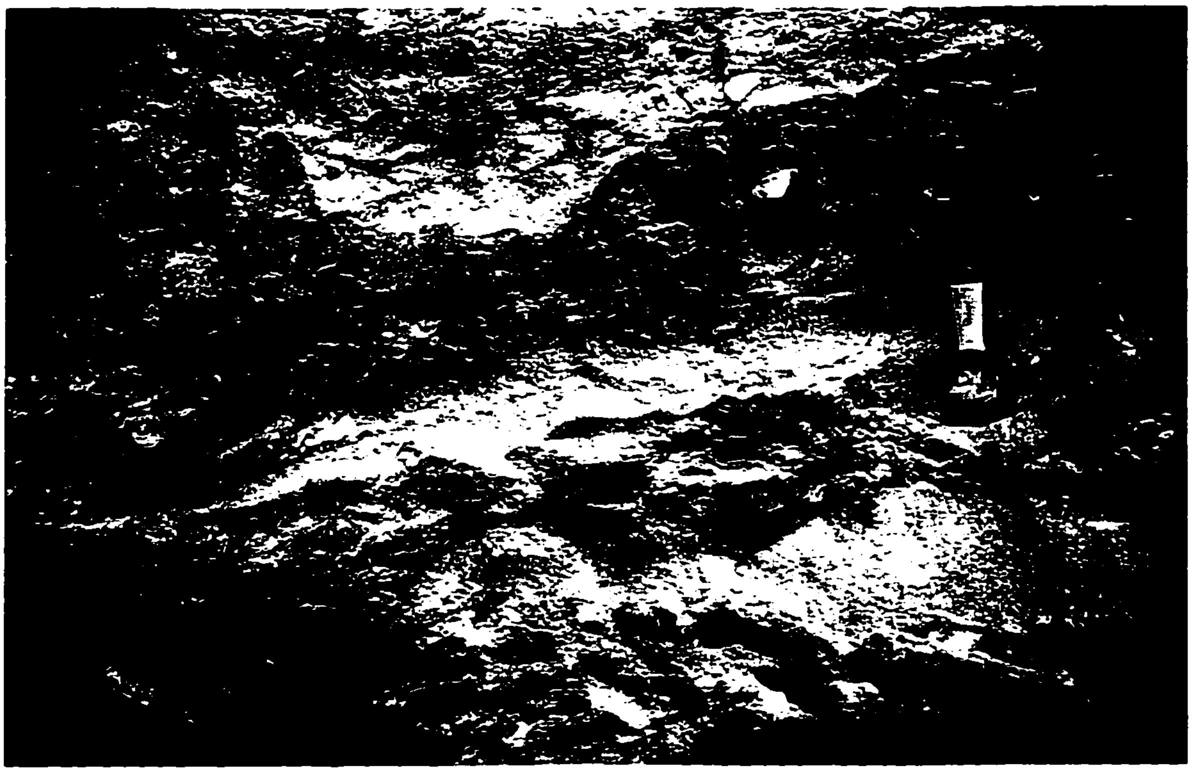

Figure 4-4. Mélange at the base of exposure NB-01 is composed of sand ribbons and stringers that display variable degrees of deformation and mixing with diamicton.

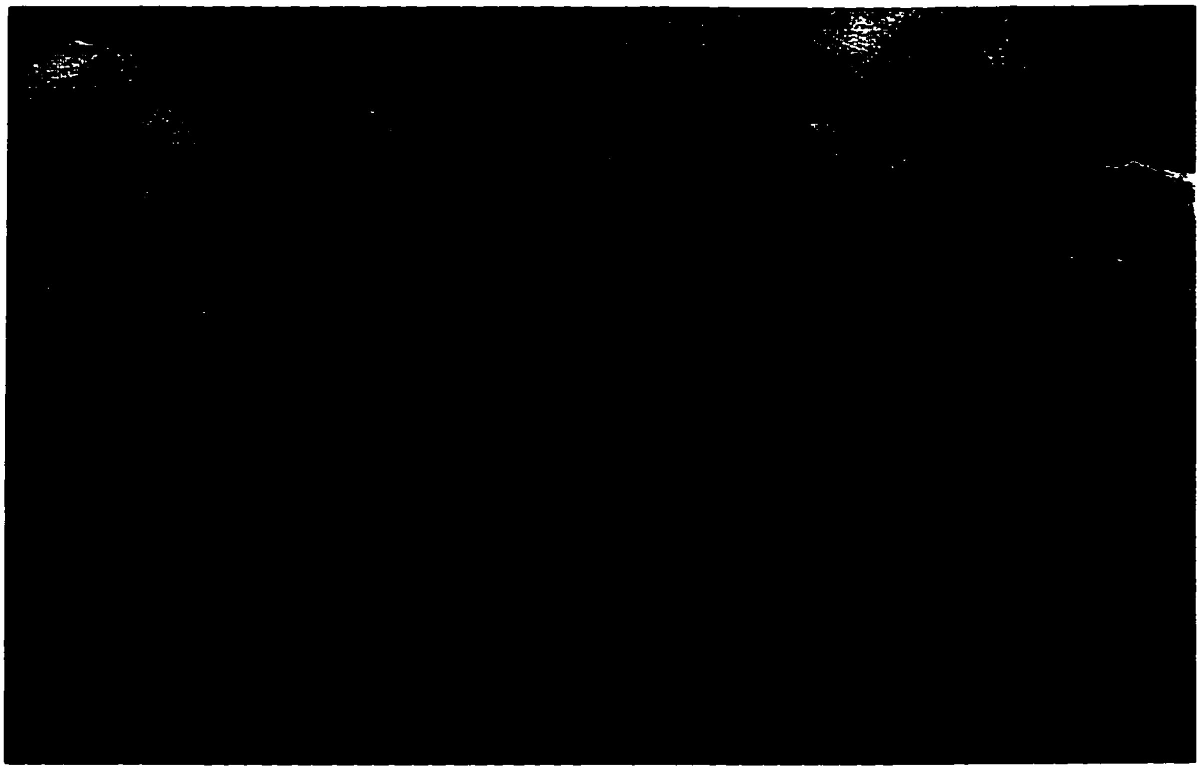

Figure 4-5. The stoss end of the fluting ridge associated with exposure NB-01 is paved with a dense cover of boulders. The direction of flow was from left to right. Exposure NB-01 is located in the pit at the right side of the photograph.

Exposure NB-02

Exposure NB-02 is located in the same gravel pit as exposure NB-01 (Fig. 4-1) as it extends 0.5 km to the southeast along the southwest flank of the fluting ridge. The gravel pit lies parallel to the long axis of the fluting ridge, exposing the sediments along its flank approximately 30 m downslope from the crest. The exposed sediments are composed primarily of sand and gravel overlying diamicton. Nowhere do the surface stratified sediments exceed 3 m in thickness. Nearest to the crest of the fluting ridge, southward dipping deposits of bedded sand alternate with units of sand containing very small and abundant till balls (Fig. 4-6). Individual units are 1 to 2 cm in thickness. The sand beds are overlain by a 1.2 m unit of sandy pebble gravel that contains numerous till balls of variable size and a maximum diameter of 0.7 m. The surface deposit, 0.3 m of slightly imbricated sandy cobble gravel (Fig. 4-7), was deposited by a southward flow. The multimodal, surface gravel deposits are traceable down the flank of the fluting ridge for 50 m. At the lowest point in the gravel pit, 2 m of gravel rests directly on diamicton with no intervening sand unit. Generally throughout the deposit, the surface sediments are thinnest and coarsest near the crest of the fluting ridge and become thicker and finer with increasing distance down the flank of the ridge.

Exposure NB-03

Exposure NB-03 (NE26-44-17-W3) is located north of exposure NB-01 (Fig. 4-1) at the stoss end of a low fluting ridge truncated by the rim of the North Saskatchewan River valley. It is separated from the fluting ridge associated with exposure NB-01 by a single shallow groove. The distance between the crests of the fluting ridges is 0.8 km. A large pit in the face of the river bank exposes 50 m of medium-fine, plane and cross bedded sand that generally dips 10° toward the west. The lateral extent of the sand deposit does not exceed 300 m as it slopes steeply downward on both its northern and southern flanks from its apex to the base of the exposure. Overlying the sand deposit, at a position that corresponds to the crest of a fluting ridge, is a 1 m unit of sand and diamicton. The sand is incompletely mixed with the stony diamicton and contains no observable discrete blocks

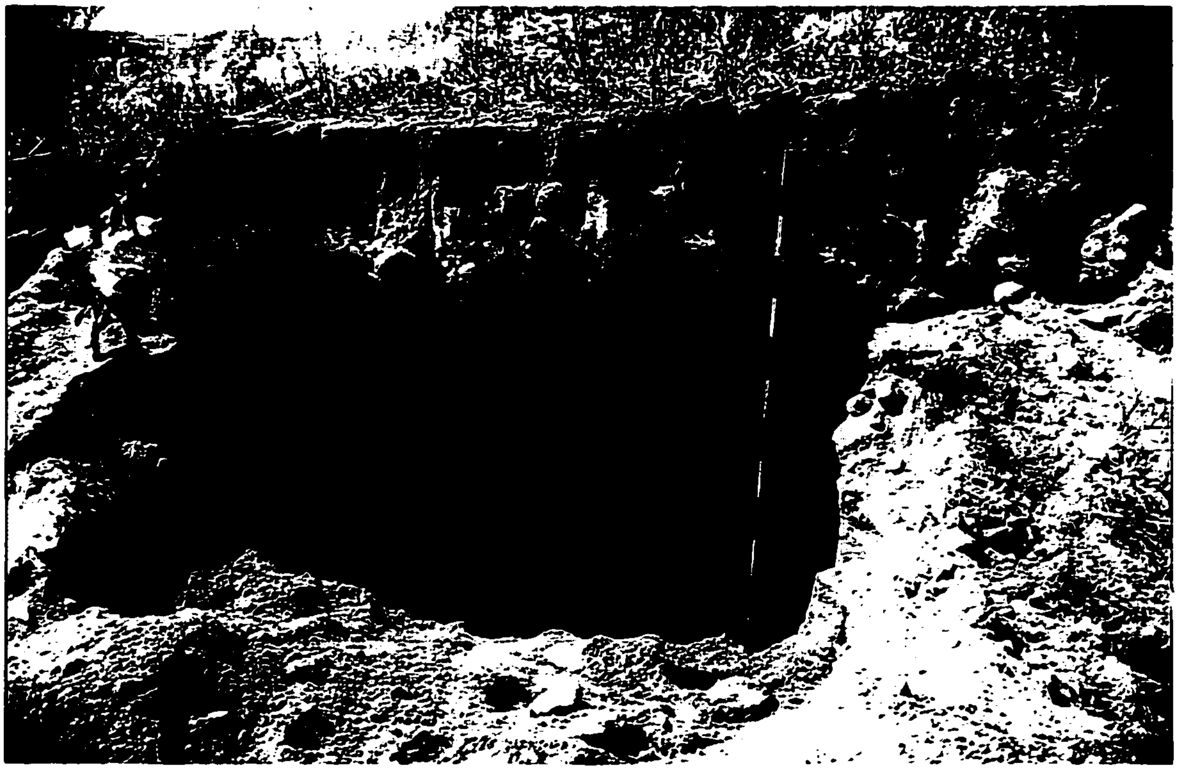

Figure 4-6. Exposure NB-02 is located 0.5 km southeast of exposure NB-01 along the southwest flank of a prominent fluting ridge. Approximately 30 m downflank from the crest of the fluting ridge, bedded sand units (light coloured layers) that alternate with units of sand mixed with very small till balls (dark coloured layers) are overlain by a unit of gravel that contains large till balls. The surface sediments are imbricated coarse gravels and a mantle of fine sand and silt (disturbed at the location of this photograph).

Figure 4-7. Multimodal surface gravels deposited on the southwestern flank of the fluting ridge associated with NB-01 and NB-02 extend from the crest of the ridge to at least 50 m downflank. The deposits become thicker and finer with increasing distance from the crest (toward the right in the photograph). The dark soil horizon marks the natural surface that is overlain by disturbed material.

or ribbons of sand. In some places the diamicton unit contains neither sand nor large clasts, with the exception of infrequent cobbles. The top of the diamicton is demarcated by a boulder pavement. Where the surface materials are not disturbed, a 0.8 m unit of fine, massive sand rests on the boulder pavement. The northern margin of the exposure consists of 2 to 3 m of very compact, massive, and blocky diamicton that contains relatively few clasts. The lower boundary of the diamicton rests on the northern flank of the sand deposit. The top of the diamicton unit corresponds to the surface morphology of the northwestern flank of the fluting ridge. Sediment beneath the southeast flank of the fluting ridge is also primarily diamicton, with minor surface deposits of gravel. At this site at the bank of the North Saskatchewan River, the original surface morphology of the fluting ridge has been extensively modified by Holocene alluvial and colluvial processes.

Site HWY73C-38

Site HWY73C-38 is a rehabilitated Department of Highways and Transportation gravel pit (NW13-44-17-W3 and SW24-44-17-W3) that is located south of exposure NB-01 (Fig. 4-1) along the southeast flank of a smaller fluting ridge. Though no information is available regarding sedimentary structures or palaeoflows, grain size data indicate that the distribution of sediment types is similar to that associated with the fluting ridge to the north. The gravel pit extends for a distance of 1 km along the flank of the fluting ridge and is roughly parallel to the long axis of the ridge. The northern edge of the pit ranges from 25 to 50 m downflank of the crest of the ridge and extends into, but does not reach, the lowest point of the adjacent groove. The stoss end of the ridge is composed predominantly of diamicton and small pockets of gravel and sand. Stratified material lies both on top of and below diamicton. In cross section, the sediment is generally coarsest near the crest of the ridge and finer downflank, with silt near the bottom of the groove. Small areas of gravel, however, also occur near the base of the groove. In longitudinal section, the sediments tend to coarsen toward the southeast as gravel becomes more prevalent than sand. Test hole data in this area show that 1 to 2 m of diamicton is commonly found on top of sand and silt. Based on small exposures of imbricated multimodal gravel at the surface, it appears that the direction transport of the surface stratified material was from north to south, transverse to the long-axis orientation of the fluting ridge.

Site HWY73C-64

A second inactive and overgrown Department of Highways and Transportation gravel pit is located at NW31-44-16-W3 (Fig. 4-1) in the zone of very closely spaced fluting ridges and grooves northwest of North Battleford (Fig. 3-7). The gravel deposit is located along the southwest flank of the fluting ridge that forms the southern edge of this zone. The widespread sand and gravel deposits are, at most test holes, covered by 1 to 2 metres of diamicton. No information is available regarding sedimentary structures or palaeoflow direction. The coarsest deposits are located near the crest of the fluting ridge and finer material in the adjacent groove. None of the fluting ridges in this zone has surface sand and gravel deposits associated with it. A limited number of exposures in ditches in the area are less than 1 m deep and show only diamicton and a surface layer of boulders (Fig. 4-8). The fluting in this area is expressed as very low relief, closely spaced undulations (Fig. 3-8).

Exposure NB-04

Exposure NB-04 (NW9-44-16-W3) is located on the eastern perimeter of North Battleford (Fig. 4-1) in a small borrow pit near the stoss end of a large fluting ridge that continues for another 17 km toward the southeast. It is aligned with the fluting ridge associated with exposure NB-01, though the ridges are not continuous. They are separated by a distance of roughly 6 km that is characterized by very subtle ridges and grooves that have a maximum relief of less than 2 m (Fig. 4-9). The fluting in this area is composed primarily of diamicton with a dense surface cover of boulders and sporadic, small surface deposits of coarse gravel along the southwest flanks of the ridges.

The fluting ridge associated with exposure NB-04 has a width of 1 km, a long, gently sloping southwest flank, and a steeper, shorter northeast flank that is typical of all the

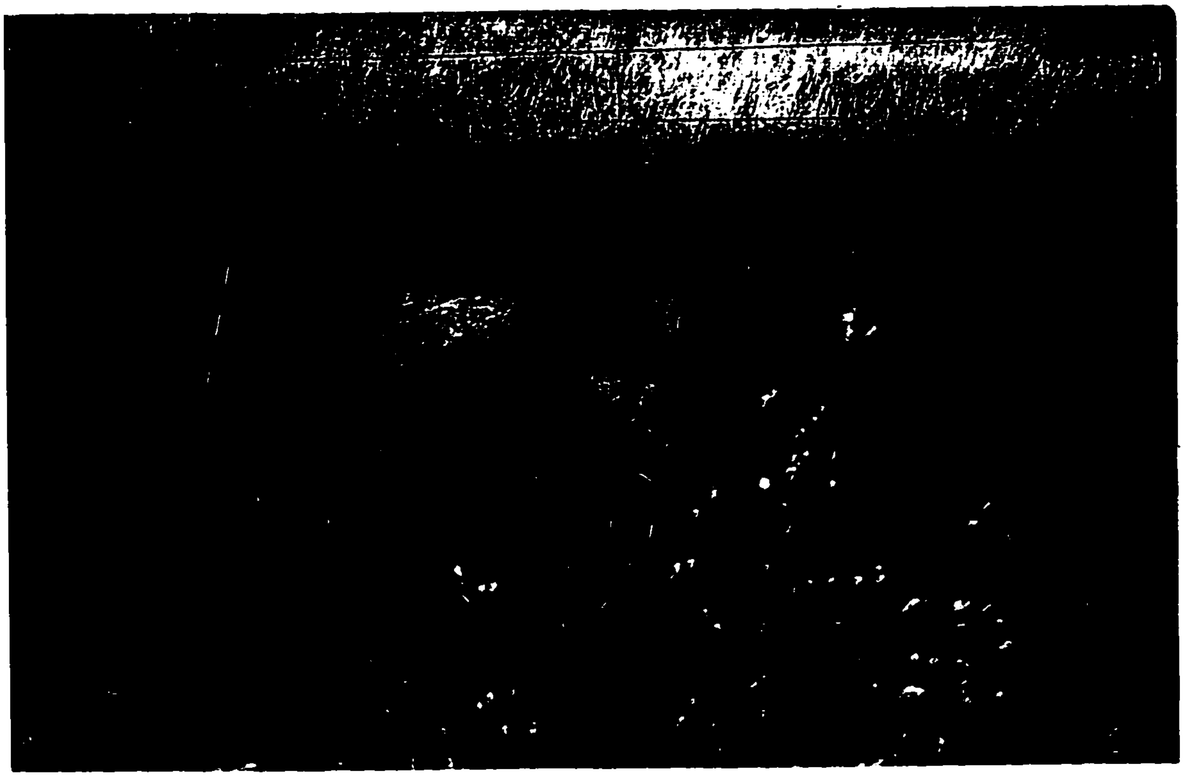

Figure 4-8. A surface boulder pavement embedded in diamicton characterizes a zone of very narrow and closely spaced fluting ridges and grooves that begins at the rim the North Saskatchewan River and extends 10 km toward the southeast. The flow direction was from the bottom right corner of the photograph to the top left The surface morphology in this area is very difficult to discern without the aid of aerial photographs. The scale is marked in 10 centimetre intervals.

Figure 4-9. Very subtle fluting ridges and grooves in the vicinity of North Battleford separate well-defined fluting that begins at the rim of the North Saskatchewan River to the northwest from the largest fluting ridges and grooves that occur to the southeast. This photograph was taken from the crest of a ridge looking toward the northwest along its axis. Grooves are marked by greener vegetation. Stone piles shown on the right edge of the photograph indicate the prevalence of surface boulders.

well-developed fluting ridges in the area. The surface of the fluting, however, is marked by superimposed, smaller scale ridges and grooves. Exposure NB-04 cuts through the southernmost edge of the fluting ridge across a smaller ridge defined by a superimposed groove (Fig. 4-10) that has a width of approximately 80 m.

The west facing, 9 m wide and 3.5 m deep exposure reveals a variety of textures and sedimentary structures. The dominant features are highly variable diamicton and deformed, elongate bodies of sand (Figs. 4-11 and 4-12). At the base of the exposure is a massive unit of highly compacted diamicton that is overlain by a unit of mélange. The mélange is composed of diamicton mixed with varying amounts of sand. Sand also occurs as ribbons, stringers and small, soft-sediment clasts that are encased in the mélange. The boundaries of the sand bodies are generally very well defined. Many of the ribbons retain undisturbed primary cross bedding structures (Fig. 4-13) or are massive beds of sand. The sand ribbons span the width of the exposure (Fig. 4-11) though their longitudinal extent could not be determined. One sand ribbon contains numerous vertical microfaults along its extent with little additional deformation of the primary bedding structures (Fig. 4-14). The northern edge of the exposure corresponds to a broad groove superimposed on the larger ridge. The lowermost sediments consist of a large mass of sand-rich mélange that extends upward into a narrow, horizontal neck that has abundant pebbles and cobbles (Fig. 4-11). The mélange unit is overlain by a discontinuous pavement of angular boulders (Fig. 4-11) that extends across a portion of the exposure in a 1 m wide band that conforms roughly with the surface morphology of the ridge. The boulder pavement is best defined near the crest of the ridge and toward the southwest flank. Sand ribbons occur between upper and lower boulders at the northern extent of the boulder pavement. The mélange and boulder pavement are overlain by 1 to 1.5 m of massive, stone-rich diamicton with apparent rhythmic variations in clay content near the groove on the north side of the ridge. The remainder of the diamicton unit is very uniform in composition. The surface material consists of a very thin, coarse gravel deposit that has been largely disturbed due to excavation.

Figure 4-10. Exposures NB-04 and NB-05 are located in a borrow pit that is excavated into a smaller ridge defined by a superimposed groove on the southwestern flank of a 1 km wide and 17 km long fluting ridge. The width of the smaller ridge is approximately 80 m. This photo was taken from the top of the exposure looking toward the southeast.

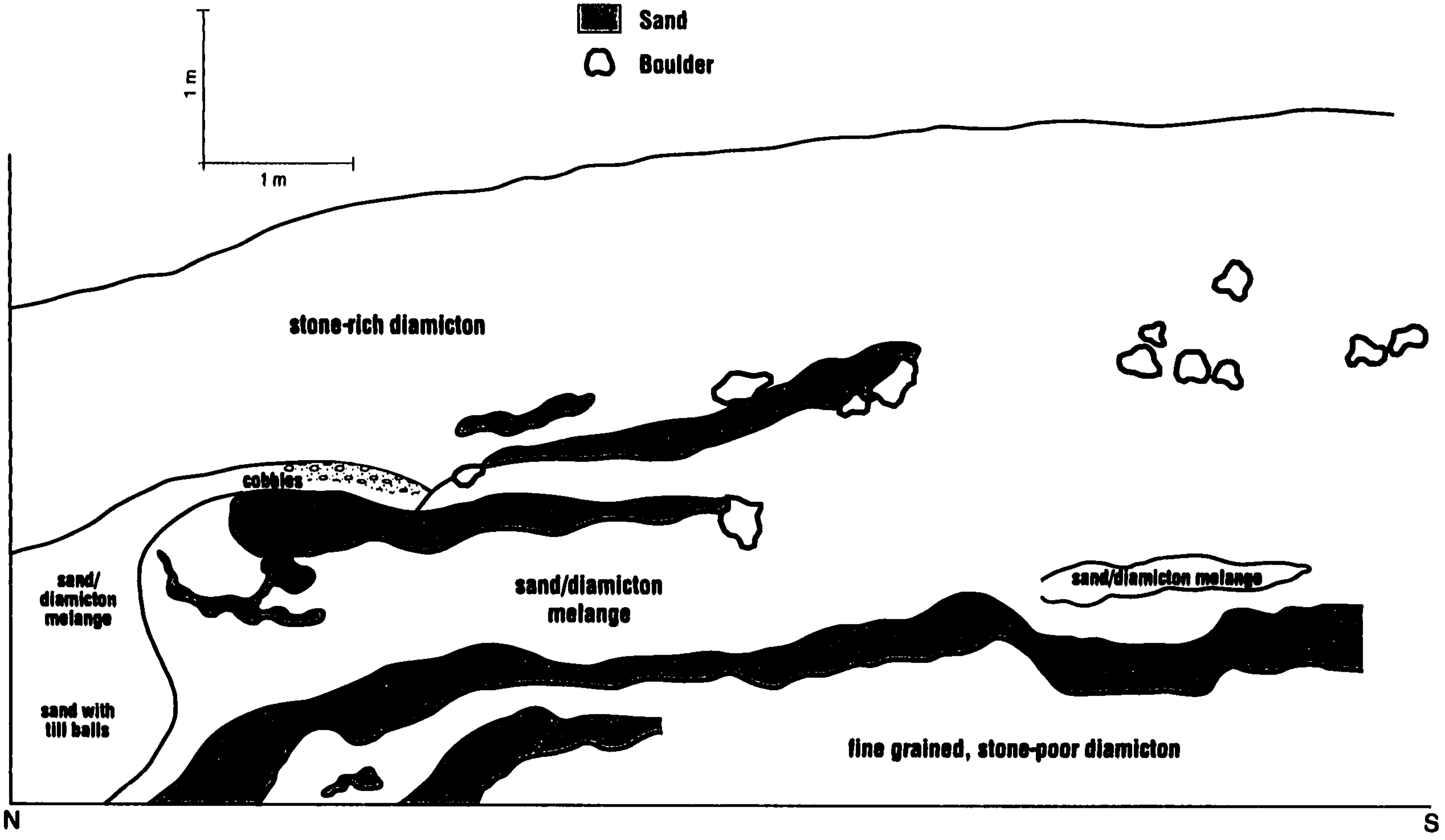

Figure 4-11. Exposure NB-04 (NW9-44-16-W3) sedimentary sequence. Perpendicular to long axis of fluting ridge.

Figure 4-12. Exposure NB-04 is located at the southwestern flank of a large fluting ridge across a smaller ridge defined by a superimposed groove. The exposure is composed of a complex mixture of diamicton and intratill sorted sediments.

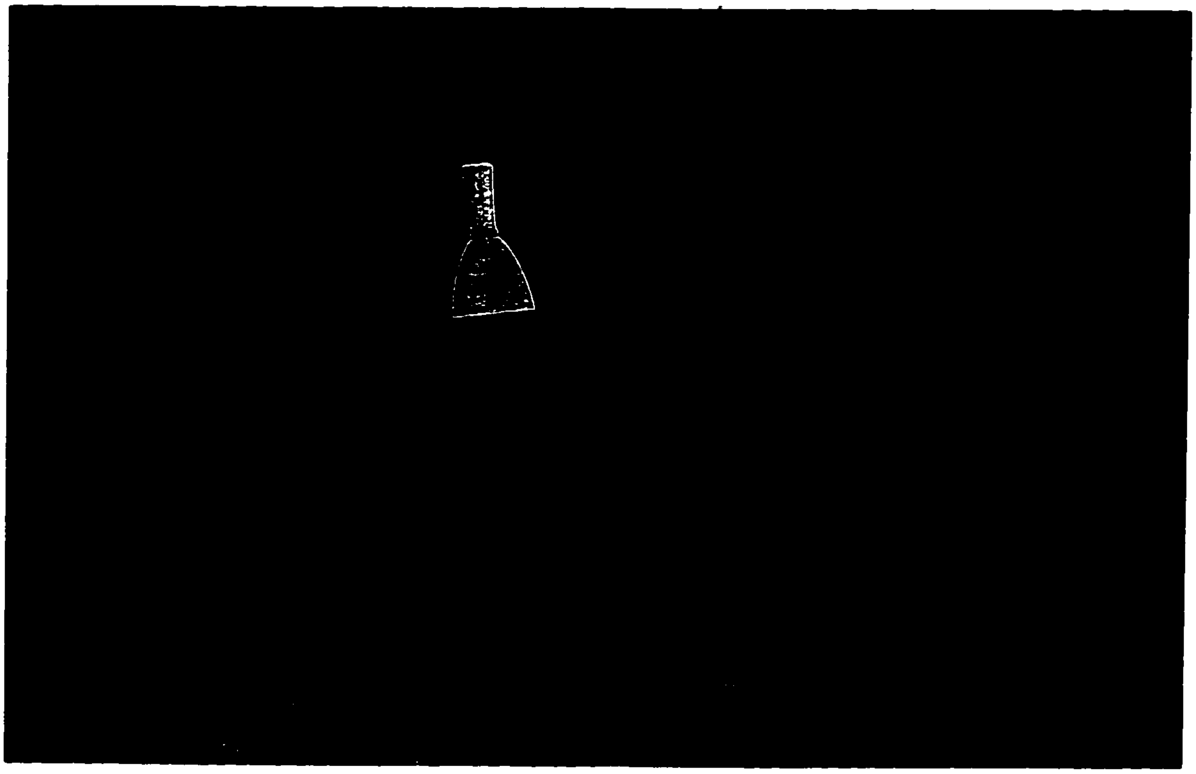

Figure 4-13. Mélange associated with the base of exposure NB-04 is characterized by stringers and pockets of sand of variable size and texture encased in diamicton mixed with sand.

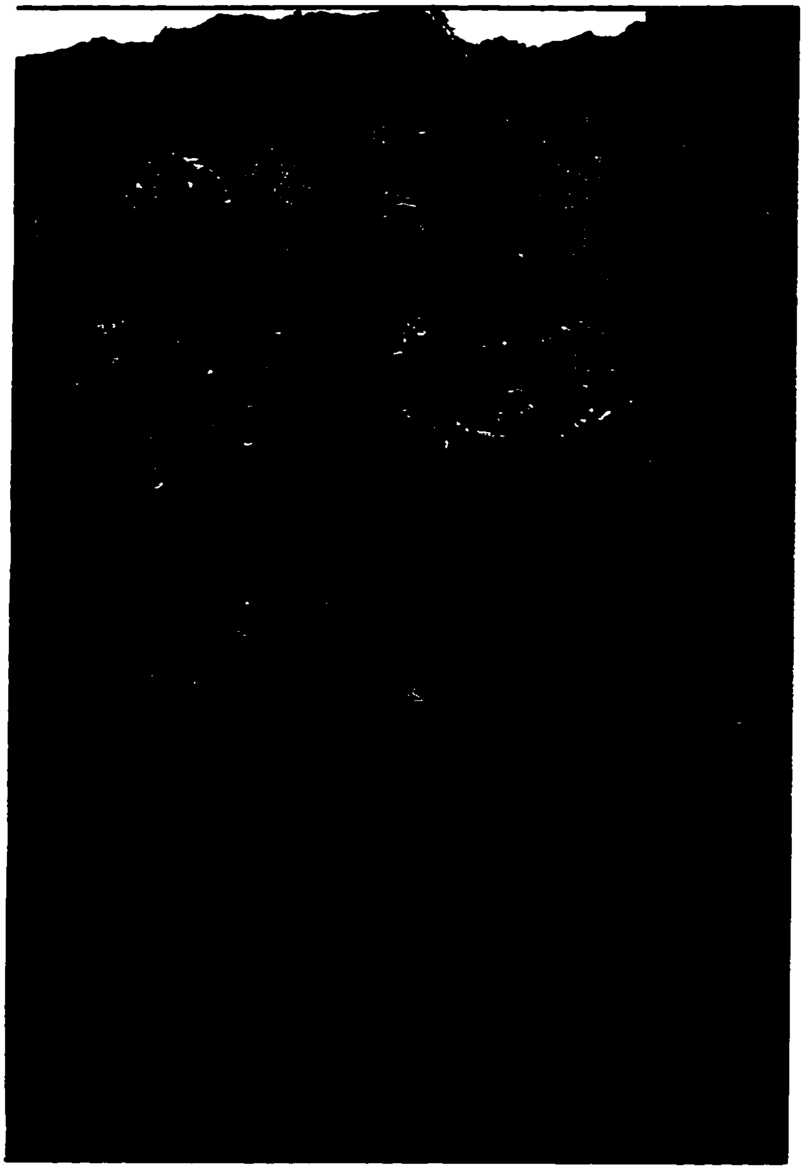

Figure 4-14. A lower unit of mélange in exposure NB-04 contains vertically faulted ribbons of sand with varying degrees of additional deformation and large bodies of graded sands. The upper unit of diamicton is uniform, massive, and stony.

Exposure NB-05

Exposure NB-05 is 12 m long section that is adjacent and perpendicular to exposure NB-04 (Fig. 4-1). The orientation of the section roughly corresponds to the long axis of the fluting and cuts through the superimposed groove that defines the small ridge at the edge of the larger fluting ridge. The south-facing section is 2 m deep, though an unknown thickness of gravel and other sediments has been excavated from the surface at the site. The sediments at the base of the section consist of stony diamicton, while the upper 1.7 m, however, consists of two units of sand (Figs. 4-15 and 4-16) that are separated by an indistinct boundary. The lower unit is composed predominantly of fine sand and abundant pebbles. Portions of the unit also contain large amounts of silt and clay. At the base of the lower unit is a diapiric structure, a ribbon of very fine sand, and a small body of mélange that grades into the surrounding matrix. The lower unit grades upward into a unit composed of very uniform, planar laminated sand that coarsens slightly upward and contains very few pebbles.

Exposure NB-06

Exposure NB-06 (NW10-44-16-W3) is located in a cluster of fluting ridges northwest of exposure NB-04 (Fig. 4-1). On aerial photographs, the ridges and grooves are distinctive in that they do not have the smooth surface appearance that is characteristic of other areas of the fluting field (Fig. 3-2). On the ground, the orientation and the morphology of the fluting and the relationship between adjacent ridges and grooves are difficult to observe due to the scattered tree and shrub vegetation (Fig. 3-10). The fluting ridges generally have the same asymmetric cross profile that is typical of other fluting ridges in the area, though in places the southeast flank is both extensively eroded and excavated resulting in a steeper drop to the adjacent depression. Exposure NB-06 is located in a 4.5 km long fluting ridge, approximately 2 km from its stoss end. The exposure is in a 4.5 m deep and 2 m wide cut into the northeast flank of the ridge approximately 100 m downslope from the crest. The lower 4 m of the exposure is composed primarily of massive, very compact stony diamicton. Near the base of the

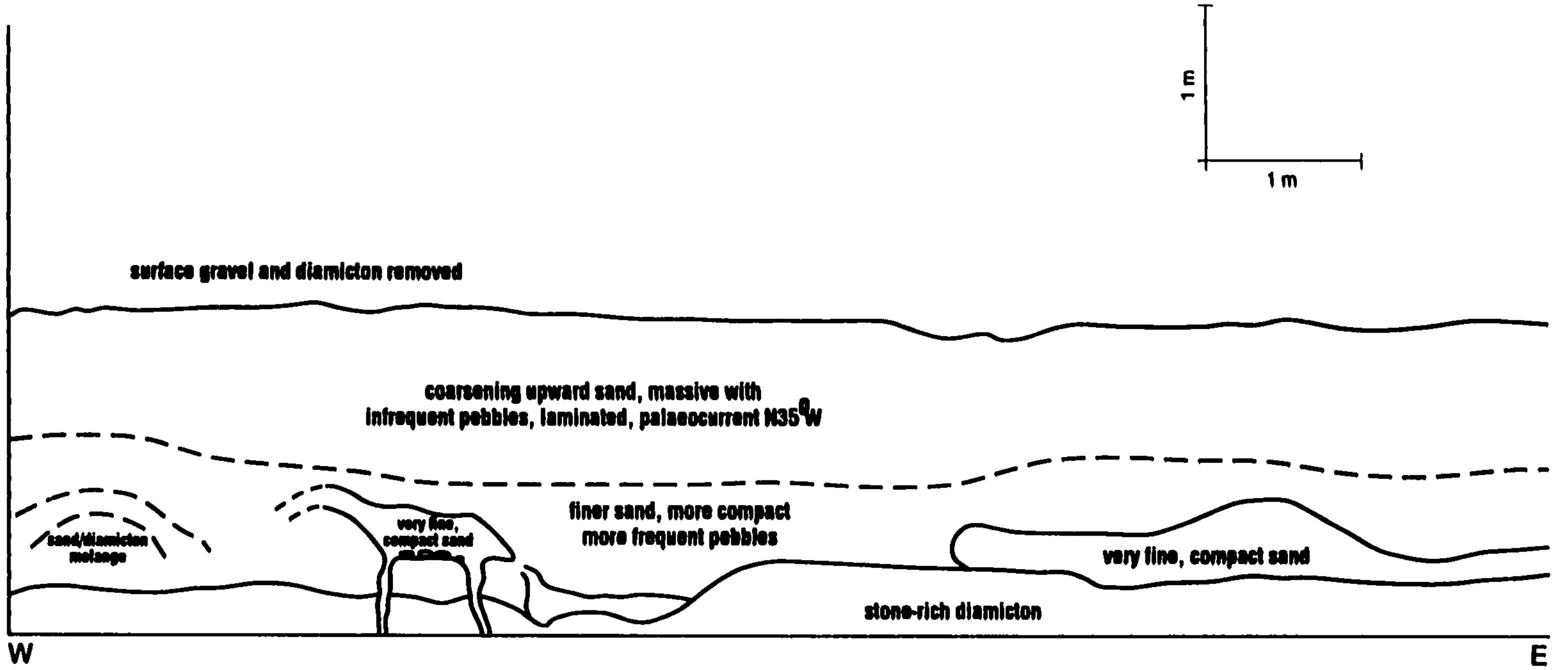

Figure 4-15. Exposure NB-05 (NW9-44-16-W3) sedimentary sequence. Parallel to long axis of fluting ridge.

Figure 4-16. The orientation of the south-facing exposure NB-05 roughly corresponds to the long axis of a fluting ridge. The section is adjacent and perpendicular to exposure NB-04. The lower unit of fine sand contains small diapiric and ribbon structures and grades upward into a unit of planar laminated, sightly coarser sand.

exposure on a cut perpendicular to the long axis of the fluting ridge are angular blocks of diamicton that are identifiable by their darker colour. The largest blocks have a maximum width of 0.7 m. The blocks are completely encased in stony diamicton though their longitudinal extent parallel to axis of the fluting ridge is unknown. The section of the exposure that is parallel to the long axis of the fluting ridge is composed entirely of uniform, massive, compact till with the exception of a narrow ribbon of medium-fine sand that varies in width from 0.5 to 2 cm. Undisturbed parallel laminations are clearly visible within the sand. Deformation of the sand is limited to a small section of the ribbon that had been slightly pulled apart. The upper 0.5 m of the exposure consists of a pavement of boulders and cobbles capped by sandy diamicton. The surface sandy diamicton thickens with distance down the northeast flank of the fluting ridge. About 6 m northwest of the exposure and 5 m closer to the crest of the fluting ridge is a small section that reveals undisturbed surface sediments. At this site, the unit of sandy diamicton is 0.6 m thick and is overlain by a thin layer of diamicton containing a second layer of cobbles and boulders and a thin cap of sandy pebble gravel. The remainder of the exposure is composed of compact, blocky diamicton similar to the sediments in the adjacent pit.

Exposure NB-07

Exposure NB-07 (NW10-44-16-W3) is in a small gravel pit in the same fluting ridge described for exposure NB-06 (Fig. 4-1). It is, however, located on the southwest flank 20 m from the crest of the ridge. From its crest, the fluting ridge drops in elevation approximately 20 m toward the southwest to a very broad, shallow groove. The maximum depth of the pit is 3 m, though much of the surface material in the immediate area is disturbed. The dominant deposit is sandy pebble gravel. The dip of the beds indicates that the gravel was deposited by a southwestward flow, roughly perpendicular to the long axis of the fluting ridge. Generally, the gravel is thinnest and coarsest nearer the crest of the fluting ridge and becomes thicker and finer down the flank of the ridge. The entire deposit is capped by a unit of diamicton that is 0.3 m thick near the crest of the ridge and thickens downflank.

Site HWY73C-118

The groove on the northeast side of the fluting ridge described for exposure NB-05 and NB-06 (Fig. 4-1) contains thick and extensive deposits of sand and gravel. These sands and gravels are part of the same deposit described for exposure NB-03 at the rim of the North Saskatchewan River valley. Data obtained from the Saskatchewan Department of Highways and Transportation and the Saskatchewan Research Council show that the sand deposit varies from 20 to 70 m in depth and is restricted to a relatively narrow band that extends from the bank of the North Saskatchewan River to 15 km to the southeast, though it is likely that these are minimum limits. A small, 3 m deep exposure in the sand at the base of the groove near exposures NB-05 and NB-06 reveals extensive cross-bedding that indicates a westward palaeoflow direction. Loading structures are also identifiable. Where the surface materials are not disturbed, the sand is capped by a thin unit of sandy pebble gravel and abundant cobbles at the surface.

Site NB-08

Site NB-08 is an area located south of the North Saskatchewan River near the downflow limit of the North Battleford fluting field (Fig. 4-1). The fluting ridges and grooves are contained in a small area confined on the south by the steep rise of the Missouri Coteau and on the north by the river (Fig. 3-5). Though much of the area has been modified by post-glacial alluvial and colluvial processes, fluting ridges and grooves are identified that continue across the North Saskatchewan River with no change in orientation. The fluting ridges are shorter and wider than those upflow and have heavily eroded surfaces, while the grooves are shallower and have floors that rise rapidly in a downflow direction. The fluting is associated with broader, more ovoid features that have tapering stoss and lee ends in both plan and long-profile view. On aerial photographs the ovoid features appear to have a distinct rippled surface texture (Fig. 3-5) that is caused by superimposed, transverse ridges with steep, up-flow sides densely covered with angular boulders (Fig. 3-6) and gentle lee slopes that have surface materials almost entirely composed of very fine grained, uniform sediments. The transverse ridges vary in size from

0.5 m in height and 1.5 m in length on ridges near the river to 5 m high and 10 m long on the ridge farthest from the river. With the exception of boulders on the stoss side of ridges, there is very little evidence of clasts of other sizes at the surface. Very few exposures exist in the area though there are indications of small areas of scattered surface gravel. The only large deposit of sandy pebble gravel in the area is associated with post-glacial stream development. A small exposure along a road cut reveals a boulder pavement capped by a unit of stony diamicton that appears to be a primary glacigenic deposit, though it is difficult to relate to other sediments and features in the area.

Interpretation

The sediments in exposures NB-01, NB-02, and NB-03 reveal the relationship between subsurface sediments, sediments in the fluting ridges, and the surface morphology at the proximal end of the fluting field. Exposure NB-03, excavated into the eastern wall of the North Saskatchewan River valley, shows that the process of fluting formation modified only a thin layer of the surface sediments. Sediments at greater depths represent conditions that prevailed prior to the formation of the fluting and are undisturbed by the fluting forming mechanism. At exposure NB-03, the observed subsurface sediments are predominantly composed of a thick sand deposit that is likely associated with proglacial ice advance conditions and an overlying till of variable thickness derived from subsequent glacial deposition. General ice advance toward the south and southwest disrupted the regional drainage resulting in westward palaeoflows that deposited the sand. The sand extends for an undetermined distance to the west, though, at the site of exposure NB-03, the sand deposit is dissected by the modern North Saskatchewan River. Therefore, either the valley did not exist in its present position prior to ice advance or it was infilled during ice advance and later reincised. The unit of very tough, massive till overlying the sand that is exposed at the northern edge of the exposure is stratigraphically lower than sediments modified by the fluting forming process. The till represents a primary glacial deposit that was likely emplaced by lodgment during ice advance.

The surface sediments exposed in the fluting ridge at the river bank (exposure NB-03) and at the stoss end of a nearby fluting ridge (exposure NB-01) are composed primarily of mélange derived from the incorporation of primary sediments into the basal zone of the ice with minimal dispersion during subsequent transport. The mélange can be attributed to two possible sources. The overriding ice sheet may have locally entrained clasts of preglacial sediments into the basal zone with incomplete mixing. The resulting deposit would be expected to be composed of a diamicton matrix encasing soft sediment clasts that exhibit varying degrees of deformation. In the North Battleford area, the large sand deposit may have been the source of the subtill sediments that became incorporated into the diamicton. The deformation of the sand clasts can be explained by mixing and attenuation due to short-distance transport in the basal ice. Alternatively, Shaw et al. (in preparation) attribute the primary source for mélange in fluting ridges in north-central Alberta to subglacially deposited till and intrabedded sand and gravel. Small-scale fluvial processes that result in the development of a network of connected channels at the base of the glacier are identified as a significant component of subglacial drainage. Such channels opened quickly in response to thermal erosion and hydraulic jacking (Nye, 1976) and were infilled by the rapid deposition of material transported by sediment-laden meltwater. The channels were short-lived due to rapid plastic closure induced by the pressure of the overlying ice (Nye, 1976). Episodic deposition in the network of subglacial conduits results in units of sorted sediments enclosed in basal till that are subsequently deposited and deformed (Shaw, 1982, 1987).

Regardless of whether the formation of the mélange in the North Battleford fluting ridges involved the entrainment of subtill sediments or the inclusion of subglacially and englacially formed sorted sediments, its formation is attributed to basal transport and subsequent deposition by melt-out. Dreimanis (1988) describes melt-out till based, in part, on the fabric and the presence of soft sediment clasts. From exposure NB-01 it was determined that the diamicton has a moderately strong fabric and preferred upglacier dip of clasts that are in general agreement with the dominant direction of regional ice movement toward the south and southwest. The difference in the orientation of the fabric and the orientation of the fluting is significant in that it suggests that the process by which the till was deposited was not directly related to the process that formed the fluting. In addition, the inclusion of intact clasts of either subtill sediment or in situ sorted sediments further supports melt-out as the primary mode of deposition. If the mélange sediments in the fluting ridges are interpreted to be deposited by melt-out, the mechanism of fluting formation could not be related to the deformation of subglacial sediments. It unlikely that the sorted sediments could have survived either the layer by layer accretion of till in the lodgment process or extensive deformation. The presence of deformed sediments in the fluting ridges, therefore, needs to be explained by some other process that occurred prior to fluting formation. The formation of fluvial intratill beds or the entrainment of clasts of subtill sediments and their subsequent basal transport and deposition by melt-out provides a plausible explanation.

A large-scale erosional event that occurred subsequent to the deposition of the mélange left a widespread boulder lag that was observed at exposures NB-01 and NB-03, as well as near site HWY73C-64 in the area of narrow, closely spaced fluting. At exposures NB-01 and NB-03 the boulder lag is overlain by surface stratified sediments, while near site HWY73C-64 the boulder pavement is at the surface. In both areas, however, the boulder pavement reflects the surface morphology of the fluting. This suggests that the erosional event that produced the boulder pavement also produced the fluting. Furthermore, the presence of the boulder pavement in ridges in different parts of the fluting field again provides evidence that all portions of the fluting field were created at the same time by the same event. Because it is not likely that direct glacial processes could have produced the observed selective sorting, the most probable erosional mechanism that produced the boulder pavement is a large-scale flow of subglacial meltwater. Furthermore, the formative flow must have been very vigorous flow to have had the competence to transport the boulder-sized clasts. The lack of rounding of the boulders suggests that they were not transported far prior to final deposition and that the source of the boulder lag, therefore, was likely the underlying mélange. The density and broad extent of the boulder pavement implies that a very large volume of mélange sediments were eroded and transported away from the area during the meltwater flow event.

Exposures NB-04 and NB-05 are located on the southwestern edge of a large fluting ridge with a surface marked by superimposed grooves ridge, 10 km southwest of the proximal end of the fluting field. The sediments in these exposures are similar to the sites already described in that they are predominantly mélange derived from primary till and sand deposits. The mélange in exposure NB-04, however, has more of the characteristics of sediments that are expected to result from the development of a network of small-scale subglacial conduits. The lowermost unit of highly compacted diamicton that underlies the mélange may be a primary glacial deposit that may correlate with the unit that underlies the mélange at exposure NB-03 at the rim of the river valley. With its limited exposure, however, it is difficult to determine with certainty. The predominant mélange sediments consist of a sandy diamicton matrix that encases sand bodies of highly variable texture, structure, and geometry. Many of the sand bodies are composed of undisturbed or slightly disturbed plane and cross-bedded laminations and have a more clearly defined ribbon configuration than at other exposures. The intratill ribbons of sand were likely derived from the subglacial flow of meltwater in a rapidly changing network of conduits as described by Shaw et al. (in preparation). The sand bodies vary in size, texture, and structure suggesting that the conduits were short-lived and operated episodically. Because of the well-preserved state of the sand bodies it is again likely that the sediments were deposited by melt-out. The slight deformation of the sorted sediments could have occurred during the depositional process or subsequent to deposition as relatively unconsolidated diamicton became consolidated due to the pressure of overlying ice.

The mélange at exposure NB-04 differs from other sites near the proximal end of the fluting field in that it contains a poorly defined, discontinuous boulder pavement that is overlain by diamicton. The boulders appear to be roughly accordant with the surface morphology of the fluting ridge. With its limited lateral extent, however, this could not be determined with certainty. Because of the overlying unit of diamicton, it appears that the origin of this boulder pavement is not related to the event that formed the fluting as was interpreted from other exposures. The process that resulted in the development of the boulder pavement in exposure NB-04, however, was also a high energy fluvial event that removed large amounts of sediment. The presence of an overlying unit of diamicton indicates that the fluvial erosion occurred subglacially. Shaw et al. (in preparation) recognized that meltwater depositing sediment in short-lived conduits at the base of the ice also flowed in sheets that eroded extensive subglacial boulder pavements. Meltwater, therefore, flowed at the base of glacier with varying intensities, at different times, and with different depositional and erosional consequences.

The sedimentological complexity of exposures NB-04 and NB-05 is in sharp contrast to the uniformity of the sediments of exposure NB-06. Exposure NB-06 is located northeast of exposures NB-04 and NB-05 and is excavated in a fluting ridge that is composed almost entirely of undisturbed primary glacial sediments. The upper 0.5 to 1 m of the sediments at exposure NB-06 are comparable to the sequence observed at other exposures. The multiple boulder pavements and mélange sediments represent the interaction of glacial and fluvial depositional processes at the base of the glacier. Again, the uppermost boulder pavement marks an erosional surface that was created by the process responsible for the fluting formation. The predominant sediment is diamicton that contains large soft sediment clasts that are also composed of diamicton and a single, thin intratill sand body. Deposition of these sediments by lodgement or deformation would not be expected to allow for the preservation of either the soft sediment clasts or the delicately bedded sand that was deposited in a subglacial conduit carved into unconsolidated till. Subsequent consolidation of the sediments caused slight attenuation of the sand deposit, though the original geometry and internal structure of the conduit deposit are retained. Consolidation of the diamicton is also indicated by the single diapiric structure that cross cuts the conduit deposit. The coarser sand of the diapiric structure was injected into a fracture that could only have formed if the diamicton was consolidated and brittle.

Site HWY73C-118 provides the only exposure of the sediments in a groove adjacent to a fluting ridge. Field observations and Saskatchewan Research Council subsurface data indicate that the exposed cross-bedded sands are part of the preglacial sands identified at the rim of the river valley (exposure NB-03) at the proximal end of the fluting field. The uppermost units of the sand at site HWY73C-118 were truncated by the fluting forming event that removed all glacial sediments as the grooves were carved. This site, however, is not typical of other areas of the fluting field and is merely a reflection of the subsurface sediments.

The same general sedimentary sequences can be recognized within ridges over a large portion of the proximal end of the fluting field even though the thicknesses of the units and their specific character vary significantly at different sites. Regardless of the location in the fluting field, however, the ridges and grooves have the same long axis orientation and surface morphology. Furthermore, the nature of the sediments in the ridges indicates that they were predominantly deposited by melt-out. The preservation of intratill sand bodies, diapiric structures, and soft sediment clasts shows that the sediments were not subjected to the subglacial deformation described by Boulton (1987). Therefore, deposition from a deforming subglacial bed can be discounted as the likely mechanism of fluting formation. In contrast, the combined sedimentological and geomorphological observations of the fluting ridges lead to the conclusion that the internal character of the fluting ridges is independent of the process that formed them.

The proximal end of the fluting field is characterized by discontinuous surface deposits of stratified material that occur preferentially along the southwest flanks of the many of the fluting ridges. They have the effect of infilling the southwest flank, and in some cases, increasing the height of the fluting ridges. These deposits vary in thickness from approximately 3 m (exposure NB-01 and NB-02) to a very thin surface veneer (exposure NB-03 and NB-04). They have in common a dip toward the south that indicates a formative flow that is almost perpendicular to the longitudinal axes of the fluting ridges. The surface materials are interpreted to have been deposited at some time after the event that produced the fluting. The site from which the most information regarding the surface sorted sediments can be derived is associated with exposures NB-01 and NB-02. Thinly bedded alternating units of sand that vary in the amount of sand and granule sized till balls were produced by short distance sediment transport in water that flowed over till. The north to south flow encountered the fluting ridges resulting in the lee side deposition of the sand and gravel. Possible sources of water for this depositional event are the waning flow from the fluting forming event, an unrelated smaller scale subglacial meltwater event, or meltwater flows related to deglaciation of the area. Regardless of the source of the surface sands and gravels, the effect of the flow did little to modify the morphology of the fluting field.

Exposure NB-08 is at the distal end of the fluting field between the North Saskatchewan River and the Eagle Hills. Ridges and grooves of the fluting field occur on both sides of the North Saskatchewan River. Additional broader ridges on the south side of the river may also have formed at the same time as the fluting. While little sedimentological information could be obtained, this area is significant because it is has a surface character shaped almost entirely by intense fluvial erosion. Boulders exist at the surface throughout the area, though they are preferentially concentrated on the stoss side of small-scale, transverse ridges that are superimposed on the large, broad ridges. The continuation of the fluting field on the south side of the the modern North Saskatchewan River has implications for the interpretation of the evolution of the river valley. Because the fluting ridges and grooves are dissected by the modern valley, it is possible that the fluting formed prior to the incision of the valley. The initiation of the fluting forming event, however, required the pre-existence of the upflow facing rim of the river valley at the proximal end of the fluting field. Therefore, the sheet flow that formed the fluting may have continued southeastward with little interference from the river valley at the distal end of the fluting field as well. The broader, fluvially eroded ridges may have formed at the same time at the fluting field or they may be associated with subsequent sheet flows or with subglacial or proglacial drainage events that were confined to the existing channel.

Chapter 5

GEOMORPHOLOGY OF FEATURES ASSOCIATED WITH THE NORTH BATTLEFORD FLUTING FIELD

Introduction

The fluting field is one element in the broader regional landscape of the North Battleford area. The southwestern margin of the fluting field is defined by the steeply rising Eagle Hills that form the southern wall of the embayment in the Missouri Coteau. In contrast, the northeastern margin of the fluting field is characterized by a more gradual transition into other elements of the landscape. The northeastern boundary of the study area is defined by two large, discontinuous channels incised into the Thickwood Hills on the north wall of the embayment in the Missouri Coteau. The channels are parallel to the orientation of the fluting field and terminate near the downflow limits of the fluting field. An intervening narrow zone of very low relief topography contains subtle features that are morphologically dissimilar but have the same general orientation (Fig. 3-1). Based on these large-scale observations, I conducted a detailed geomorphological investigation of the area adjacent to the fluting field to determine the existence of a possible genetic link between the various elements of the landscape.

Geomorphological Description

The northern boundary of the study area is defined by the Thickwood Hills of the Missouri Coteau (Fig. 1-3). The topography of the underlying Cretaceous Lea Park Formation (Fig. 1-2) rises steeply to form a narrow ridge that served as the drainage divide between the preglacial Battleford Valley and the nearby preglacial Hatfield Valley to the north (Whitaker and Pearson, 1972). The preglacial valleys merge less than 200 km to the southeast. The surficial materials throughout the Thickwood Hills are almost entirely of glacial origin. Thick drift deposits have resulted in a broad area that rises gently approximately 100 m from the Saskatchewan Plain that contains the North

Saskatchewan River and the North Battleford fluting field to the top of the Missouri Coteau. It is characterized by a moderately to strongly rolling topography that consists of a complex network of hummocks and depressions (Acton et al., 1960). The area is classified by Campbell (1987a) as hummocky moraine and morainal plains with large zones of glaciofluvial and glaciolacustrine deposits (Fig. 1-4).

The Thickwood Hills are characterized by a complex assemblage of features that together provide information regarding its genesis. Abundant, small, closed depressions, that may or may not contain water, are randomly distributed throughout the area (Fig. 5-1). The area generally lacks a well developed, integrated drainage system, though in the area north of North Battleford a series of parallel streams drain southwestward from the uplands of the Missouri Coteau to the plains below. Large, shallow lakes are also common and are typically smaller than the basins that contain them. Dry lake beds can also be recognized. Most of the large lakes are preferentially located in depressions along the high relief southwest edge of the Thickwood Hills. Hummocks in the area are circular to linear in plan view and may occur in isolation or have a clustered or linear arrangement. The general elevation of the Thickwood Hills is 650 to 670 m a.s.l., though some hills and ridges reach a maximum elevation of 720 m a.s.l. Floors of deep depressions and channels are as low as 560 m a.s.l. along the margin of the upland area, though most are shallower. Dispersed throughout the area, are large tracts of flat, almost featureless land that are at an elevation that corresponds to the height of many of the hummocks and ridges. The impression created is that the relief in the area is almost entirely a result of downcutting. Surface materials are predominantly till, though stratified deposits consisting of gravel, sand, silt, and clay are dispersed throughout the area. The complexities of the landscape are reflected on aerial photographs by the diversity in land use. Few roads traverse the mixture of cultivated land and pasture and many of the subtle aspects of the landscape are masked by the relatively densely scattered tree and scrub vegetation (Figs. 5-1 and 5-2).

The southwest margin of the Thickwood Hills is particularly significant in its apparent association with the North Battleford fluting field. It is characterized by a strongly linear arrangement of lakes and ridges. Long, narrow lakes that trend S45°E to S55°E are

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Figure 5-1. Low relief terrain (LRT) associated with the North Battleford fluting field to the southwest is bounded on the northeast by the Thickwood Hills. The typical hummocky terrain (HT) characterized by water-filled depressions and nonoriented hummocks is bounded on the southwest margin by channelized hummocky terrain (CHT). The channelized area has small channels contained within a single larger channel, linearly arranged lakes and high relief topography.

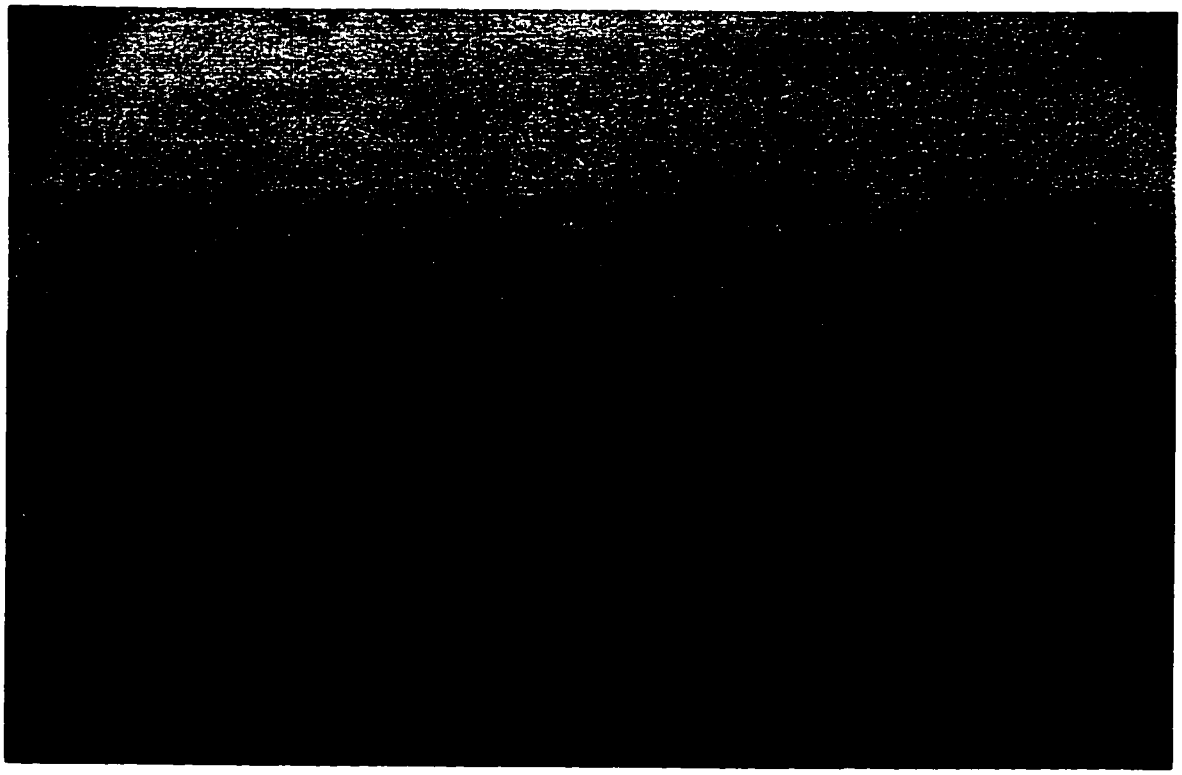


Figure 5-2. The terrain along the channelized southwest margin of the Thickwood Hills typically includes hummocks with varying morphology and size that are separated by narrow, rudimentary channels. The channels frequently contain small water-filled depressions. This photograph was taken from the top of a hummock looking northward across a northwest-southeast trending channel.

contained within a broad, shallow, discontinuous channel that trends S55°E (Fig. 3-1). The channel has its origin in an area presently occupied by Jackfish, Scentgrass, and Murray lakes and their associated marshes, 30 km north of North Battleford. It can be traced 50 km southeast of North Battleford where it abruptly turns southward and terminates. Extensive sand and gravel deposits associated with the channel mouth are superimposed on the downflow limits of the fluting field. Sand deposits that were subsequently reworked into dunes are the dominant surface features though spindle-shaped depressions and subtly expressed ridges and grooves can still be identified in places. Gravel deposits are located south of the sand deposits in closer proximity to the North Saskatchewan River. Within the area of gravel is a large, north-south oriented ridge with inset boulders on the lee side of smaller, transverse surface ridges giving it the appearance of large-scale, ripple-like features on aerial photographs. The ridge is 2.5 km long and 5 to 8 m above the surrounding terrain. Other smaller, less distinct ridges with variable orientations but similar surface morphologies characterize most of the area covered by gravel.

The channel at the margin of the Thickwood Hills has a pseudo-anabranching pattern as small channels with abrupt beginnings and endings merge with and diverge from the main trunk channel. The banks of the channel range from steep and clearly defined to indistinct and, in some places, nonexistent. Within the banks, the terrain is heavily eroded with numerous upstanding erosional remnants, depressions, hummocks, and smaller, secondary channels. The southern bank of the channel is bordered by a series of small fluting ridges and grooves that have the same orientation of S50°E to S60°E as the channel and the fluting field. The fluting ridges have the same rounded crests and gently sloping flanks as the larger features in the main fluting field and the grooves contain linearly arranged circular and elongate depressions. A second channel that has the same point of origin, trends in a more easterly direction and is located to the north of the first channel. It is also a broad channel that is very heavily eroded throughout its length but has fewer secondary channels. It terminates abruptly as it shifts its course southward into a deep cul-de-sac accentuated by a 100 m high hill with a surface of very stony diamicton. The hill continues as a gently arcing, 5 km long, row of hills that gradually decrease in size until they merge with the surrounding land.

The channels and the fluting ridges and grooves that mark the edge of the Thickwood Hills are separated from the main part of the fluting field by a 15 km wide tract of very low relief terrain. The area is almost entirely devoid of fluting ridges, though it does contain very shallow, broad grooves (Fig. 3-1). The grooves are difficult to identify on the ground but are easily recognizable on aerial photographs that show the associated linearly arranged, water-filled depressions (Fig. 3-7). The most prominent characteristic of this area, however, are clusters of small mounds that occur in conjunction with straight to slightly arcuate, narrow ridges. The mounds, which are less than 10 m high, are very uniform in size and form (Fig. 5-3). They have maximum diameters of 200 m and range in shape from circular to moderately elongate. The moderately elongate forms have orientations that range from transverse to parallel to the orientation of the long axes of the fluting. The ridges are straight to arcuate in form and range from clearly defined and sharp crested to barely discernible. As with the mounds, they are less than 10 m in height and have lengths that are generally 300 to 400 m. Most of the ridges are transverse to the long axes of the flutings, though small areas have a rectilinear pattern. The mounds are not superimposed anywhere on either the fluting ridges to the southwest or the uplands to the northeast. In contrast, the ridges are, in places, superimposed on a small number of fluting ridges and their associated grooves.

The mounds and ridges are contained in a southeast trending tract of land that is oriented parallel to the northeast margin of the fluting field and the southwest flank of the Thickwood Hills (Fig. 3-7). The mounds, however, show no discernible small-scale pattern in their distribution. The ridges are sub-parallel and, where arcuate, are concave toward the northwest. The southeastern extent of the mounds and ridges is sharply defined where the distal portion of the fluting field merges with hummocky terrain. The northwestern extent of the features is less clearly defined as the mounds gradually become less densely distributed. As with the fluting, the mounds continue sporadically beyond the limits of the study area. In contrast, the ridges do not continue beyond the area

Figure 5-3. Small mounds occur in a northwest-southeast trending zone adjacent to the ridges and grooves of the North Battleford fluting field. The photograph was taken looking toward the northeast.

immediately north of North Battleford. The mounds and ridges are most numerous and best defined in an area that corresponds to the best developed fluting. The tract of land containing the mounds and ridges also has large zones of flat, featureless land. Notably, there is little overlap of the various elements of the landscape. The fluting field that formed on the gently sloping land adjacent to the North Saskatchewan River gives way to the mounds, small depressions, and ridges on the very flat and otherwise featureless land to the northeast. The mounds and ridges, in turn, abruptly give way to the channels and ridges that mark the beginning of the Thickwood Hills (Fig. 3-3).

Interpretation

Geomorphological and sedimentological observations indicate that the North Battleford fluting field was likely formed as vortices in a regional-scale, turbulent flow of subglacial meltwater preferentially eroded grooves that define a series of upstanding remnant ridges. The best developed fluting formed as the sheet flow encountered the upflow facing rim of the river valley. The lateral extent of the sheet flow, however, was not limited to the area in which the fluting forming process was initiated. As would be expected with the type of flow hypothesized for the formation of the fluting, adjacent areas also show geomorphological evidence of large-scale fluvial erosion. To the southwest, the fluting field is bounded by the North Saskatchewan River valley and the steep rise to the Eagle Hills of the Missouri Coteau. The topography of this area has been shaped largely by modern alluvial and colluvial processes that have extensively altered the influence of Pleistocene processes. Consequently, the southern extent of the sheet flow is difficult to determine and was not pursued in this study. Either the flow was confined by the position of the Missouri Coteau or the meltwater flowed over the plateau.

The landscape northwest of the fluting field, in contrast, comprises various landscape elements that were likely formed at the same time and by the same process that formed the fluting field. The fluting field occupies a narrow tract of land that slopes to the southwest toward the North Saskatchewan River. The topography changes abruptly toward the northeast from the well-developed ridges and grooves to a tract of almost featureless plain that is oriented parallel to the fluting field. The plain is devoid of fluting ridges except for a small number of isolated features that formed at the margin of the Thickwood Hills to the northeast. Though there are no prominent ridges, the plain is characterized by a series of very subtle erosional grooves that have the same orientation as the grooves in the fluting field. Hypotheses of fluting formation that require the construction of ridges as the primary form (Shaw and Freschauf, 1973; Boulton, 1987; Bluemle et al., 1993) are not applicable in this area. The grooves are broad and very long, though much shallower than those in the fluting field. Many are accentuated by spindle-shaped depressions and linearly arranged circular depressions. The similarity in orientation and morphology of the grooves in the plain and in the fluting field suggests that they were all formed by a common event. The less pronounced erosional effect of vortices in the sheet flow in this area can be attributed to the position of the plain relative to the rim of the river valley. The plain, with its very subtle features, was shaped by the same turbulent sheet flow of meltwater that formed the fluting field. The flow, however, did not encounter the large-scale interference that occurred at the rim of the river valley. Less intense erosion by vortices produced shallower grooves that did not grow sufficiently large to define prominent intervening ridges.

The morphology of the grooves in the plain is indicative of a fluvial origin. Concave grooves mark were eroded where vortices in the formative flow developed. There is evidence of different scales of formation with grooves as large as several kilometres in length and smaller spindle-shaped and circular depressions contained with in the grooves . The smaller scale depressions occur almost exclusively in the grooves and have the northwest to southeast orientation that is common to all elements of the fluting field and the grooves in which they are contained. The grooves and the contained depressions formed at the same time by the same process. Spindle-shaped erosional marks described in numerous regions have been attributed to subglacial meltwater erosion (Shaw and Sharpe, 1987; Shaw, 1988; Tinkler and Stenson, 1991).

The plain is also characterized by clusters of randomly oriented mounds showing an overall pattern that appears to be related to the grooves and ridges of the fluting field.

The mounds occupy an area that is oriented from the northwest to the southeast. Whereas the shallow grooves and aligned depressions are more prevalent near the proximal end of the plain, the mounds are more numerous near the distal end. The mounds can, however, be traced to the northwest beyond the limits of the study area as isolated features and in smaller groups. This pattern is identical to that observed for the fluting field. As with the grooves, the mounds formed in an area that was not influenced by flow interference induced by the rim of the river valley. It is likely that the mounds were produced in response to changing flow conditions in the formative sheet flow. The elongate, arcuate ridges have the characteristics of crevasse fills (Stalker, 1960). The ridges are narrow, relatively sharp-crested, and in places, form a characteristic rectilinear pattern. The formation of the crevasses fill occurred after the formation of the fluting and, perhaps during, recoupling of the ice sheet with the bed. The crevasse fill ridges formed as the weight of the overlying ice pressed subglacial sediments into crevasses at the base of the ice. Stalker (1960) hypothesized that the necessary conditions for the formation and preservation of crevasse fill were stagnant masses of ice left on the landscape during deglaciation since any subsequent movement of the ice would destroy the ridges.

The northeastern boundary of the study area is marked by discontinuous channels at the margin of the Thickwood Hills. Discontinuous channels have generally been attributed to deglacial environments as meltwater flowed in an ice marginal position (Parizek, 1969), in streams issuing from under the ice (Greer and Christiansen, 1963), or as spillways that formed with the catastrophic drainage of proglacial lakes (Kehew and Lord, 1986). Sjogren and Rains (1995) offer the additional possibility that at least some of these types of channels were formed as meltwater flowed in a subglacial environment. The geomorphology of the channels at the margin of the Thickwood Hills and their relationship to the fluting field suggests that they were formed subglacially. The general orientation of the channels is from the northwest to the southeast, in accordance with other elements of the fluting field suggesting a genetic link. The nature of the channels indicates that their formation was by a short-lived, turbulent flow that did not have sufficient time to incise an integrated channel system. The input of water into the southern channel system occurred at various points along its course as small streams that generally have their beginnings in the lower elevation plain to the southwest joined the main channel. The abrupt beginnings of the smaller channels and the direction of flow from low to higher elevation areas indicates that the formative flow must have moved through englacial channels before they encountered the substrate and incised channels into the basal sediments. Similarly, in portions of the channel, divergent flow carried water away from the main channel into the ice sheet leaving discontinuous and progressively shallower distributary channels with poorly defined margins on the landscape. The discontinuity of the channels implies that erosion was downward into the substrate as well as upward into the overlying ice. The floor of the main channel is heavily eroded. The many erosional remnants, depressions, and secondary channels indicate a highly variable, turbulent, short-lived formative flow.

Both of the channels at the margin of the Thickwood Hills terminate abruptly near the distal end of the fluting field. The southern channel becomes very indistinct as its course shifts in direction toward the south. The channel emerges from the Thickwood Hills, where its effect was primarily erosional, into a large area of sand and gravel deposition. The sand and gravel is superimposed on the distal end of the fluting field where the ridges and grooves are muted though still discernible. The fluting field, therefore, formed before the channelization of the Thickwood Hills. The sand and gravel, however, is not a typical fan deposit that has the coarsest sediments deposited proximally and the finer sediments distally (Reineck and Singh, 1986). The reverse conditions are found with sand nearest to the mouth of the channel and gravel in the most distal areas. This distribution of sediments can be explained if the channel continued englacially toward the south before depositing its sediment load.

The geomorphology of the northern channel provides more information regarding the formative processes active at the margin of the Thickwood Hills. The channel terminates very abruptly in a deep cul-de-sac that could not have formed subaerially or subaqueously. The formative flow could only have continued upward into an overlying ice sheet under hydrostatic pressure. Therefore, the northern channel must have been formed in a subglacial environment. The similarities with the southern channel in orientation and southward diversion imply that it also formed subglacially during the same event.

The margin of the Thickwood Hills is mapped by Campbell (1987b) as hummocky moraine formed by ablation and the chaotic disintegration of stagnant ice. The area is characterized by hummocks in the channels, on the channel margins, and on interfluves between anabranches of the main channels. Their form and distribution has generally been attributed to the upward squeezing of debris into openings into the base of the ice (Stalker, 1960) or the ablation and let-down of supraglacial and englacial debris onto the landscape (Gravenor and Kupsch, 1959; Parizek, 1969). Both explanations require the wasting away of large masses of stagnant ice during deglaciation for the formation and preservation of hummocks. The orientation of individual hummocks and of groups of hummocks, and their prevalence within the channels suggests, however, that their formation is linked to the formation of the channels. It is difficult to explain the relationship between the channels and the hummocks using the ice-pressing or ablational hypotheses of hummock formation. The geomorphological observations need to be combined with an investigation of sediments in the channels and in the hummocks to understand the distribution and origin of the hummocks.

Based on geomorphological observations, the North Battleford fluting field appears to be genetically related to other elements of the landscape. Therefore, the flow that created the fluting field likely extended northward onto the Thickwood Hills at least as far as the northern channel. Given the inherent instability of sheet flows, it is expected that during the waning phase of the flood event the flow would necessarily become channelized. It is likely, therefore, that the channels at the margin of the Thickwood Hills were incised immediately after the formation of the fluting field and the area of subtle grooves and mounds and prior to the recoupling of the ice sheet and the bed and the formation of the crevasse fills.

Chapter 6

SEDIMENTOLOGY OF FEATURES ASSOCIATED WITH THE NORTH BATTLEFORD FLUTING FIELD

Introduction

I investigated the sediments in the area adjacent to the North Battleford fluting field by logging existing exposures and collecting samples where appropriate. The locations of the exposures and other sediment information are shown on Figure 4-1. All of the exposures in the area adjacent to the fluting field are located within the channelized margin of the Thickwood Hills. Gravel pits and road cuts reveal the types of sediments both in hummocks and in swales between hummocks in this area. Additional maps and grain size data from the Saskatchewan Department of Highways and Transport provide information regarding sediments in gravel pits that are presently inaccessible. The sedimentological and geomorphological observations allow for an interpretation of the origin of channels at the margin of the Thickwood Hills and provide evidence for the genetic link between the channels and the fluting field.

Sediment Description

Exposure NB-09

Exposure NB-09 (NE7-45-14-W3) is located along the southern margin of the Thickwood Hills (Fig. 4-1 and 3-11) 20 km northeast of North Battleford on the south side of a west to east oriented road. The road cut exposes undisturbed sand and overlying diamicton in the upper 3 m of a large hummock (Figs. 6-1a 6-1b). Most of the hummock is composed of massive, stony diamicton that overlies sand with undisturbed graded and cross-bedded units (Fig. 6-3). The contact between the sand and the diamicton is very sharp with no sign of deformation except for injected veins of diamicton at the western edge of the sand exposure (Fig. 6-4). At the eastern edge of the exposure the sand reaches the surface. The dip of the sand beds ranges from 5° to 10° toward S10°W. The

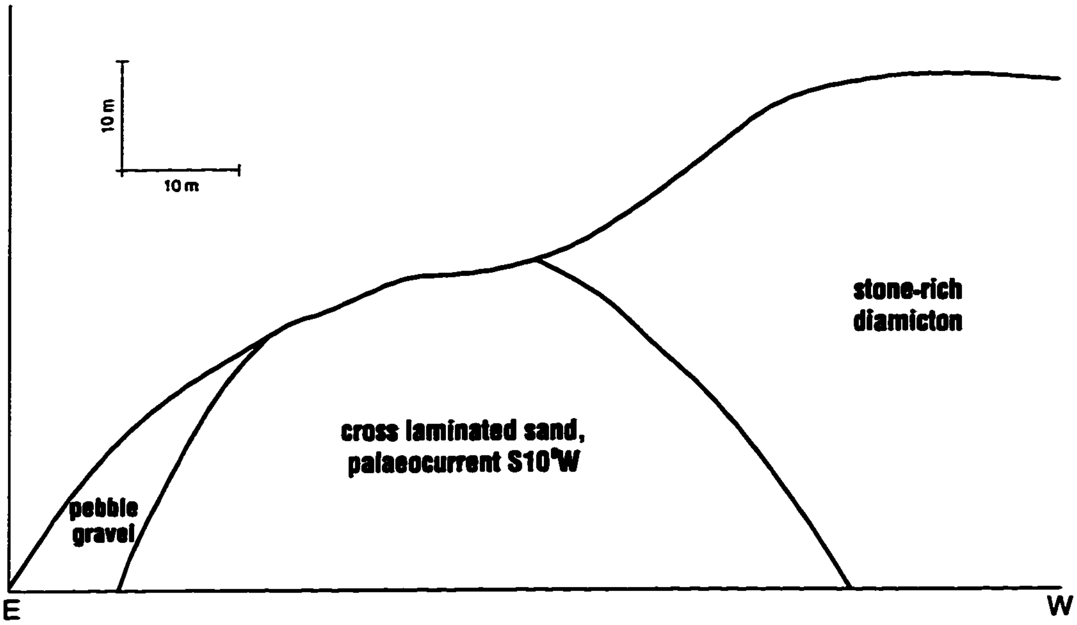


Figure 6-1a. Exposure NB-09 (NW7-45-14-W3).

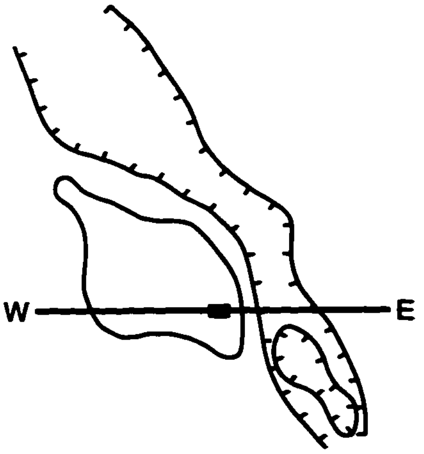


Figure 6-1b. Location of Exposure NB-09 in hummock. Orientation of long axis of hummock and adjacent channel is S35°E.

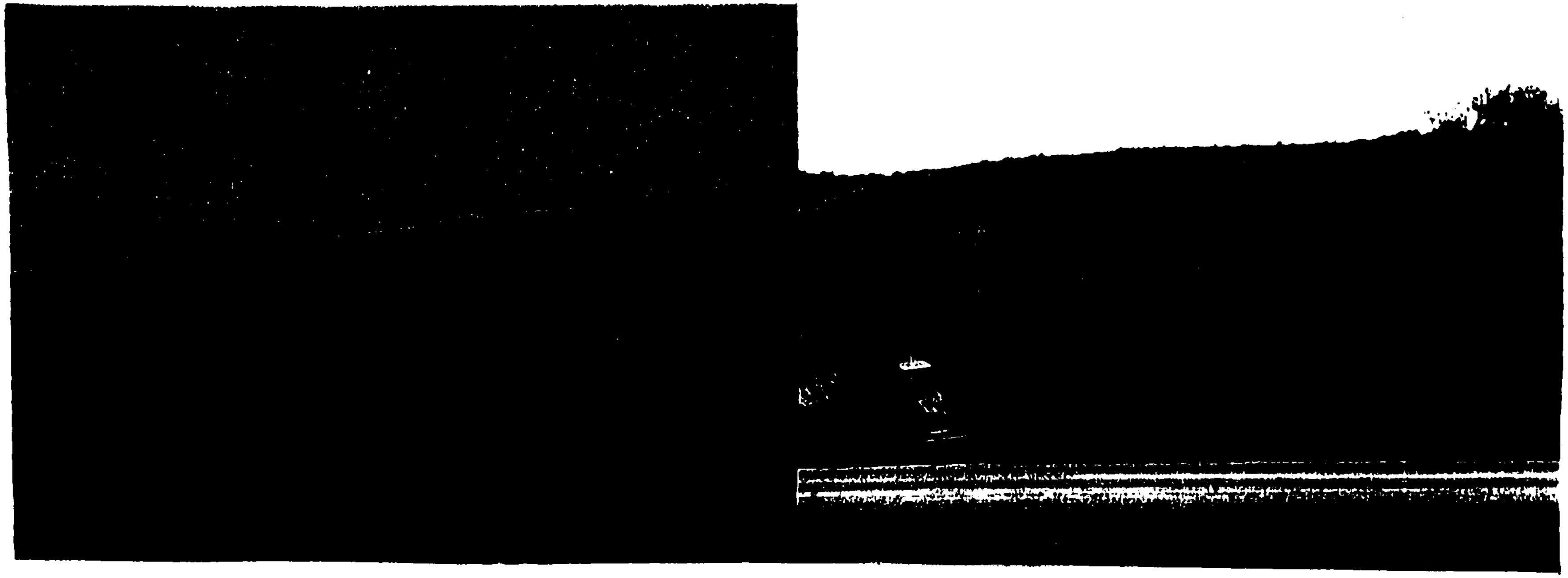


Figure 6-2. Exposure NB-09 is located in a large northwest-southeast oriented hummock at the margin of the Thickwood Hills. While most of the hummock is composed of stoney till (vegetated area), the eastern edge is composed of very uniform, bedded sand with bedded sand with a palaeoflow direction toward the south.

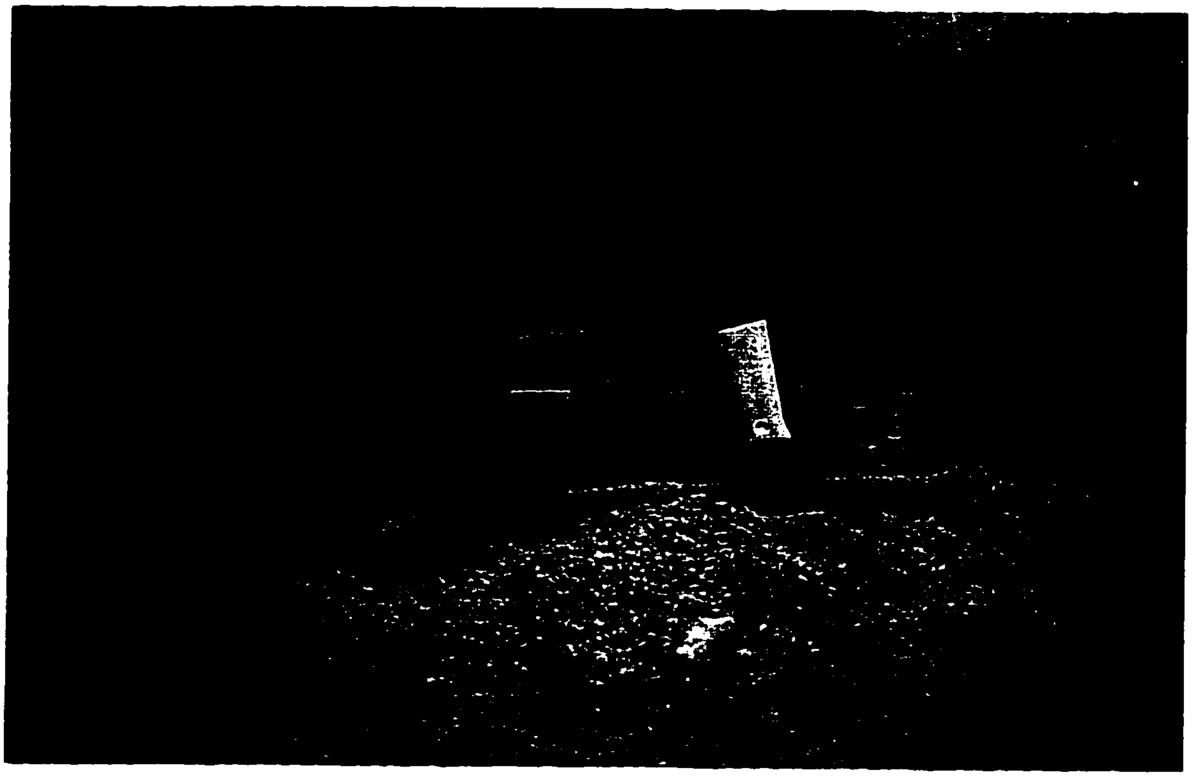


Figure 6-3. Undisturbed cross-laminated sand occurs throughout exposure NB-09.

Figure 6-4. The contact between cross-laminated sand and the overlying diamicton in exposure NB-09 is very sharp and shows little evidence of deformation other than injected veins of diamicton.

sand has a minimum thickness of 2.5 m and a minimum lateral extent of 40 m in an east-west direction.

The streamlined hummock is 0.5 km long and, at its maximum, is 0.3 km wide though it tapers sharply at its stoss and lee ends. It has a long axis orientation of S35°E (Fig. 6-1b) and is adjacent to a secondary channel with a similar orientation that joins the larger southern channel at the margin of the Thickwood Hills. The secondary channel has its origin 4 km to the west where it emerges from a shallow groove that is bordered on the south by a small fluting ridge. The floor of the channel is characterized by elongate and aligned lakes, as well as numerous smaller depressions that may or may not contain water. Associated with the hummock containing exposure NB-09 are depressions in both upflow and downflow directions (Fig. 6-1b). The difference in relief from the top of the hummock to the base of the large depression to the east is approximately 30 m. A second smaller and shallower, comma-shaped depression is located near the northern end of the hummock (Fig. 3-12).

Exposure NB-10

Like exposure NB-09, exposure NB-10 (SE29-45-14-W3) is associated with the channels at the margin of the Thickwood Hills (Figs. 4-1 and 3-11). The exposure is located in a gravel deposit perched at the head of a deep, narrow channel that extends downflow into the main channel. Immediately northwest of the gravel deposit is an area of high elevation and very high relief hummocky terrain. The deposit of predominantly sandy pebble gravel ranges in depth from 4 to 5 m and is underlain by till. Overall, the deposit has a very uniform grain-size and, at some sites, shows undisturbed cross bedding to the surface. The only apparent modification of the surface gravels are infilled scour zones and ice wedge casts (Fig. 6-5). The lithology of the gravel is predominantly subangular to subrounded crystalline and carbonate clasts and some quartzitic clasts. A coarse surface layer of multimodal gravel that contains abundant cobbles occurs at the northern limit of the pit. Its thickness varies but is generally 1.5 m. Imbrication of the coarser unit indicates a palaeoflow from west to east. The dips of the lower gravel units

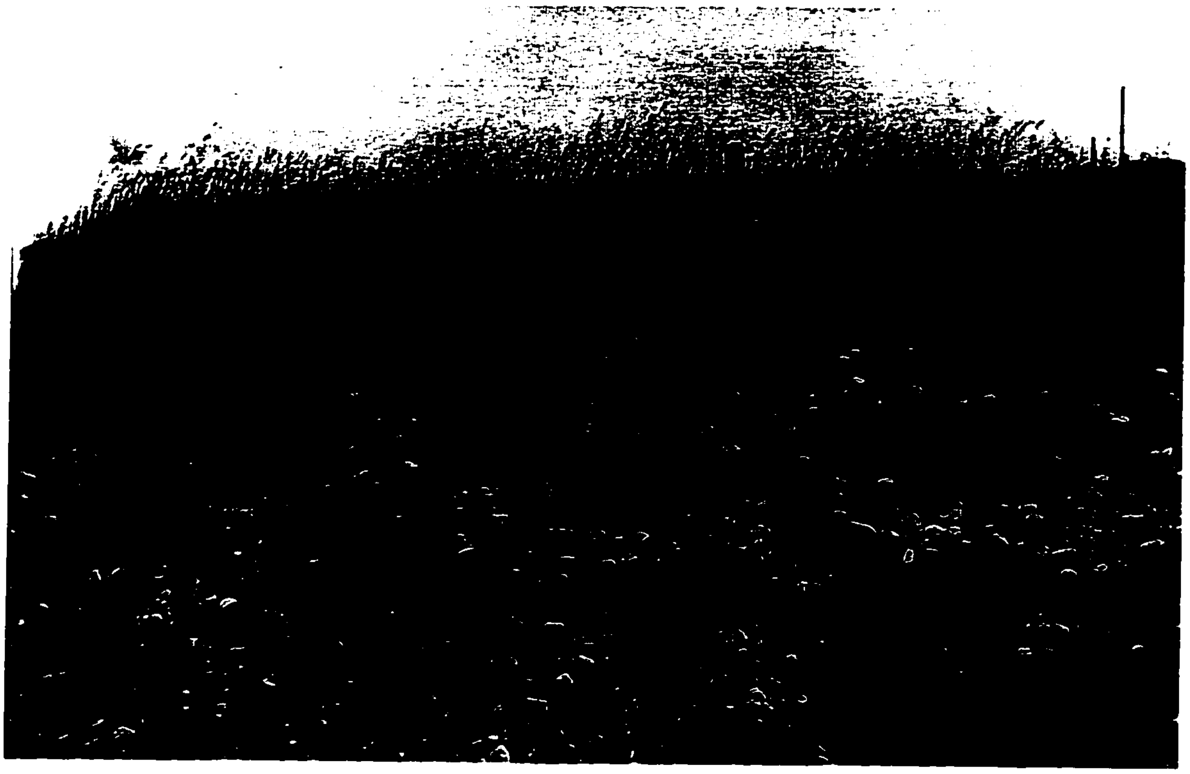


Figure 6-5. Exposure NB-10 is composed of very uniform sandy pebble gravel and an upper unit of coarse cobble gravel. The surface sediments are undisturbed with the exception of infilled scour marks and ice wedge casts.

indicated a variable palaeoflow direction ranging from S25°E to S60°E. Approximately 50 m west of the main gravel pit and at a slightly higher elevation is a small gravel ridge with an orientation of S60°E. A small 2 m deep exposure in the ridge that is transverse to its long axis orientation reveals a coarsening-upward sequence of graded beds of sandy pebble gravel. The dip of the beds indicates a palaeoflow direction from the northwest to southeast. The gravel deposit has a very small areal extent. At its northern limit, the deposit is truncated by a sharp 15 m drop into a broad, north-south oriented low located between adjacent hummocks. The area is largely inaccessible, though a limited number of road cuts and ditches reveal only till. To the west and south of the gravel pit is the margin of a large area of high relief hummocky terrain at a higher elevation than the gravel deposit (Fig. 6-6). A large hummock immediately to the west rises steeply to approximately 25 m above the gravel deposit and appears to be composed entirely of bouldery till at the surface.

Site HWY73B-131

Site HWY73B-165 (NW21-45-14-W3) is an inactive Saskatchewan Department of Highways and Transportation gravel pit that is located at the southeastern extent of the same deposit described for exposure NB-10 (Fig. 4-1). As in exposure NB-10, the sediments are primarily sandy pebble gravel with a coarser unit at the surface. The only variation is greater amounts of sand at the north east margin of the deposit. The depth of the gravel is generally 4 to 5 m though, in some test holes, till was encountered at 2 m. At its southeast margin, the deposit drops very steeply 25 m into the narrow channel that is a tributary of the main channel (Fig. 6-7).

Exposure NB-11

Exposure NB-11 (SW18-45-13-W3) is in a gravel pit that was excavated in a small, circular hummock near the eastern edge of the Whitehall Lakes (Fig. 4-1). The Whitehall Lakes are a series of large shallow lakes that are contained within the main portion of the southernmost channel on the edge of the Thickwood Hills. The gravel deposit is roughly

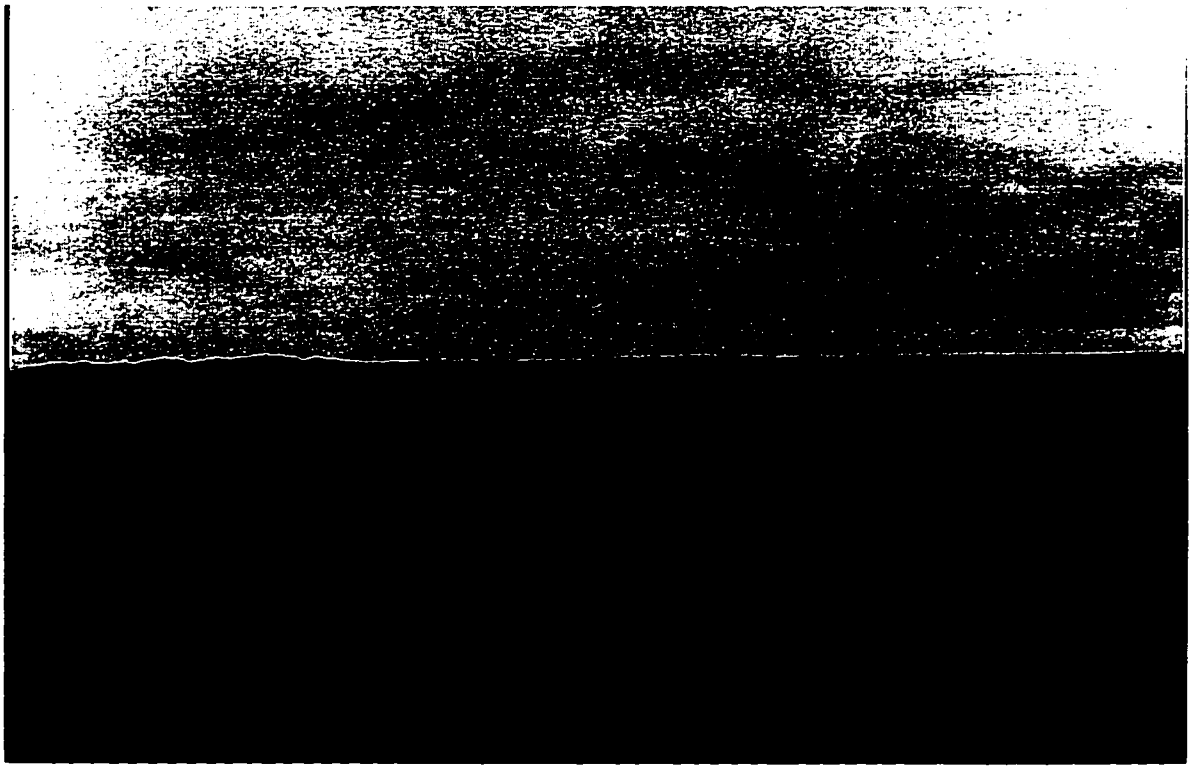


Figure 6-6. Exposure NB-10 is in a gravel deposit that is bordered by high elevation and high relief hummocky terrain to the south and west and by steep drops to the north and east. The photograph was taken from the top of a till surfaced hummock west of the pit.

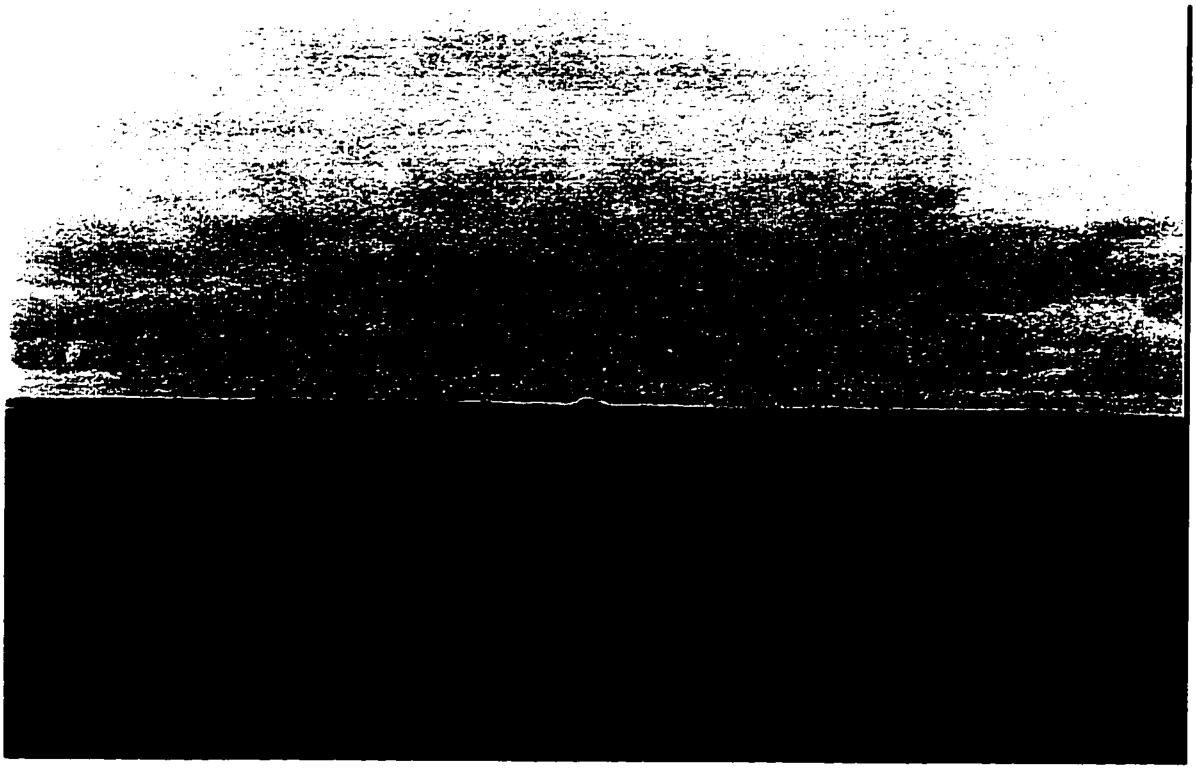


Figure 6-7. Site HWY73B-131 is an inactive gravel pit at the eastern limit of the deposit associated with exposure NB-10. The gravel deposit is sharply truncated at the head of a deep, narrow channel that extends southeast into the main channel system at the margin of the Thickwood Hills.

8 km southeast of exposures NB-09 and NB-10. The south-facing section is composed of a 10 m thick deposit of horizontally bedded and graded gravel units. The sediments are primarily units of very sandy pebble gravel. Of lesser abundance are thin units of parallel laminated and cross bedded coarse sand that contain small pebbles and units of pebble gravel with very little matrix. The beds are clearly truncated by the hummock form at the eastern margin of the exposure with no evidence of deformation of the primary deposits. Imbricated clasts indicate a direction of transport from north to south. The hummock is circular in form so that its orientation cannot be determined. However, it does exist in alignment with a small ridge to the northwest and a second circular hummock to the southeast. Together the features have an orientation of S35°W. The hummock is bordered on the south by a narrow, deep channel that has its origin in hummocky terrain less than 1 km to the northwest and runs parallel to the main channel until they merge 2.5 km to the southeast. The small channel is separated from the main channel by a heavily eroded ridge. The floors of the channels are characterized by densely spaced hummocks and depressions of widely varying sizes and morphologies.

Exposure NB-12

Exposure NB-12 (SE21-44-13-W3) is in a hummock located approximately 15 km southeast of exposures NB-09 and NB-10. The south-facing exposure is cut through a hummock that is composed of alternating beds of graded gravel, sand and silt (Fig. 6-8). The uppermost observable sediments near the apex of the hummock are primarily sand and silt, while the lower sediments are sand and gravel. The lowermost units of pebble gravel also contain abundant pebble-sized till balls. The sand units are cross bedded and indicate palaeoflows from west to east. All beds are clearly truncated on the western edge of the hummock. Minor faulting cross cuts multiple beds near the truncated surface, though the primary bedding structures remained easily identifiable (Fig. 6-9).

The hummock is located in an area of high ground that separates two anabranches of the main channel. The interfluve is a high relief area of many randomly oriented, circular and elongate depressions and hummocks. The channel to the south of the hummock

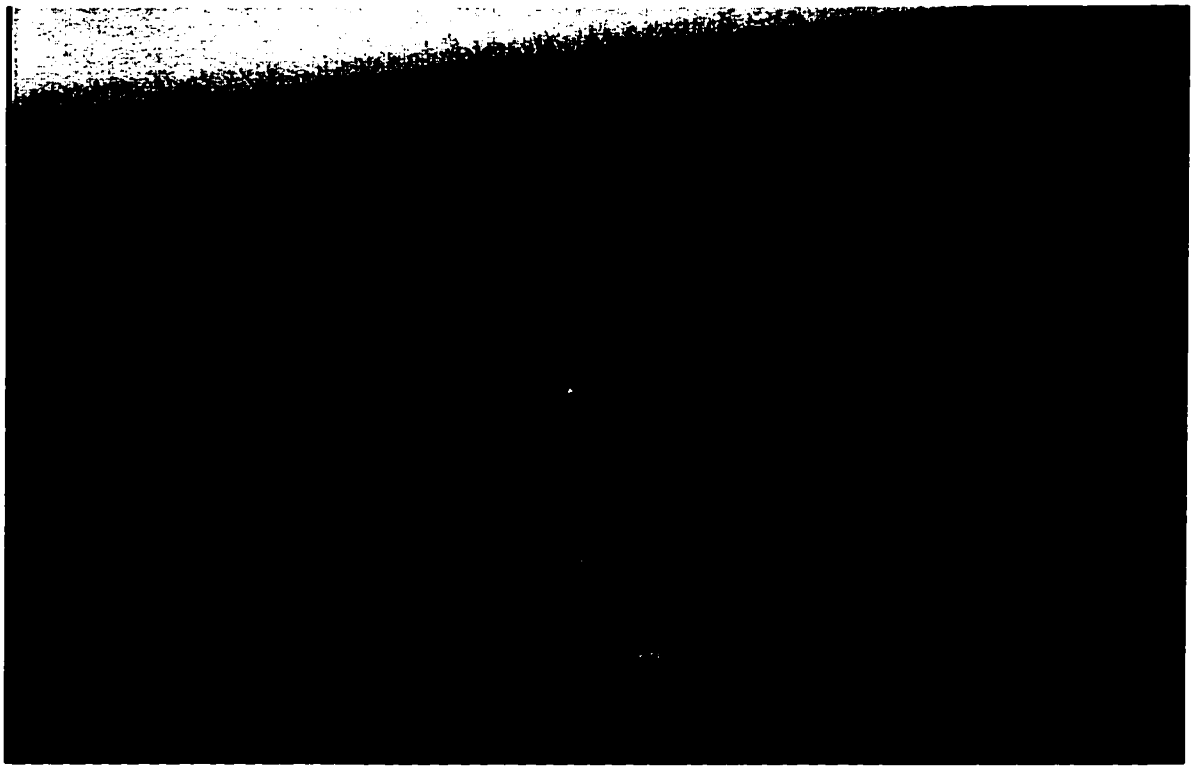


Figure 6-8. Exposure NB-12 is a south-facing section in a hummock composed of undisturbed, alternating beds of sand and gravel. The hummock is located on an interfluve between two anabranches of a poorly defined portion of the southern channel at the margin of the Thickwood Hills.

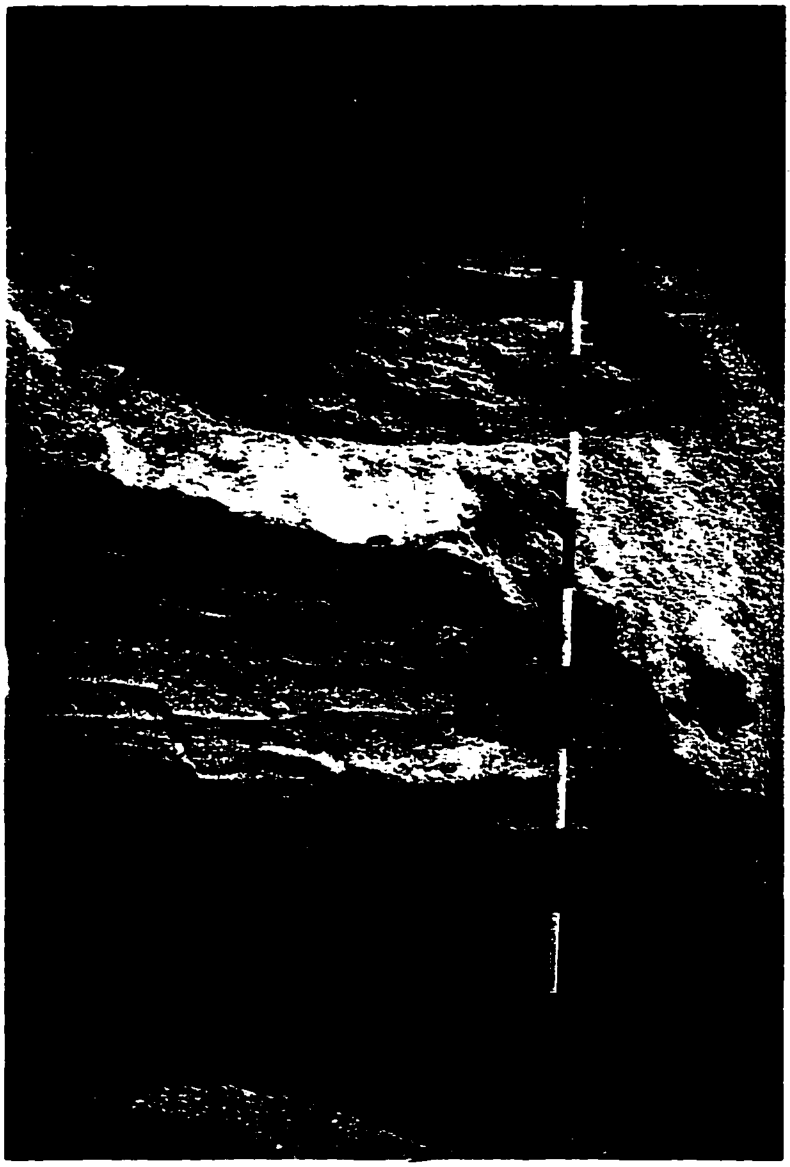


Figure 6-9. At the western margin of exposure, NB-12 alternating beds of sand and gravel are truncated by the hummock form. Deformation of the beds is limited to minor vertical faulting that cross-cuts multiple beds.

contains a long, narrow lake that is oriented northeast-southwest. The channel can be traced upflow to the northwest where it rises rapidly and becomes an increasingly narrow series of disconnected, deep, steep-sided depressions. This portion of the main channel has very indistinct margins and small, discontinuous tributary channels that emanate from the fluting field to the south.

Exposure NB-13

Exposure NB-13 (SW3-45-12-W3) is associated with the northern channel at the margin of the Thickwood Hills (Fig. 4-1). The channel begins directly north of North Battleford and continues in an easterly direction for 45 km. At its downflow limit, it abruptly ends in a cul-de-sac that is defined by a steep rise of 60 m on all sides to the level of the surrounding hummocky terrain. The southern bank of the channel is further accentuated by a hill that rises 100 m above the base of the channel. The hill continues as a tapering ridge that decreases in height and width for approximately 5 km toward the south until it becomes indistinguishable from the surrounding terrain (Fig. 6-10). In some places near its southern extent, the ridge is breached leaving a row of aligned hills that gradually decrease in size. The hills have a very steep eastern margin and more gently sloping western margin. Sediment is exposed by an east-west road cut 2 km south of the peak of the first and largest hill that defines the cul-de-sac. Near the base of the 3 m high north-facing exposure is a layer of cobbles in a sand matrix, topped by 10 to 15 cm of clay and silt. Most of the exposure, however, is composed of a 1.5 m fining-upward sequence of alternating units of sand and very sandy pebble gravel (Fig. 6-11). The uppermost unit of stratified material is composed of sand and gravel that has many deformation structures, including faulting and diapiric structures (Fig. 6-12). The sequence of stratified material is overlain by a unit of diamicton that is thinnest at the crest of the hill and very thick on the western slope. Where observable, the contact between the till and the sand gravel is very sharply defined, even where there is deformation of the stratified sediments. The till is very stony with many pebble and cobble sized clasts of crystalline, carbonate, and quartzitic lithologies. A second road cut through the hill 3 km to the south is located in

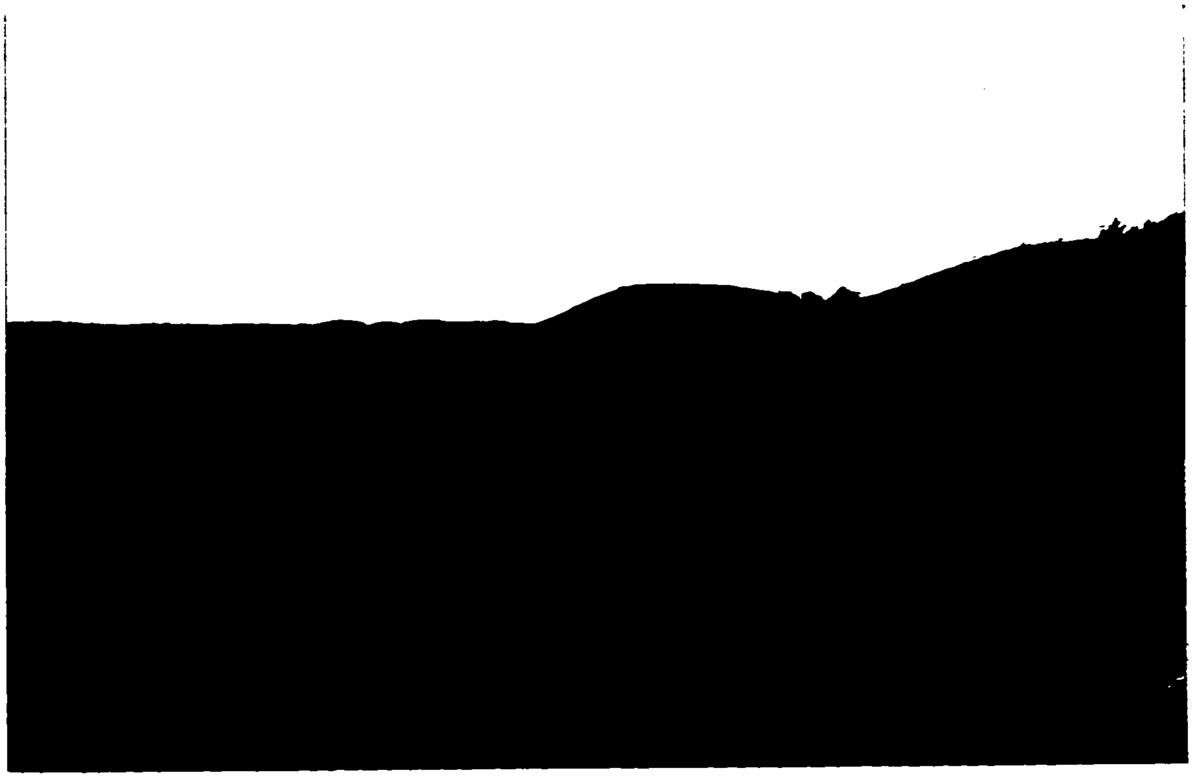


Figure 6-10. The northern channel at the margin of the Thickwood Hills terminates in a 5 km long row of hills that extends southward from a deep cul-de-sac (not shown in photograph).

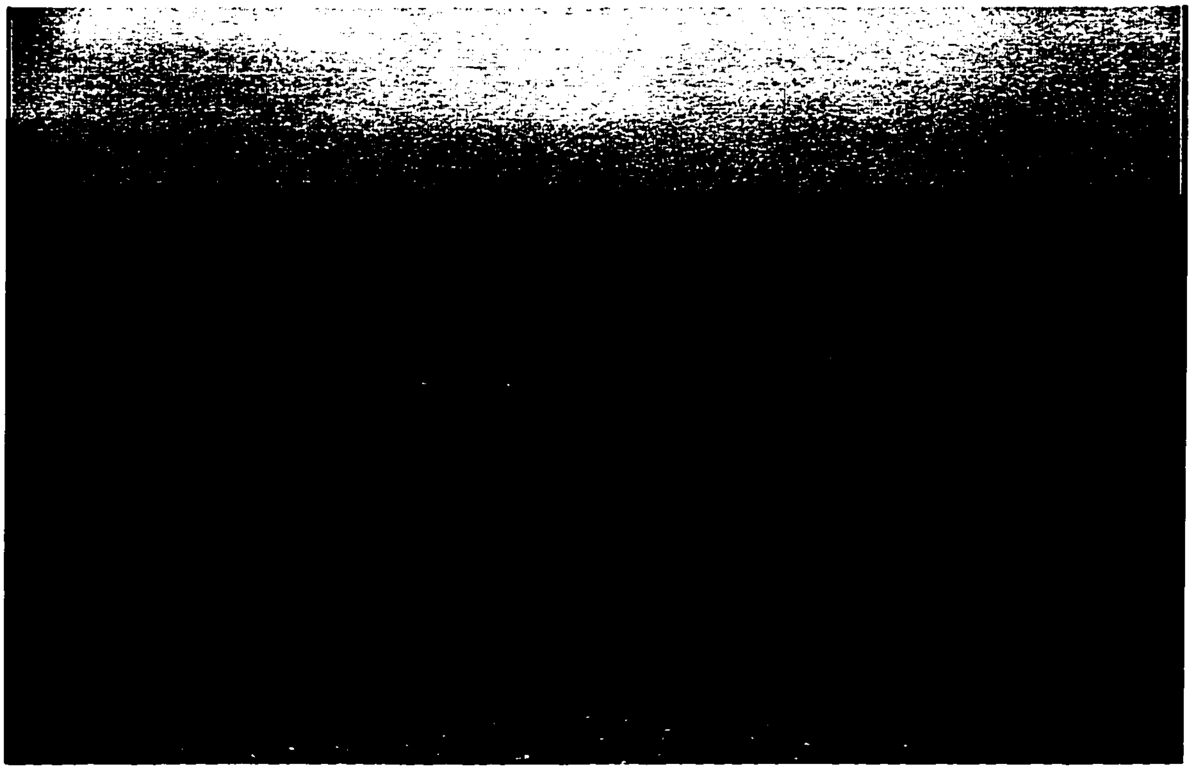


Figure 6-11. Exposure NB-13 is a north-facing section that cuts across the crest of a hill 2 km from the cul-de-sac that marks the end point of the northern channel at the margin of the Thickwood Hills. Alternating beds of sand and very sandy pebble gravel are overlain by 1 m of diamicton. The diamicton thickens downslope to the east and west.

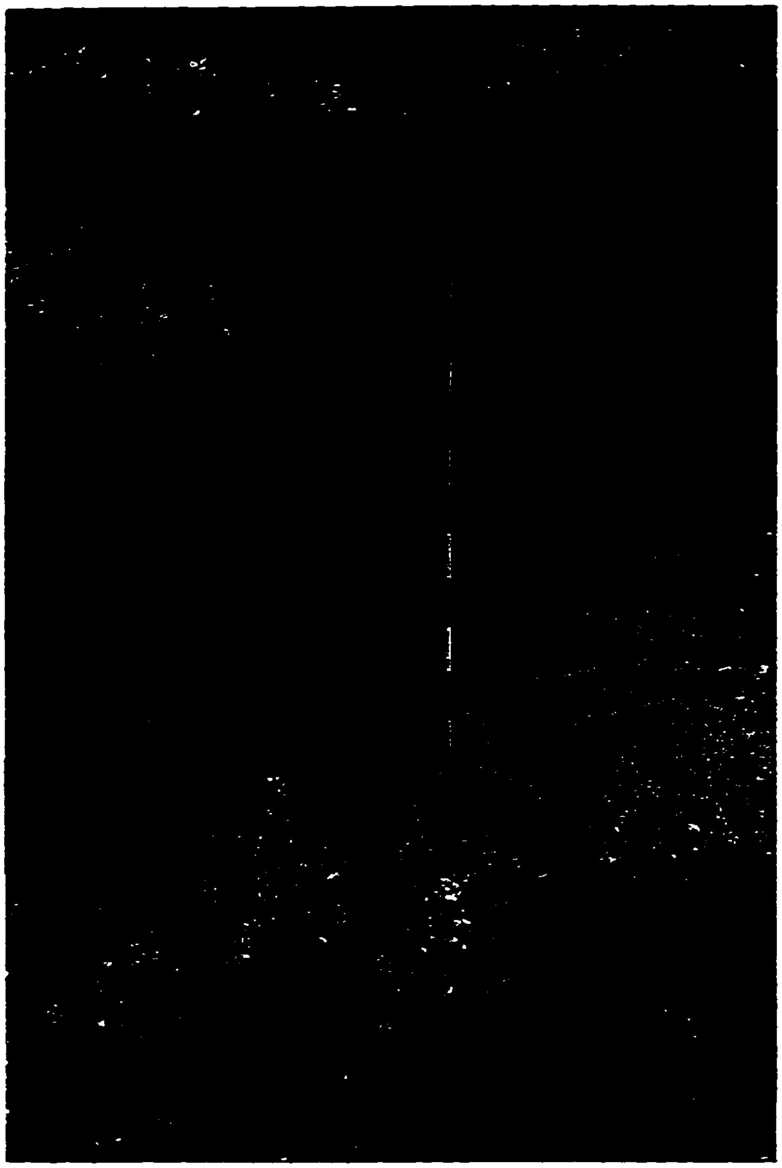


Figure 6-12. The contact between the stratified material and the overlying diamicton in exposure NB-13 is very sharp and marked by deformation structures including faulting and diapiric structures.

the area where the hills are breached. The 5 m high hill is composed predominantly of stony diamicton.

Exposure NB-14

Exposure NB-14 (SE3-45-12-W3) is associated with the rows of hills described for exposure NB-13. It is located in a small, 2 m deep pit excavated along the eastern margin of the hills approximately 1 km south of the cul-de-sac. The pit is situated 8 m from the crest of the ridge. At the base of the exposure, multiple units of cross-bedded sand are overlain by sandy pebble gravel. The uppermost unit of stratified material consists of cobble gravel. The sequence is capped by 1 m of very compact stony diamicton (Fig. 6-13). The contact between the till and gravel is very sharp with no evidence of deformation. At the crest of the hill near exposure NB-14, a small excavation reveals approximately 0.5 m of till on gravel. Gravel is exposed in gullies along the eastern flank of the ridge in the area at various points due to modern gullying.

Exposure NB-15/Site HWY73B-202

Exposure NB-15 (SE2-41-12-W3) is located at the extreme southeastern limit of the North Battleford fluting field and directly south of the mouth of the southernmost channel at the margin of the Thickwood Hills (Fig. 4-1). The channel shifts abruptly from its dominant southeast trend to a southward direction where it quickly becomes indistinguishable from the surrounding terrain. Widespread deposits of sand and gravel are superimposed on the distal extent of the North Battleford fluting field though spindle-shaped depressions and small, indistinct grooves and ridges are distinguishable. Sand deposits that occur nearest the mouth of the channel were reworked into dunes that are presently stabilized. South of the dunes, shallow deposits of gravel extend toward the North Saskatchewan River. Exposure NB-15 is located in a 4 m deep gravel pit (site HWY73B-202) excavated on the west side of a gully that drains from the north into the North Saskatchewan River. The deposits are multimodal with grain-sizes ranging from sandy pebble gravel to cobbles. The clasts are mainly of crystalline and carbonate

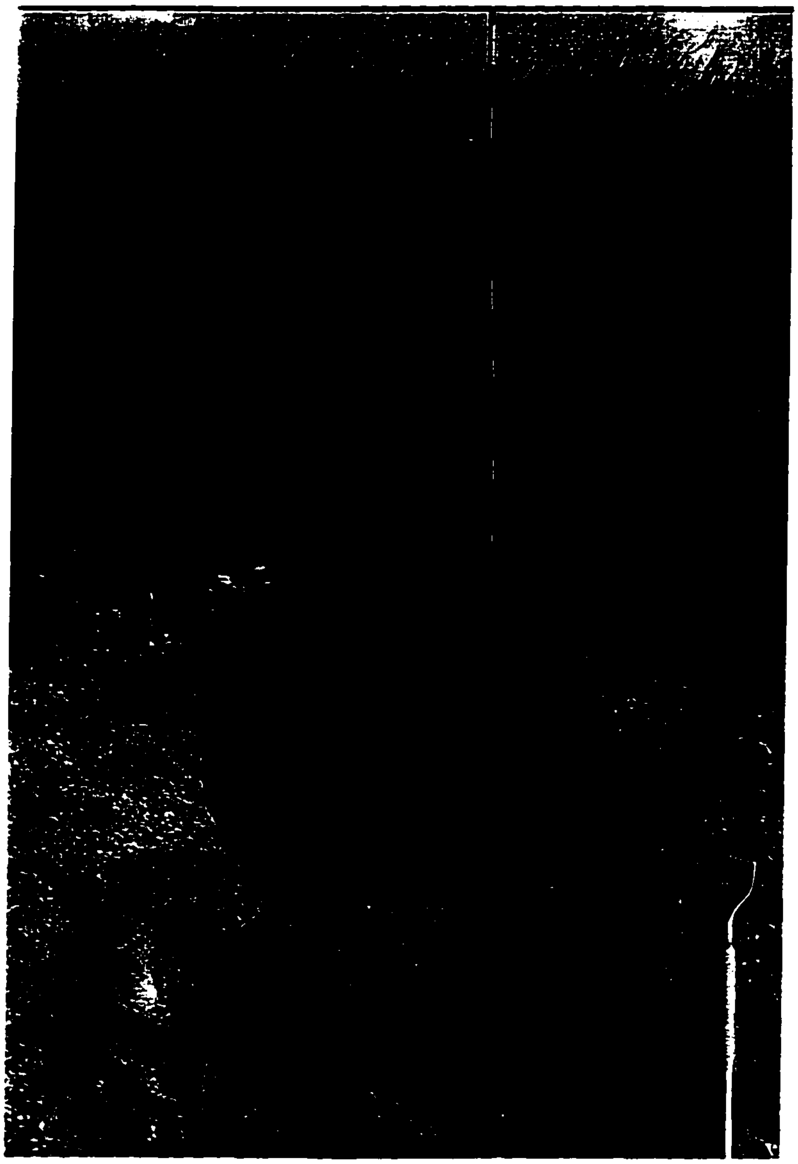


Figure 6-13. Exposure NB-14 is located in a small gravel pit approximately 1 km south of the cul-de-sac that marks the end of the northern channel at the margin of the Thickwood Hills. 1 m of stony diamicton overlies sandy pebble gravel and cross-bedded sands. The contact between the diamicton and the stratified material is very sharp with no evidence of deformation.

lithologies and are generally angular to subangular. The dips of cross bedded sand units and imbricated gravel units indicate a palaeoflow direction toward S20°W. Saskatchewan Department of Highways and Transportation data for site HWY73B-202 indicate that the generally uniform gravel deposit extends over an area of at least 5 km^2 and that, in many test holes, surface till occurs on top of stratified material. The thickness of the till and the stratified sediments is highly variable.

Site 73B-133

Site 73B-133 is an inactive Saskatchewan Department of Highways and Transportation gravel pit (SE1-41-12-W3) located on the east bank of the gully associated with exposure NB-15 (Fig. 4-1). The pit has highly variable depths of multimodal gravel that ranges from test holes with no gravel to those with sorted sequences up to 4 m thick. The composition of the deposits at site 73B-133 is very similar to that at site 73B-202 on the west side of the gully, though with a more frequent occurrence of till balls. Much of the area also has thick till deposits of at least 4 m in depth on top of stratified sediments. Associated with the gravel deposits in this area are large ridges with smaller transverse ridges on their surfaces that have lee-side, inset boulders. The largest of these ridges is oriented north to south though smaller, less distinct features have variable orientations.

Interpretation

The hummocky terrain of the Thickwood Hills is composed of a complex mixture of fluvial, lacustrine, and glacial sediments. The deposits investigated in this study provide a preliminary overview of some of the sediments associated with the extensively eroded southern margin of the uplands. Most of the sites described are contained within the southernmost channel that has its origin in the large depressions that presently contain lakes north of North Battleford. Additional exposures near the distal end of the northern channel were also investigated The observed sediments represent different types of primary depositional processes and environments, though they have in common, present morphologies that resulted from a subsequent erosional event.

Exposures NB-09, NB-10, NB-11, and NB-12 are in hummocks located in the southernmost channel at the margin of the Thickwood Hills. The hummocks are composed, at least in part, of stratified sediments that are interpreted to have been deposited prior to the event that formed the hummocks. The sediments in exposure NB-09 are undisturbed units of graded and cross-laminated, fine-grained sand. The minimum thickness of the deposit of 2.5 m and the sedimentary textures and structures indicate that a lower flow regime depositional flow continued for an extended period of time. The presence of till at the base of the adjacent channel, as well as overlying the sand unit, indicate that the deposition of the sand occurred subglacially in a large-scale conduit. The contact between the sand and the till is very sharply defined. The only observed significant deformation of the sand is minor amounts of diamicton that were intruded into the sand to a maximum depth of approximately 0.3 m. Palaeocurrents indicate that the formative flow that deposited the sands was from north-northeast to south-southwest, though the long axis orientation of the hummock is from northwest to southeast. In addition, the surface hummock form truncates the sand unit such that the sand comprises only a portion of the eastern margin of the hummock which is composed primarily of till. The sand is merely a remnant of a deposit that was, at one time, more extensive. The very sharp contact between the sand and the till, the truncated eastern margin and surface of the sand unit, and the lack of conformity between the palaeoflow and the orientation of the hummock do not support the hypotheses that these types of hummocks are all constructional features (Gravenor and Kupsch, 1959; Stalker, 1960; Parizek, 1969). Conversely, the evidence shows that the hummock is an erosional feature and that the internal sediments are unrelated to the external form of the hummock.

The sediments in exposure NB-10 and site HWY73B-131 are part of a gravel deposit that is perched at the head of a steep drop into a deep, narrow channel. The texture and structure of the gravel is indicative of high regime fluvial processes. The gravel, characterized by imbricated cobbles, a uniformity in grain size, and a small fraction of fine grain sizes, was deposited by a high velocity flow in an environment with a high rate of deposition. The undisturbed bedding structures that reach the surface show that the gravel is a primary fluvial deposit. The surface was subsequently eroded by a fluvial event that left zones of broad scour and fill features. The orientation of the long axes of the scours indicates that the erosive event flowed approximately from northwest to southeast. Sediment filled ice wedges also formed at the surface, though at some later time in a periglacial environment. Based on the scope of this study, it is not possible to determine when the features formed, how long the periglacial conditions persisted, or where the ice front was at the time of formation of the ice wedges. It is not likely, however, that the periglacial features could have survived the fluvial erosion that shaped most of the present landscape. Therefore, the erosional event occurred prior to the development of the periglacial features. Furthermore, the landscape has been subjected to only minor modification subsequent to the erosional event.

As with exposure NB-09, the present extent of the gravel associated with exposure NB-10 represents only a remnant of the original deposit. The gravel deposit is truncated on its southeast margin where the land drops steeply into a deep, narrow channel. The perched position of the gravel at the head of the channel suggests that it was deposited first and subsequently eroded by the event that produced the channel. The gravel deposit is limited to a very small area of approximately 500 m^2 and is less dramatically truncated at other margins by swales between large, till-surfaced hummocks. The lack of waning flow deposits and longitudinal sorting suggests that the high energy flow that was responsible for the gravel must have deposited a more extensively distributed sediments than are currently present. It is likely that the remainder of the deposit was removed by the fluvial event that channelized the margin of the Thickwood Hills.

The sediments in exposures NB-11 and NB-12 were also deposited in fluvial environments that existed prior to the formation of the hummocks in which they occur. At exposure NB-11 a moderate and steady flow regime produced well-sorted, sandy pebble gravel, mainly in parallel laminated and cross stratified beds. The highly variable textures of the beds in exposure NB-12, on the other hand, represent regularly changing flow conditions. The presence of till balls in the lower gravel units at this site indicates that the formative flow passed over till. It is likely this till was the source material for these units and that the distance of transport was relatively short to allow for the preservation of the till balls. Regardless of the differences in the character of the deposits and the types of flows that produced them, it is again significant that the bedding in both hummocks is almost entirely undisturbed and that the palaeoflows, from north to south at exposure NB-11 and from west to east at exposure NB-12, are significantly different from the northwest to southeast orientation of the hummocks in the area and of the channel in which they are situated. The minor faulting observable at the western margin of exposure NB-12 crosses multiple beds and, therefore, occurred after the deposition of beds. At both sites, the presence of beds that are truncated by the surface of the hummock form provides the strongest evidence that the hummocks are erosional.

The sedimentological evidence from exposures NB-09, NB-10, NB-11, and NB-12 shows that the formation of hummocks can not be attributed to processes that involve the ablation and let-down of debris onto the land surface as stagnant ice melted (Gravenor and Kupsch, 1959; Parizek, 1969; Stalker, 1969). It is unlikely that the structure of the stratified sediments observed in the hummocks could have been preserved as perfectly as they are had these processes been dominant. Furthermore, beds that conform to some degree to the shape of the hummock surfaces are not present in this area. Most convincingly, the processes of ablation and let-down could not have produced the beds of stratified material truncated by the hummock form that are prevalent throughout this area. The sedimentological evidence clearly shows that the hummocks are erosional, rather than constructional, features and that the internal sediments are almost wholly independent of hummock morphology. The average relief of individual hummocks is in the range of 10 m, though the maximum relief is approximately 30 m from the level of the lower relief hummocky terrain to the northeast to the lowest point in the channels. An important implication of an erosional hypothesis for hummock formation is that, if one assumes that the initial subglacial till surface was relatively flat and uniform prior to erosion, vast amounts of material were eroded and removed from the area.

The channels at the margin of the Thickwood Hills were produced by fluvial erosion. The presence of erosional hummocks within the channels suggests that they were also produced by fluvial erosion. The sedimentological evidence of the hummocks considered so far, however, does not provide convincing arguments for either an ice marginal or a subglacial formative environment. The sediments at the terminal areas of the both the southern and northern channels, on the other, do provide evidence in support of a subglacial origin of the channels. Exposure NB-13 is composed of fluvially deposited sediments that are overlain by a thick unit of glacially deposited sediments. In contrast to the previous exposures that are located within channels, exposure NB-13 is located in a hill that rises 40 m above the surrounding land surface. As subglacial meltwater flowed from the northwest to the southeast, it eroded the system of channels into the existing substrate. In the area of exposure NB-13, the flow was abruptly diverted southward and upward into the overlying ice. Consequently, the northern channel terminates in a high-walled cul-de-sac. Without an overlying sheet of ice, there is no mechanism by which water could have flowed up and over the hill. Unlike other areas, the intratill gravel is likely associated with the flow that is responsible for the surface morphology. As the water flowed upward into the ice, its reduced competency to transport sediment resulted in the deposition of alternating beds of gravel, sand, and silt. The flow continued southward in a subglacial conduit depositing a gradually decreasing amount of sediment onto the land surface. The cessation of flow through the conduit was followed by a period of glacial deposition prior to its closure. The contact between the sand and gravel and the overlying till ranges from very sharp, with no signs of deformation, to highly deformed with complex folding and faulting and abundant injection features. The deposition of the surface till was likely by melt-out with deformation resulting from the pressure of the overlying ice as it recoupled with the bed.

The terminal area of the southern channel is very different from the northern channel in that it grades more gradually from an area of erosion to one of deposition. The northwest to southeast flow was diverted southward with a consequent reduction in velocity and ability to transport its sediment load. The flow in this case expanded as it deposited discontinuous sheets of gravel that extend at least as far as the North Saskatchewan River, covering the distal portion of the fluting field. The shallow, multimodal gravels that characterize exposure NB-15 and sites HWY73B-202 and HWY73B-133 are indicative of a very high energy, short-lived flow. The multimodal gravels are also associated with large ridges that are characterized by a surface coverings of dense boulder lags. The presence of the surface boulders is additional evidence of very vigorous fluvial erosion that removed all but the coarsest surface material.

The combined geomorphological and sedimentological observations of the landscape indicates that the North Battleford fluting field and associated features were formed by a large-scale, subglacial meltwater flood event. The flood event, therefore, had a northeastern extent that reached at least as far as the margin of the Thickwood Hills. Where the flow encountered large-scale interference, vortices were set up that eroded the prominent grooves and left the remnant ridges of the fluting field. Where lesser interference was encountered, the erosional effect of vortices in the flow was greatly diminished resulting in the plain adjacent to the fluting field. With the waning stage of the flood event, it would be expected that the flow would become progressively channelized. The features at the margin of the Thickwood Hills likely represent an early stage of this channelization. The flow that produced the channels was short-lived and unstable such that it did not allow for the development of an integrated drainage route. The presence of erosional hummocks in the channels, and in areas adjacent to the channels, indicates that they may also form in a subglacial environment.

Chapter 7

DISCUSSION AND CONCLUSION

Introduction

The North Battleford area of west-central Saskatchewan comprises numerous landscape elements that formed during the last episode of Pleistocene glaciation. The geomorphological and sedimentological observations of the North Battleford fluting field and adjacent areas indicate that many of these elements are genetically related. Consequently, a regional-scale perspective is required to investigate the integrated set of landscape elements that formed in a common environment by a common process. The objectives in such an approach, then, are to determine which landscape elements are genetically related and to develop an interpretation that can explain the genesis of the individual components as well as the relationships between them. The comined geomorphological and sedimentological evidence from the North Battleford area are interpreted to indicate a landscape that was primarily created by erosion, and that the erosive agent was the large-scale, turbulent, sheet flow of meltwater in a subglacial environment. The subglacial meltwater sheet flow that formed the fluting field also shaped at least some aspects of the adjacent plain and hummocky terrain. The hypothesized existence of catastrophic subglacial flow events has implications for hypotheses regarding the formation of the various types of landforms, as well as the present understanding of the dynamics of continental ice sheets and their effect on landscape evolution.

Discussion

One of the most striking features of the North Battleford fluting field is the morphological uniformity of the grooves and ridges. Despite this outward consistency, the sediments within different ridges are highly variable. The variation in sedimentary textures and structures are interpreted to represent deposition and erosion by various glacial and glaciofluvial processes that were active at the base of the ice sheet prior to the formation of the fluting. The sediments represent a long period of glacigenic erosion and deposition that allowed for the accumulation of the thick drift deposits. The sediments observed in the fluting field are primarily diamicton, though they also include significant amounts of intrabedded stratified and mélange sediments that are associated with small-scale, subglacial fluvial processes. The variation in the diamicton throughout the area is the result of the complex interactions of ice, water, and the substrate that persisted as ice advanced over the landscape.

Shaw (1994) presented a progression of subglacial geomorphic and sedimentary phases that provide a model of subglacial landscape evolution. Using the thermal model of ice advance characterized by an inner thawed bed zone and an outer frozen bed zone (Moran et al., 1980), the initial phase of ice advance is described by Shaw (1994) as being a period of high geomorphic activity in which complex thermal and dynamic conditions promoted high rates of glacial erosion and deposition. As the glacier melting zone expanded downglacier with ice advance into areas where previous freezing and accretion had occurred, large amounts of material were entrained by the glacier and transported toward the ice margin. The concurrent sliding of debris-rich basal ice resulted in the formation of glacial striations and, with further melting, deposition of debris by lodgement and possible transport by deformation. This initial phase represents the time of maximum subglacial and ice marginal deposition. This phase is also characterized by the rapid advance of the ice sheets that may have been caused by surging and consequent extended and flattened ice sheets. The second phase described by Shaw (1994) involves widespread ice stagnation and episodes of surging and quiescence. The stagnation of the relatively thin ice sheet and concurrent basal warming resulted in extensive deposition of basal debris by melt-out and the development of complex stratigraphies of till and sorted sediment. The deposition of till was periodically suspended as subglacially flowing meltwater from subglacial or supraglacial sources locally separated the glacier and the frozen bed from the unfrozen bed. Meltwater flowed in short-lived conduits where it deposited sediment and in sheet flows that formed extensive boulder pavements (Shaw et al., in preparation). It is these types of meltwater events that likely produced the intratill sorted sediments and mélange units in the observed exposures in the North Battleford fluting field.

The sediments in the fluting ridges do not show evidence of extensive deformation resulting from glacially induced strain as concluded by Stauffer et al. (1990). Nor do they have the characteristics of sediments deposited by lodgement. In contrast, the high degree of preservation of the soft sediment clasts, the primary bedding structures, and the geometry of the sand bodies suggests that the deposition of the diamicton was likely by melt-out from a quiescent glacier. The large-scale deformation of subglacial sediments pushed up into large ridges could not have allowed for the preservation of the delicate structures observed. Deformed sediments, however, are an important, though not a ubiquitous component of the deposits in many portions of the fluting field. Therefore, the deformation process was not an integral part of the fluting formation. The presence of deformed sediments in the fluting ridges in this area is, therefore, attributed to other processes. The sediments in the North Battleford fluting field are representative of a complex history of long, slow accumulation of glacial and glaciofluvial sediments at the base of the glacier that occurred prior to the event that shaped the fluting in which they now exist.

Stauffer et al. (1990) interpreted the presence of boulder pavements in the fluting ridge sediments as erosional surfaces that are unrelated to the process that formed the fluting. Christiansen (1968, 1992) identified a widespread boulder pavement in west-central Saskatchewan as a commonly occurring marker that separates tills deposited during different episodes of glaciation. A sandy older till is identified as the Early Wisconsinan upper till of the Floral Formation. The overlying base of the Battleford Formation is commonly marked by a layer of boulders that are surrounded on the bottom and sides by older till. Where boulders occur at the surface, the Battleford Formation was interpreted to have been removed subsequent to deposition. The boulder pavement was interpreted to have been produced by erosion of an older till prior to the advance of the glacier that deposited the upper most unit of till (Christiansen, 1968). Stauffer et al. (1990) interpreted the boulder pavement observed in the fluting ridges to represent this erosional surface. Based on the hypotheses of fluting formation by the deformation of subglacial sediments (Boulton, 1987), the authors further concluded that the fluting ridges were carved into the uppermost Battleford Formation and the older Floral Formation. This, however, does not account for the presence of the multiple boulder pavements observed in some ridges. Furthermore, large-scale deformation of the sediments would not likely have allowed for the maintenance of an undisturbed, continuous boulder pavement. A possible alternative explanation for the presence of the boulder pavements is that they were produced by episodic subglacial fluvial erosional events as large amounts of debris were removed from the landscape, leaving only the coarsest material as a lag deposit.

The combined geomorphological and sedimentological characteristics of the North Battleford fluting field indicate that the process of its formation was likely erosional. If the fluting ridges are composed of generally undisturbed pre-existing material that was deposited in response to changing conditions at the base of the ice sheet, they cannot be interpreted to be primary constructional features. The evidence indicates that the formation of the fluting field was largely independent of the sediments of which it is composed. Gravenor and Meneley (1958) made the significant observation from their investigation of fluting in the Interior Plains that the form, distribution, composition, and structure of fluting is controlled by the formative medium, not the physical characteristics of the sediments or the topography. The development of alternating, parallel zones of variable pressure at the base of the ice were postulated to have resulted in the incorporation of material eroded from areas of high pressure into the ice and its subsequent deposition into ridges in areas of low pressure. It is difficult, though, to account for all the characteristics of the North Battleford fluting field and its associated features if ice was the erosive agent. Many aspects of the landscape are better explained by fluvial rather than glacial erosion.

The presence of a well sorted boulder pavement in many ridges of the fluting field and undisturbed bedded sand in one of the intervening grooves represent fluvially truncated surfaces. The nature of the formative flow that produced these surfaces can be inferred from the geomorphology of the fluting field. The consistency in the orientation and form of large- and small-scale features shows that the erosion of the landscape operated at different scales and that the entire field formed at the same time. The position of the proximal end of the fluting field at the upflow facing rim of the North Saskatchewan River valley is a key point in the interpretation of its origins. As the sheet of subglacial meltwater flowed from the northwest it encountered the pre-existing rim of the valley. In response to interference in the flow, longitudinal vortices developed that eroded a series of parallel, concave grooves leaving intervening remnant ridges. Where the flow did not encounter an upflow facing step, the effects of longitudinal vortices within the sheet flow acted with less intensity producing very shallow grooves. The main portion of the fluting field and the features of the adjacent plain, therefore, represent an assemblage of landscape elements that were produced at the same time by the same event.

The formation of the North Battleford fluting field by the turbulent sheet flow of subglacial meltwater requires the pre-existence of the upflow facing rim of the present of North Saskatchewan River valley. The evolution of this valley, therefore, was polygenetic and involved the incision of at least segments of it in a subglacial environment as a tunnel channel. Shaw et al. (in preparation) postulated that large-scale tunnel valleys in north-central Alberta were formed by the catastrophic release of subglacially stored water in episodic, high discharge outbursts. It is possible that portions of the North Saskatchewan River valley were also formed by a similar process. Subglacial incision of the tunnel valley provided an upflow facing step of sufficient magnitude to generate longitudinal vortices in the subsequently occurring sheet flow that formed the fluting. The most prominent portion of the fluting field is located on a broad plain that slopes gently to the south toward the North Saskatchewan River valley. The high degree of preservation of the fluting field indicates that the slope formed prior to or during the formation of the fluting.

It is also likely that the tunnel channel served as a route for channelized flow during the waning stages of the flood event. The valley was further incised during the final deglaciation of the area as meltwater drained away from the retreating ice margin that deposited thick units of very coarse gravel in the valley bottom at a position stratigraphically lower than the fluting ridges. It is significant that fluting ridges located at the bank of the modern North Saskatchewan River show very little modification of their primary form. This suggests that during its use as a proglacial spillway, meltwater in the valley was confined to the present path of the modern river. Broader erosional zones that are common in other spillways on the prairies that formed by the catastrophic drainage of proglacial meltwater (Kehew and Lord, 1986) are absent in this area with the possible exception of the broad, boulder covered ridges on the south side of the modern river near the distal end of the fluting field. These, however, may have been eroded during various stages of its evolution as meltwater was preferentially routed through the valley.

The glaciofluvial event that formed the fluting field was a large-scale catastrophic sheet flow of subglacial meltwater that flowed from the northwest to the southeast. The high discharge of water necessary for the formation of the fluting field requires the storage and sudden drainage of a meltwater reservoir. Shaw et al. (in preparation) identify the origin of the Lac la Biche fluting field as part of the subglacial megaflood event that shaped large tracts of land in Alberta. The likely genetic relationship between the North Battleford and Lac la Biche fluting fields has been noted by various researchers (Gravenor and Meneley, 1958; Jones, 1982; Andriashek and Fenton, 1989). Rains et al. (1993) placed the time of the Livingstone Lake event near the time of Late Wisconsin glacial maximum with a calculated flow volume on the order of thousands of cubic kilometres (Shoemaker, 1995) flowing generally southward in a large-scale anabranching system. Shaw et al. (in preparation) identify a southeast flowing anabranch of this event may have formed the Lac la Biche and North Battleford fluting fields. The effects of the sheet flow of were almost entirely erosional as vast amounts of sediment from the substrate and the base of the ice were transported away from the area. The consequent nearly debris-free basal ice would have little erosive capacity subsequent to the flood event and recoupling of the ice sheet with the bed (Shaw et al., 1989). Posterosional modification of the landscape is limited to a small zone of crevasse fill features, a thin veneer of glaciolacustrine deposits, and minor Holocene alluvial and colluvial processes.

The discontinuous channels at the margin of the Thickwood Hills were incised during the waning flow of the flood event that formed the North Battleford fluting field. Small contributary and distributary channels begin and end in grooves in the plain adjacent to the Thickwood Hills. Hummocks in the channels and on interfluves between the channels are composed of sediments that are highly variable in texture and structure and were deposited in response to the complex interaction of various subglacial processes including glacial and glaciofluvial erosion and deposition, diapirism, and deformation. The prevalence of undisturbed primary bedding structures that are truncated by the hummock form shows that the sediments were deposited prior to the formation of the hummocks. In addition, palaeoflow indicators invariably show that the direction of flow that deposited the sediments was markedly different than both the orientation of the channels and the long axis orientation of elongate and aligned hummocks. The orientation of streamlined hummocks and linear chains of circular hummocks, however, is in accordance with the orientation of the channels, suggesting that the formation of the hummocks occurred at the same time as the incision of the channels. The channels and hummocks are purely erosional features that were carved out of pre-existing sediments at the base of the glacier by a highly turbulent flow of meltwater. The channels were quickly abandoned resulting in the complex network of scoured, discontinuous, contributary and distributary channels and remnant hummocks. The deep cul-de-sac at the terminus of the northern channel shows that the flow must have occurred subglacially as water moved upward into the overlying ice. The extent of the subglacial flood event, therefore, had a minimum lateral extent of approximately 30 km from the modern North Saskatchewan River to the northern limit of the channels at the margin of the Thickwood Hills.

The presence of erosional hummocks in the channels has implications for the various hypotheses of hummock formation and interpretations of broad tracts of hummocky terrain. The margin of the Thickwood Hills is not a high relief, hummocky, ablational and disintegration moraine as mapped by Campbell (1987a). Constructional hypotheses of hummock formation (Gravenor and Kupsch, 1959; Stalker, 1960; Parizek, 1969) do not account for the character of the sediments in the hummocks or their relationship to the hummock form. The hummocks in the North Battleford area were formed by subglacial erosion as a highly turbulent, short-lived fluvial event incised the channels into a pre-existing subglacial surface. The lower relief hummocky terrain that occurs between the two main channels and extends toward the north may be a remnant of this pre-existing surface or it may too have been subglacially eroded. The sediments at the margin of the Thickwood Hills existed subglacially prior to the formation of the fluting and the channels. The hummocky terrain, therefore, was not deposited from a stagnating ice sheet during the final deglaciation of the landscape. In contrast, most of the features of the landscape in the North Battleford area were formed subglacially before the glacier began to retreat from the area. The high degree of preservation of the various landscape elements indicates that they were subjected to minimal modification subsequent to the large-scale erosional event that formed them.

Conclusion

Most of the elements of the landscape in the North Battleford area were formed at the same time by the same erosional process. The catastrophic drainage of a subglacial sheet flow of meltwater produced a regional-scale assemblage of genetically related features. The observations of the features in the North Battleford area and the conclusions drawn regarding their genesis have implications for the interpretation of various aspects of glaciation in this region. The complex sedimentological and geomorphological characteristics of the fluting field show the importance of glaciofluvial processes that operated at various scales and various times at the base of the ice. Small-scale, large-scale, and mega-scale subglacial glaciofluvial events are all represented in this area. Relatively continuous and rapidly changing small-scale drainage was associated with the accumulation of thick sequences of glacigenic deposits during a long phase of ice advance. Deposition of sediment in subglacial conduits and erosion of existing sediments resulted in highly variable sand bodies and coarse lag deposits encased in diamicton. The continuous deposition of these sediments was interrupted by a large-scale, catastrophic release of a reservoir of meltwater that incised at least part of the present North Saskatchewan River valley as a tunnel channel. The river valley in the North Battleford area, therefore, is polygenetic as it was shaped by subglacial, as well as, proglacial and modern processes.

At some time after the incision of the tunnel channel, a mega-scale, catastrophic meltwater flood event flowed through the region leaving a wide variety of erosional features, including the North Battleford fluting field. Vast amounts of material were removed from the area as extensive, widespread erosion occurred downward into the substrate, as well as upward into the overlying ice sheet. With the cessation of the flood event, the resulting nearly debris-free ice would have had very limited geomorphic capability. The flood eroded landscape that formed under the glacier has been preserved with only minimal subsequent modification.

The occurrence of a mega-scale, subglacial flood event at some time near the Late Wisconsin glacial maximum has implications for existing interpretations of the evolution of the landscape in the North Battleford area. The need for a late-glacial, southeast flowing lobe of ice as interpreted by Jones (1982) and Andriashek and Fenton (1989) is removed to account for the position and orientation of the North Battleford fluting field. A glaciofluvial origin for this fluting field means that such features cannot be assumed to indicate former directions of ice movement. Similarly, the hummocky terrain at the northeast margin of the fluting field does not represent the large-scale stagnation of debris-laden ice during the final deglaciation of the area. The margin of the hummocky terrain was produced by fluvial processes in a subglacial environment in association with the formation of the fluting field.

Chapter 8

LOBATE GRAVEL DEPOSITS IN THE RURAL MUNICIPALITIES OF WOLVERINE AND VISCOUNT

Introduction

The southeast portion of the study area, located within the Rural Municipalities of Wolverine and Viscount, is characterized by gravel deposits that occur in large lobate forms. The area is separated from the North Battleford fluting field by widespread glaciolacustrine and glaciofluvial sediments that were deposited in association with glacial Lakes Saskatchewan and Elstow and by postglacial aeolian sediments. The lobate gravel forms are found in conjunction with hummocky terrain to the west and a rudimentary anabranching channel system to the south. These elements of the landscape represent a significant and unique episode of erosion and deposition that appears to be associated with the final deglaciation of the area. The gravel deposits are interpreted to have been deposited by a highly turbulent, subglacial sheet flow issuing from the receding glacier margin.

Location and Description of the Study Area

The Rural Municipalities of Wolverine and Viscount are located on the central Saskatchewan Plains approximately 200 km southeast of North Battleford (Fig. 1-1). The bedrock in the area is the Cretaceous, grey, marine shales of the Lea Park Formation and the younger interbedded sand, silt, and clay-shale of the Judith River Formation (Whitaker and Pearson, 1972, Fig. 1-2). The most striking feature of the bedrock surface is the southeast-trending, preglacial Hatfield Valley which was incised into the Lea Park Formation. The study area (Fig. 8-1) is contained within the Assiniboine River Plain (Acton et al., 1960) that forms a central lowland bordered on the east by the Touchwood Hills Upland and on the west by the Allan Hills Upland (Fig. 1-3). The gently undulating to rolling topography that ranges in elevation from 450 m to 600 m is characterized by a

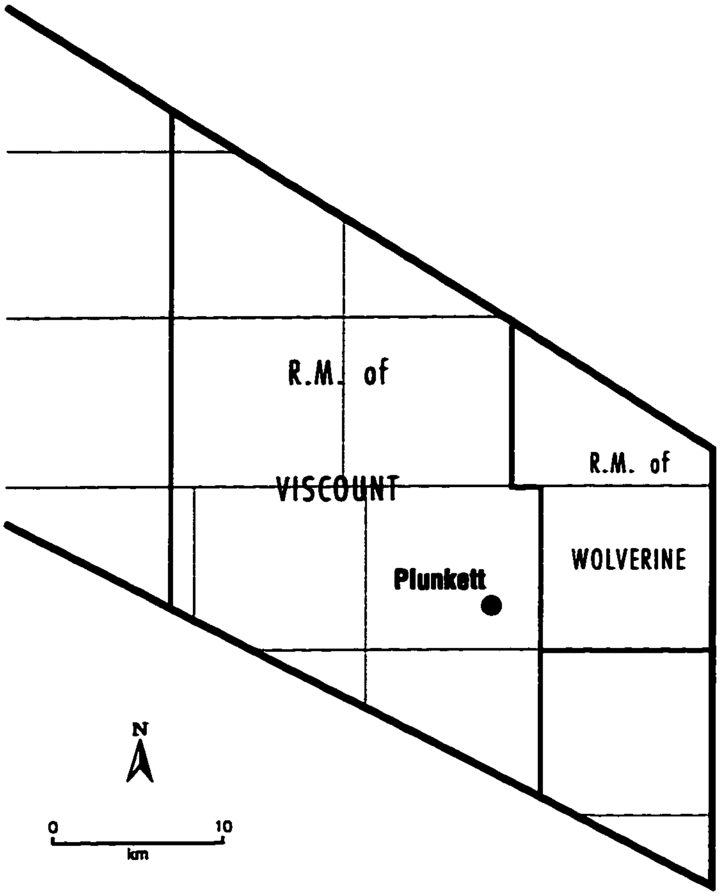
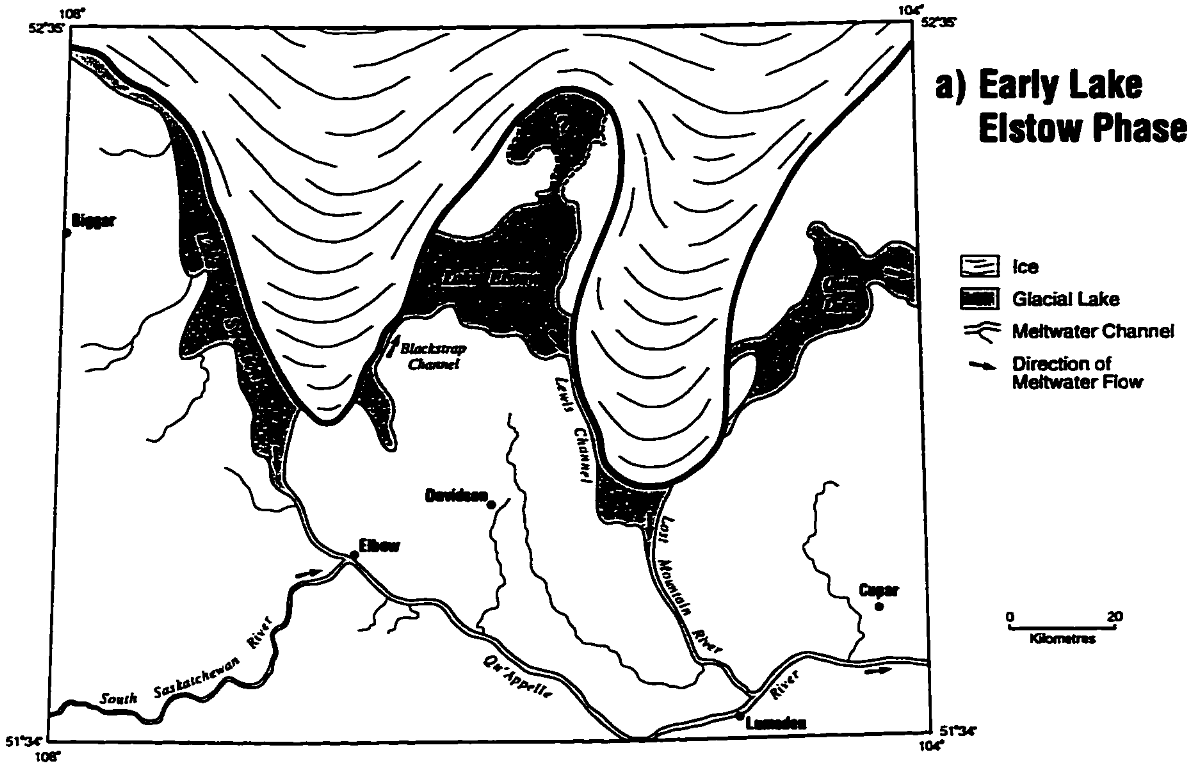


Figure 8-1. Rural Municipalities of Wolverine and Viscount in study area.

combination of almost featureless plains and hummocky terrain. The position and configuration of the Touchwood and Allan Hills, as well as other smaller areas of uplands, are interpreted by Edmunds (1962) to reflect the preglacial landscape that developed during the Tertiary Period. Drift deposits in the area vary in thickness from 1 m to more than 300 m (Fig. 1-5). The preglacial Hatfield Valley is infilled with Pleistocene deposits that range from 150 m to 225 m thick (Greer and Christiansen, 1963). The modern drainage is primarily internal as small rivers and creeks, many of which are ephemeral, empty into closed depressions and lakes. Only small creeks in the southern portion of the study area contribute runoff southward to the Qu'Appelle River system (Mitchell et al., 1947).

Regional Literature Review

Edmunds (1962) described the final retreat of the Laurentide Ice Sheet from central Saskatchewan as occurring in a series of six phases. The area of interest in the Rural Municipalities of Wolverine and Viscount became ice free during what Edmunds (1962) referred to as the Early and Late Lake Elstow Phases of ice retreat (Figs. 8-2a and 8-2b). While no attempt was made to estimate the actual time of the various phases, the oldest phase, referred to as the Early Lake Regina Phase (Edmunds, 1962), roughly corresponds to Phase 4 of Christiansen (1979) which was radiocarbon dated at 14 ka. Kehew and Teller (1995), however, suggested an alternative time period of later than 11 ka before the area was free of ice. The Early Lake Elstow Phase (Edmunds, 1962) included the complex development of glacial Lake Elstow and the Lewis, Blackstrap, and Watrous spillways. The ice front was interpreted to have consisted of two lobes separated by a marked reentrant. The large western lobe occupied the Saskatchewan Rivers Plain and the narrower eastern lobe filled the upper part of the Last Mountain Lake valley. The intervening upland in the reentrant contained glacial Lake Elstow. Edmunds (1962) used this ice front configuration to demonstrate the inferred significance of the preglacial topography on local movement of ice in the Interior Plains. He concluded that near the ice front where the ice was not thick enough to override the uplands, advancing ice tended to



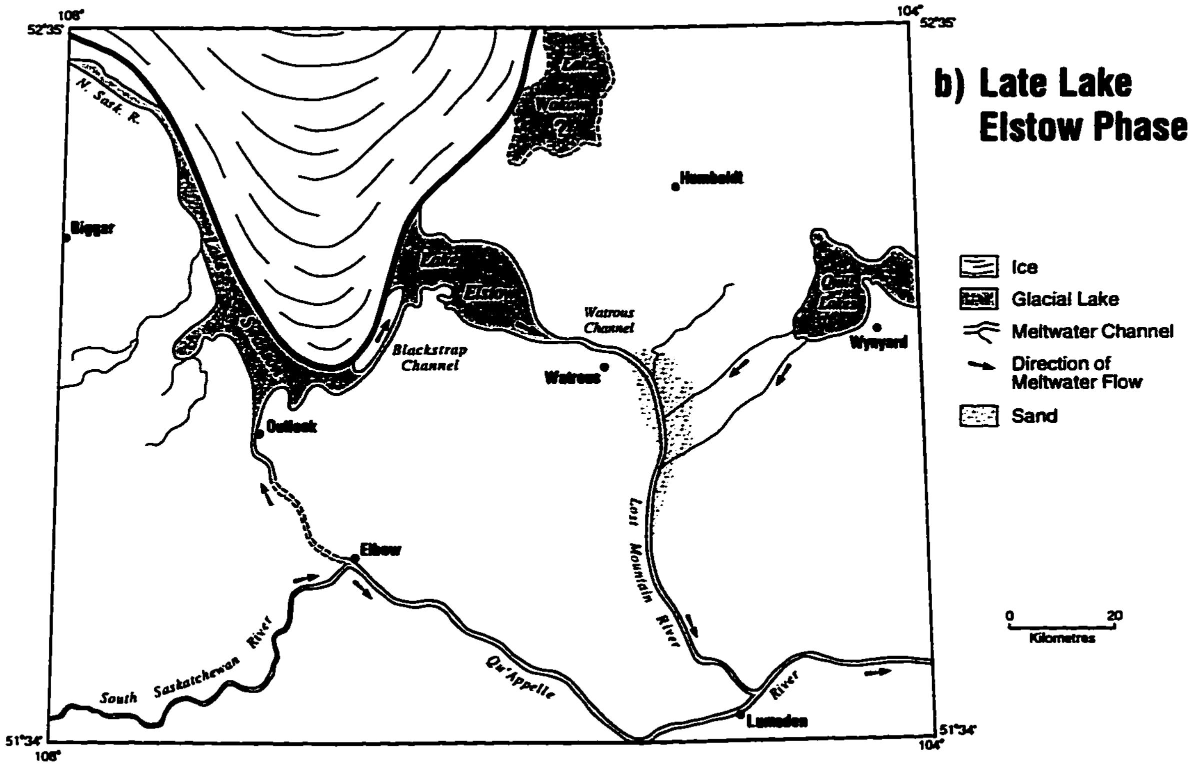


Figure 8-2. Deglaciation of R.M. of Wolverine and Viscount area of central Saskatchewan (Edmunds, 1962).

form lobes in lowlands. Similarly, during recession the ice was thought to have formed lobes in the lowlands as it disappeared first from the uplands where it was thinner.

Associated with the receding ice front, was a series of spillways and glacial lakes that were formed as meltwater drained from the glacier. Various interpretations exist concerning the location and extent of proglacial lakes and their relationship to large-scale spillways. Kehew and Teller (1995) provided a detailed synopsis of proglacial lake and spillway development in central Saskatchewan as it is currently understood (Fig. 8-3). Prior to the development of the spillways, glacial Lake Saskatchewan, glacial Lake Elstow, and glacial Last Mountain Lake were ponded in isolated basins along the ice margin. Glacial Lake Saskatchewan was located in the South Saskatchewan Lowlands west of the Allan Hills and extended northwestward as far as the North Battleford area. These events correspond to Phase 5 of Christiansen's (1979) chronology of deglaciation of southern Saskatchewan (Fig. 1-6a). Glacial Lake Elstow formed subsequently between the ice margin and the northern end of the Allan Hills and was interpreted to have ponded on top of stagnant ice along its eastern margin and at its outlet (Kehew and Teller, 1994). As melting of the ice front progressed, an outburst flood incised the Blackstrap spillway between Lake Saskatchewan and Lake Elstow across a divide of stagnant ice and over the western edge of the Allan Hills. During its early stages, glacial Lake Elstow was drained by the south trending Lewis spillway, through the Last Mountain Lake valley and into the Qu'Appelle River. As the ice lobe filling the Last Mountain Lake valley retreated northward, the Lewis spillway was abandoned in favour of the southeast flowing Watrous spillway as an outlet for glacial Lake Elstow. By this time, glacial Lake Saskatchewan no longer covered the North Battleford area as described by Christiansen (1979) in Phase 6 of his deglaciation chronology (Fig. 1-6b). This shift also corresponded to the beginning of the Late Lake Elstow Phase (Fig. 8-2b) described by Edmunds (1962). Greer and Christiansen (1963) provided more detail regarding the Early and Late Elstow Phases of deglaciation. In their interpretation, a proglacial lake developed with the initial retreat of the major ice lobe in the Last Mountain Lake valley as the northward flow of water was dammed by the glacier. The complex history of ice retreat and lake evolution was

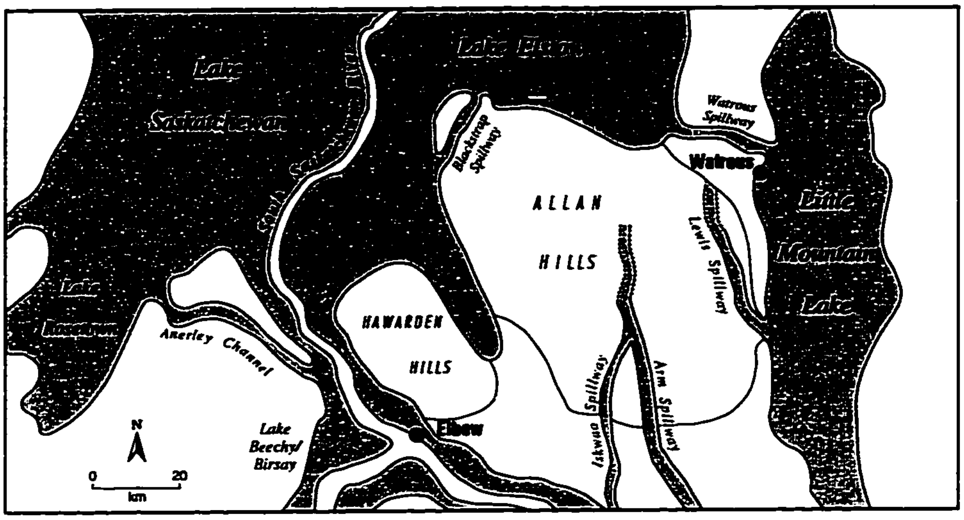


Figure 8-3. Proglacial lakes and spillways in central Saskatchewan (Kehew and Teller, 1995).

interpreted to include the development of major reentrants and at least one episode of ice readvance. Most of the meltwater flowing into the lake was believed to have originated in the interlobate area, though the Lewis spillway was also used. Greer and Christiansen (1963) suggested that this ice front configuration accounted for the numerous lobate, ice marginal channels that formed between Last Mountain Lake and the Touchwood Hills to the east. With further retreat, the glacier was interpreted to have divided into two distinct lobes (Fig. 8-4) that had subglacial streams issuing from minor reentrants. In the interpretation of Greer and Christiansen (1963), meltwater discharged from the northwestern lobe through the Watrous spillway and the more northerly Plunkett channel. Kehew and Teller (1995), however, offered a modified explanation for the formation of the Watrous spillway. In their interpretation, the lobe of ice that occupied the Last Mountain Lake valley separated from the still active glacier in the Saskatchewan Rivers Plain. Subsequently, the Watrous spillway was rapidly incised across a divide of stagnant ice by a short-lived outburst that catastrophically drained glacial Lake Elstow into glacial Last Mountain Lake.

Quaternary Deposits and Geomorphology

The predominant surficial deposits in the rural Municipalities of Wolverine and Viscount include glaciolacustrine clay and silt, till, and till-lacustrine melanges (Edmunds, 1962). The distributions of the surficial sediments are shown in Figure 1-4. The extensive glaciolacustrine and aeolian deposits in the vicinity of the city of Saskatoon are bordered on the east by low and high relief hummocky terrain that is composed primarily of till. Glaciolacustrine deposits include flat to gently undulating clay and silt and sandy deltaic deposits that have, in some cases, been reworked into dunes (Campbell, 1987b). Glacial lake limits, however, are indistinct and are inferred from the presence of discontinuous sandy beach ridges and the eroded stony clay of water washed till (Edmunds, 1962).

The lobate gravel deposits that are of particular interest in this research, are located near the eastern margin of glacial Lake Elstow and north of the Lewis and Watrous spillways. The margin of glacial Lake Elstow is characterized by thin, discontinuous

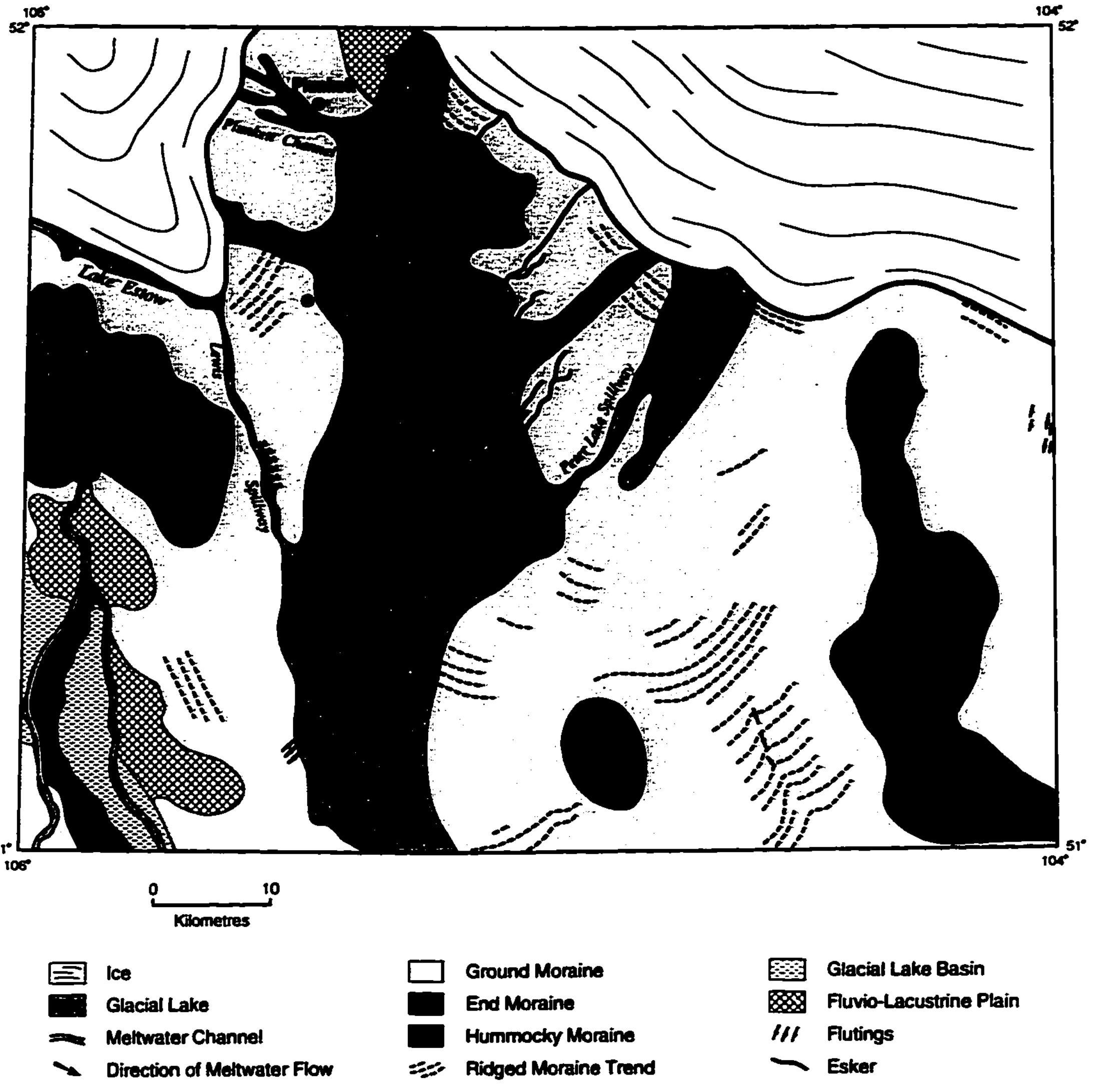


Figure 8-4. Deglaciation of central Saskatchewan and the development of the Plunkett Channel (Greer and Christiansen, 1963).

glaciolacustrine sediments that occur in conjunction with more widespread glacial deposits and grade into hummocky terrain composed of till and small pockets of glaciofluvial material. The hummocky terrain is highly variable in its geomorphological characteristics (Fig. 8-5). In the northwest portion of the study area, the hummocky terrain has an average relief of approximately 15 m and is characterized by closely spaced hummocks, separated by densely distributed, closed depressions that are frequently filled with water. Small areas of less that a few square kilometres of flat-lying lacustrine deposits also occur. Many of the hummocks have circular and near-circular rim ridges enclosing central depressions at their apex. Generally, neither the hummocks nor depressions exhibit any discernible orientation and no overall pattern within this zone is evident with the exception of its easternmost limit. At its eastern margin, this zone of hummocky terrain has strong northwest-southeast trending lineations. Linearly arranged lakes, depressions, and hummocks are contained within a 2.5 km wide, concave trough that is bordered on both sides by pronounced sharp-crested ridges. In addition, the the trough appears to truncate an area of higher relief hummocky terrain to the north that has a very distinct north-south oriented pattern. In the older, higher relief terrain, lakes and small depressions have a large length-to-width ratio and are arranged in parallel lines. The overall elevation is approximately 15 m higher than the hummocky area to the south and west and the relief ranges from 20 to 30 m.

The trough of the hummocky terrain in the northwest portion of the study area diverges at its eastern limit into a zone of low relief terrain that is characterized by a dense network of small northwest-southeast trending grooves. The grooves vary in depth and morphology from those with smooth, gently sloping sides to those with sharply defined margins, steep slopes, and pitted floors. The eastern margin of this scour zone is sharply defined by a series of large, flat-topped, lobate forms composed of coarse gravel (Fig. 8-6). The gravel lobes extend from north to south for a distance of 10 km and range in width from 1 to 2 km. The leading edge of the lobes drops steeply 10 m to an extensive tract of eroded till plain. The boundaries between individual lobes are marked by elongate depressions that are very densely paved with boulders (Fig. 8-7) and generally contain

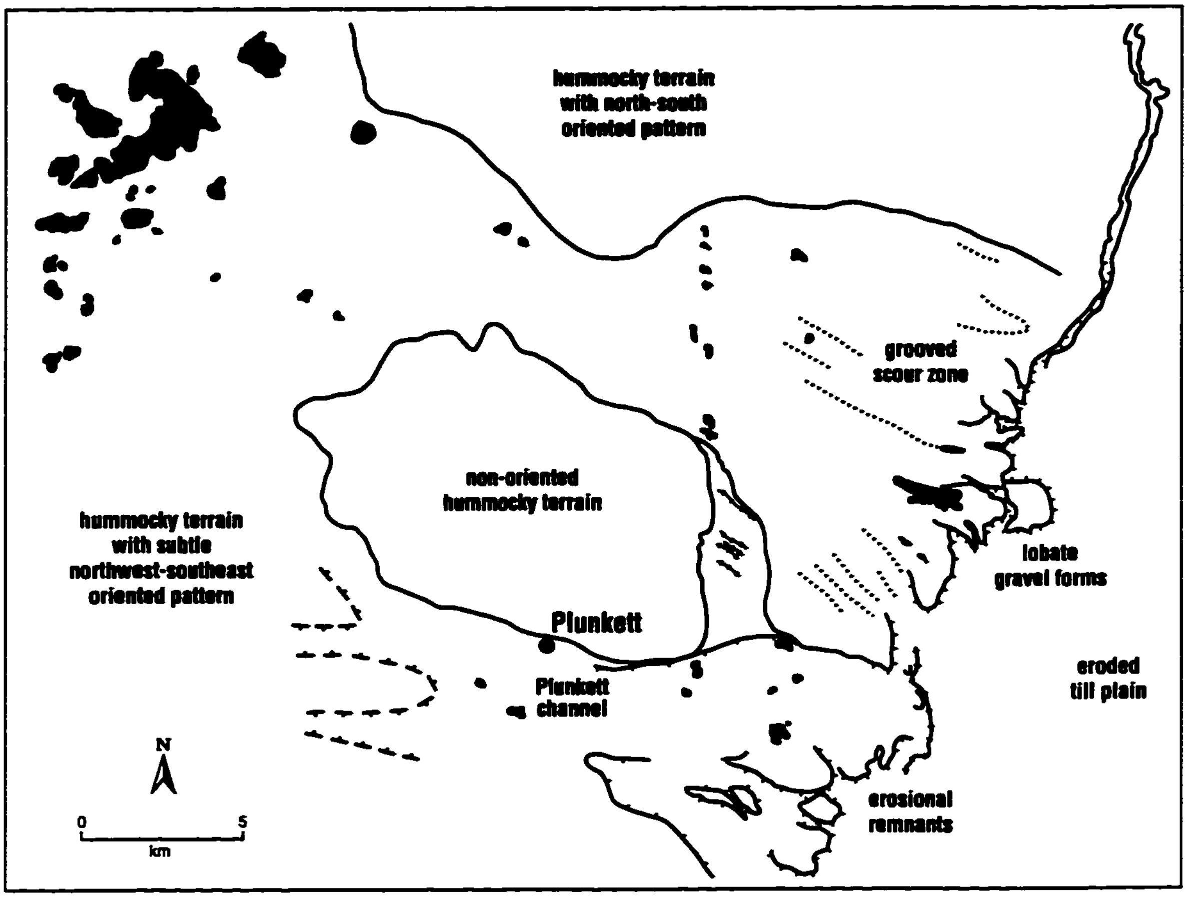


Figure 8-5. Surficial geology in the Rural Municipalities of Wolverine and Viscount.

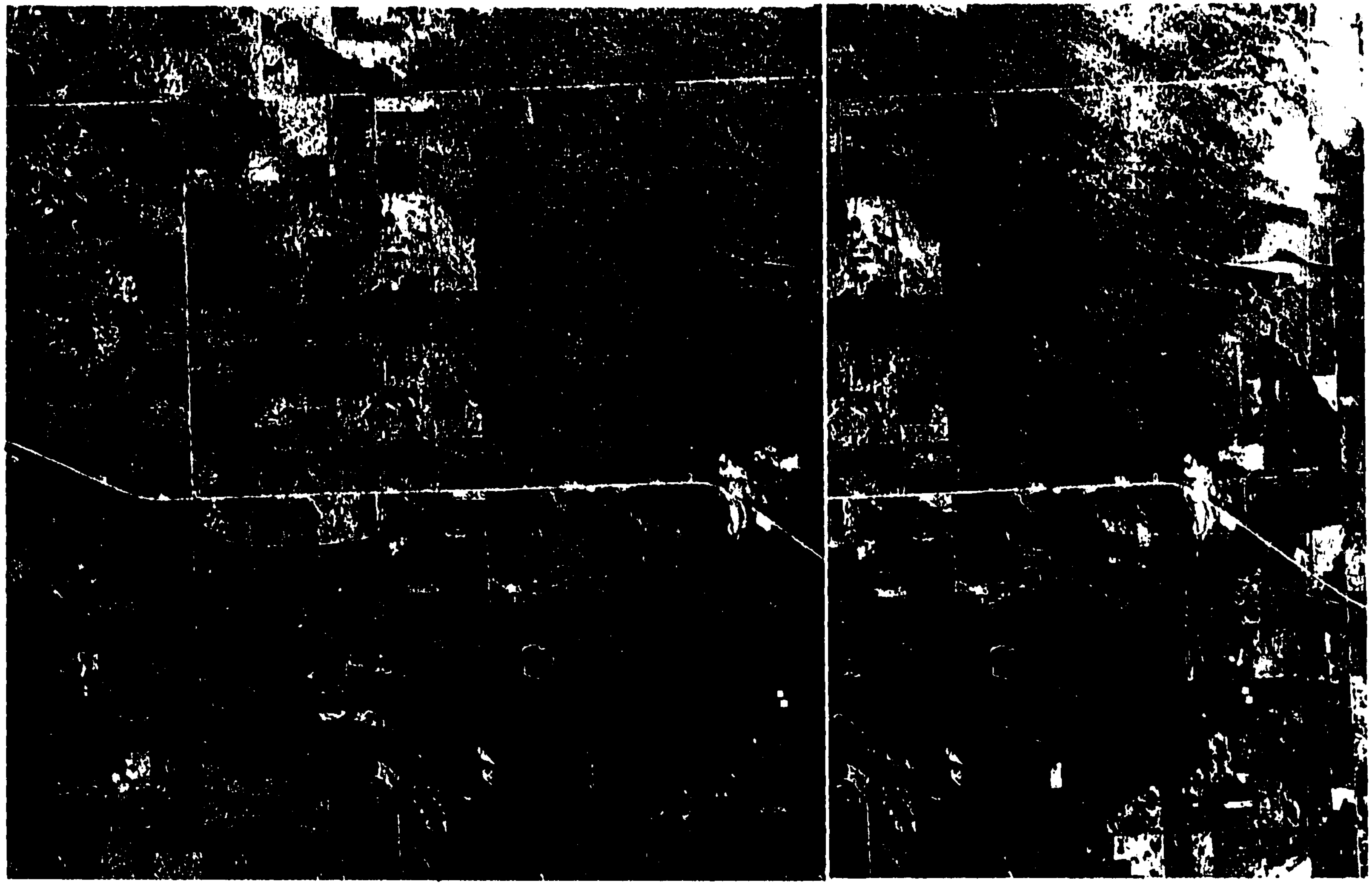


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Figure 8-6. Stereo aerial photographs of gravel lobes and scour zone in Rural Municipality of Wolverine showing the zone of scouring (SC) and depositional gravel lobes (L), hummocky terrain (H) and the Plunkett Channel (PC).

Figure 8-7. A large zone of intense scouring is located immediately west of large lobate gravel deposits in the Rural Municipalities of Wolverine and Viscount. The scours are characterized by elongate, water-filled depressions that are located in low areas between adjacent lobes and a very dense surface boulder pavement.

water.

The eastern margin of the zone of gravel lobes is very sharply defined where it is superimposed on a north-south trending tract of almost featureless eroded till plain. A soil survey map of the area shows that the soils associated with the eroded till plain are predominantly Solonetzic (Mitchell et al., 1947). The most prominent feature on the till plain is a series of sub-parallel, shallow, indistinct meltwater channels that trend northeast-southwest. Some of the channels contain permanent and ephemeral streams and lakes that presently drain toward the southeast. The modern Wolverine Lake is the largest lake in the area and is contained within the westernmost channel where the flow of water southwestward is blocked by the superimposition of the lobate gravel deposits. Aerial photographs also reveal the presence of large-scale, slightly arcuate lineations that are concave toward the northeast. Portions of the arcuate lineations are obscured by the subsequent formation of the meltwater streams. These extremely subtle variations in the topography are very difficult to discern on the ground and can be best identified on aerial photographs by the pattern of water-filled depressions. On the ground, small circular depressions that are less than 1 m in diameter and are paved with boulders can be observed.

The gravel lobes are bordered on the south by an east-west trending channel that Greer and Christiansen (1963) referred to as the Plunkett Channel. The channel has indistinct origins approximately 18 km to the west near the eastern limit of glacial Lake Elstow. The head of the channel, however, is separated from glacial Lake Elstow deposits by a topographic high of hummocky terrain that is approximately 10 to 12 m higher than the glacial lake bed and the channel. The mouth of the Plunkett Channel is composed of a series of small channels with highly variable depths that converge to form a more distinct channel that is approximately 4 km wide and 10 to 15 m deep. The floor of the Plunkett Channel is characterized by low relief hummocks and numerous water-filled depressions. Many of the hummocks have rim ridges and are linked in chain-like patterns in some areas. At its eastern limit, the Plunkett Channel abruptly widens and terminates at a position that is coincident with the position of the gravel lobes. The distributary channels are of varying depths though they share a common point of termination. The eastern limit of the channel quickly becomes indiscernible from the adjacent till plain. Near its eastern limit, the northern margin of the channel is indistinct as it grades into the southernmost gravel lobe while the southern margin curves slightly toward the southeast in a series of deeper, narrower channels that are defined by prominent erosional remnants. As with the gravel lobes, the sediments associated with the channel are superimposed on the eroded till plain to the east, obscuring the previously incised, small meltwater streams. The sediments in the Plunkett Channel are almost entirely till and are everywhere characterized by a dense surface cover of boulders (Fig. 8-8). Only very small and isolated deposits of gravel are located at the margins and mouth of the channel.

The Plunkett Channel is separated from the trough in the hummocky terrain to the north by a small, though discrete area of hummocky terrain that exhibits little orientation in either its overall extent or in the pattern of hummocks and depressions. The flow that created the lobes and that which created the Plunkett Channel merged to define the eastern limit of the non-oriented hummocky terrain. The western margin is defined by a rise from the lower relief and more widely spaced hummocky area associated with the eastern margin of glacial Lake Elstow.

Sedimentology

Sedimentological information was gathered by logging available exposures located in active gravel pits and by collecting samples were appropriate. Comprehensive maps and grain size data produced by the Saskatchewan Department of Highways and Transportation were used to provide information from sites that are not presently accessible. The locations of exposures and other sediment information are shown in Figure 8-9. Other than the active gravel pits in the study area, there are very few exposures of sediments and limited road access, particularly in the zones of high relief hummocky terrain and portions of the Plunkett Channel.

Figure 8-8. The floor of the Plunkett Channel is characterized by elongate erosional remnants have a dense covering of large, angular boulders.

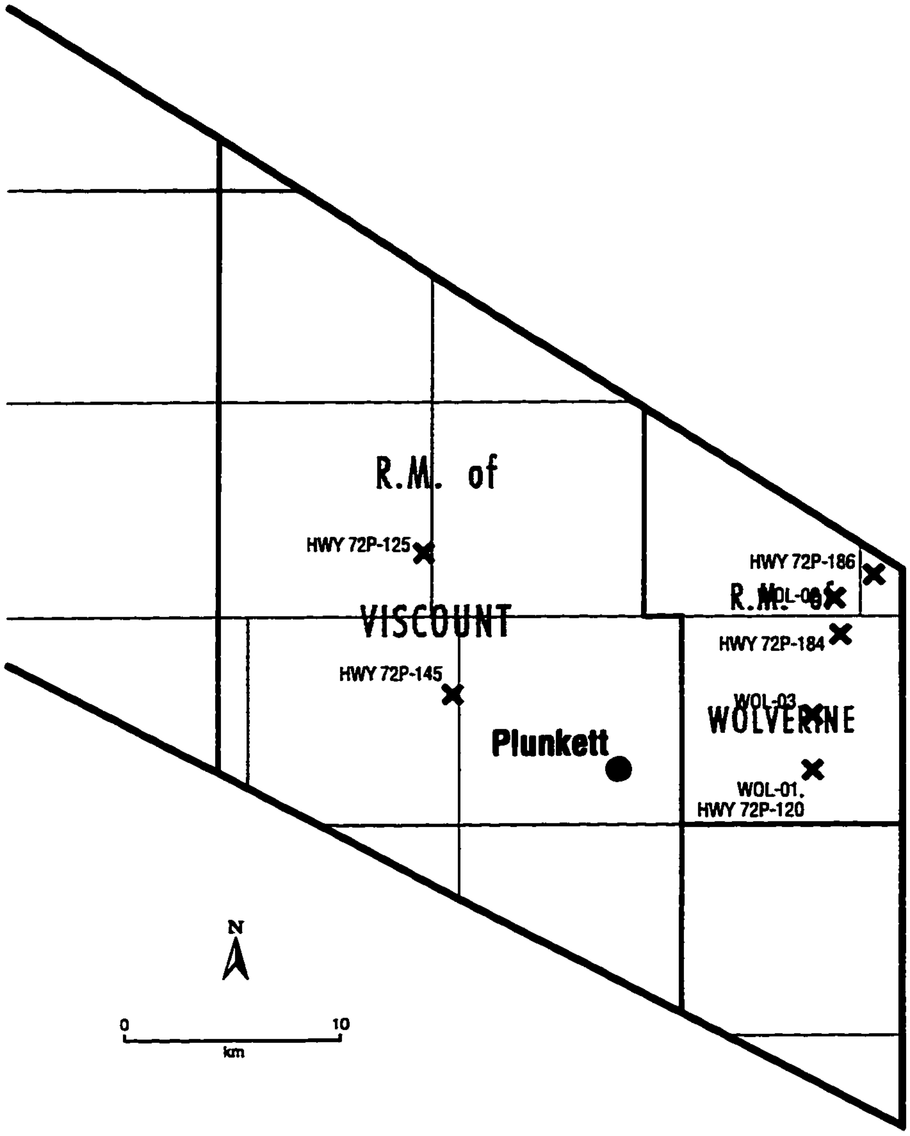

Figure 8-9. Exposure sites in Rural Municipalities of Wolverine and Viscount

Exposure WOL-01

Exposure WOL-01 (SW15-34-24-W2) is located in an active portion of a very large gravel pit near the southern margin of the lobate gravel deposits (Fig. 8-9). The exposure consists of 3 m of multimodal gravel overlying till. The clasts are mainly granule and pebble size with smaller amounts of cobbles. There is a very low proportion of sand and smaller grain sizes and no sediments larger than cobbles. The deposit is poorly sorted and composed of angular to subangular clasts of predominantly carbonate and crystalline lithologies. With the exception of a slightly coarser upper unit that varies in thickness to a maximum of 0.5 m, the deposit shows very little variation in grain size from the surface to the base. Subtly defined, large-scale cross-bedding (Fig. 8-10) indicates a palaeoflow direction from west to east.

Site HWY72P-120

Site HWY72P-120 (S15-34-24-W2) is a large Saskatchewan Department of Highways and Transportation gravel pit that covers an area of nearly 3.5 km^2, though most of it is presently inactive. The gravel pit is located 0.5 km west of exposure WOL-01 (Fig. 8-9). Grain size data derived from test holes throughout the pit indicate that the deposit is composed of very uniform gravel that shows little variation either areally or with depth and that the observations made from exposure WOL-01 are generally representative of the area. Most of the deposit is composed of multimodal gravel that is dominated by granule to cobble sized clasts with very little sand and finer material or material larger than cobbles. Sand, where it does occur in significant amounts, is restricted to scattered pockets along the margins of the lobate forms. The only areas that contain boulder sized clasts are those that are composed of till to the surface with no overlying stratified sediments. These areas of till are located near the proximal end of the lobes and are associated with northwest-southeast trending grooves that extend into the area of the lobes. Variations in the thickness of the gravel correspond to the morphology of the lobate forms. The thickest units of gravel are at least 4 m and occur near the eastern margin of the lobes. The gravel occurs as a thin surface covering between the lobes and

Figure 8-10. The sediments in the gravel lobes are multimodal gravels that range in depth from 2 to 4 m and are generally very uniform throughout the entire area. Palaeoflow was from west to east (right to left in the photograph).

near their proximal ends in the west.

Site HWY72P-184

Site HWY72P-184 (NE35-34-24-W2) is a rehabilitated Saskatchewan Department of Highways and Transportation gravel pit located near the northern margin of the gravel lobes (Fig. 8-9). While no exposures are available, test hole data indicate that the sediments are very similar to those to the south. Up to 4 m of very uniform, multimodal gravel rests on till. The thickness of the gravel varies from 0.4 m to 4 m with a general thickening of the deposit from west to east. Pockets of finer deposits that are composed primarily of sand are restricted to the eastern distal portion of the lobe. Test holes located within a groove that separates the gravel pit from the lobe to the south are composed of till with no overlying stratified material.

Exposure WOL-02

Exposure WOL-02 (SE1-35-24-W2) is located 0.5 km north of site HWY72P-184 (Fig. 8-9) in a small gravel pit at the northern edge of the gravel lobes. Again, poorly sorted, multimodal gravel dominated by granule to cobble sized clasts rests on till. The lobe in this area has a west-east extent of less than 0.5 km. At the margins of the lobe the surface materials are composed of till. The morphology of the lobe is characterized by boulder covered west-east trending ridges and swales.

Exposure WOL-03

Exposure WOL-03 (NE23-34-24-W2) is located on the flat surface of a large lobe approximately midway between the northern and southern limits of the lobes (Fig. 8-9). The lobate forms in this area are large and very clearly defined. The lobes have steep eastern margins that drop steeply 10 to 20 m to the eroded till plain to the east. The gravel deposits are similar to other areas. They are poorly sorted, multimodal sediments dominated by granule to cobble sized clasts that overlie till. The western edge of deposit is defined by large, deep scours that are paved with boulders (Fig. 8-7). To the north and south, the lobe is separated from adjacent lobes by narrow grooves that are composed of till.

Site HWY72P-186

Site HWY72P-186 (SW7-35-23-W2) is an inactive Saskatchewan Department of Highways and Transportation gravel pit located at the northern margin of the gravel lobes (Fig. 8-9) in the area that grades northward into the hummocky terrain. The depth of the gravel is comparable to other areas containing lobes. There is, however, a greater proportion of finer material including sand and silt and fewer cobble sized and larger clasts.

Site HWY72P-125

Site HWY72P-125 (NE1-35-26-W2) is an inactive Saskatchewan Department of Highways and Transportation gravel pit situated in the area of high-relief, non-oriented hummocky terrain west of the gravel lobes (Fig. 8-9). The deposit is predominantly 3 to 4 m of fine to medium sized gravel overlying till.

Site HWY72P-145

Site HWY72P-145 (SW30-34-25-W2) is an inactive Saskatchewan Department of Highways and Transportation sand pit located in an area of hummocky terrain near the head of the Plunkett Channel (Fig. 8-9). Linear and linearly aligned features in the hummocky terrain are parallel to the direction of flow that created the Plunkett Channel. The material in the deposit is very uniform in grain size and consists primarily of sand, though silt is located at the base at some test holes. The sand ranges in depth from 0.6 to 4.0 m. Where the base of the sand and silt was reached, it was found to overlie till.

Discussion

The lobate gravel deposits and the associated rudimentary anabranching channel system in the southeast portion of the study area are interpreted to be late-glacial features. While they are likely associated with deglaciation and an ice marginal environment, it is unlikely that they are associated with the large-scale, integrated system of proglacial lake and spillway development that characterizes the Interior Plains (Kehew and Teller, 1994). The gravel deposits do not have the characteristics of typical glaciofluvial facies that might be expected in a deglacial environment. Commonly occurring subaqueous fans that develop as meltwater streams flowed into ice-marginal lakes are typically characterized by well-developed bottomset, foreset, and topset deposits (Reineck and Singh, 1986). Meltwater streams carry abundant bedload and suspended load that is rapidly deposited with their entry into proglacial lakes. Bottom sets are generally horizontally bedded sand and silt that grade laterally and upward into foresets composed mainly of ripple-bedded units. These are overlain by fluvial topsets of coarse-grained pebbly sand with well-developed, large-scale cross-bedding and horizontal bedding. From the proximal to the distal end of the delta there is a gradual transition from coarse-grained glaciofluvial sediments to fine-grained glaciolacustrine sediments. Glaciofluvial subaqueous fan deposits generally exhibit lakeward progradation and a pattern of migration that involves the overlapping of sediment lobes. The resultant feature is typically a narrow fan-shaped ridge (Reineck and Singh, 1986).

Nor do the lobate gravel deposits have the characteristics of subaerial deposition in an outwash plain or sandur deposit. These types of deposits begin where glacial meltwater streams form braided outwash plains and fans (Reineck and Singh, 1986). As a stream fans out from a point source most of its coarse load is deposited in a low-slope flood fan. Where multiple meltwater streams form, individual fans may coalesce to produce a broad, gently sloping plain that is incised by streams. The outwash plains are composed of stratified glacial sediments transported and deposited in bars and channels by fluvial action. As with subaqueous fans, there is a marked, though not necessarily uniform, decrease in grain size and an increase in pebble roundness in a downflow direction away from glacial deposits. The outwash deposits are typically characterized by poor to moderate sorting, rapid alternation of beds that vary in degree of sorting, abundant scour and fill structures, and multimodal grain size distributions. With glacier retreat, outwash plains are deposited successively over glacial deposits (Reineck and Singh, 1986).

Ice contact features composed of stratified sediment, such as kames, also commonly occur in the Interior Plains. Kames are mound-like features that occur in isolation or in groups that are deposited near the ice margin under the influence of flowing water . The steep-faced mounds of stratified material are left on the landscape as the ice recedes. Typically the sedimentary structure of the kame deposits conform to the outer shape of the mound in a concentric peel pattern with abundant penecontemporaneous deformation structures (Reineck and Singh, 1986).

In contrast to these commonly occurring types of features, the lobate gravel deposits in the Wolverine and Viscount area are notable for the marked uniformity in grain size diameter and distribution with little lateral or longitudinal variation. Nor do the gravels lobes have the distinctive elements of subaqueous or subaerial fans or ice-contact features in either internal structure or external morphology. The sediments in the lobes are weakly stratified, multimodal gravels that are primarily granule to cobble size with a small fraction of finer than sand-sized particles. The multimodal grain size distribution and lack of obvious bedding represents an environment of continuous deposition of bedload and suspended load with a continuum of sizes (Shaw and Gorrell, 1991). The deposit represents a high energy facies with a powerful, unidirectional flow that rapidly deposited the gravel lobes during a single, short-lived event. There is no obvious evidence of a point source for the meltwater that would be expected in the case of a subaqueous fan or an outwash plains or of divergent and overlapping flows. The lobes in this case were simultaneously formed, in contrast to the multiple lobes of fans that form in response to changing flow conditions. In addition, there are no deformation structures in the sediments indicating that the subsequent glacial action evident in most ice contact features did not occur. The very sharply defined lobate forms at the eastern margin of the deposit indicate a very abrupt cessation of the formative flow. Deposition may have occurred in a subaqueous or subaerial environment. The preservation of the steep-fronted lobate form and the lack of evidence of reworking by fluvial or lacustrine processes subsequent to the deposition of the lobes suggests that deposition in a subaerial environment is more likely.

There is no geomorphic evidence that the deposition of the gravel was related to strongly channelized flow.

Further evidence for a high energy, turbulent, non-channelized flow of water as the formative mechanism of the gravel lobes is in the boulder paved depressions immediately upflow. The orientation of the longitudinal depressions between the individual lobes indicates a flow direction approximately from west to east in accordance with the palaeoflow that deposited the gravel. Fluvial erosion is the only process that could have formed the boulder lag. Furthermore, the size of the boulders indicates that the flow must have been very vigorous. The depressions are scour zones that are, at least in part, the source area for the material in the gravel lobes. The relationship of the gravel lobes and the scour zone to the position of surrounding hummocky terrain composed of glacial deposits suggests that the source material was diamicton. The density of the surface boulder pavement indicates that large amounts of material were eroded and removed from the area. Only granule to cobble sized material was immediately deposited. The scour zone is very shallow with poorly defined northern and southern margins. The meltwater flow that scoured the terrain and deposited the gravel was not channelized, but instead was a sheet flow that was at least as wide as the 10 km north-south extent of the scoured area.

The area of gravel deposition is very sharply defined indicating an abrupt change in flow conditions that caused a sudden decrease in the competence of the flow to carry its sediment load. Such conditions could arise from the sudden release of constrained water and subsequent flow expansion. There is no geomorphological evidence to suggest that meltwater was released by the breaching of morainal deposits. Furthermore, the separation of the area of scouring from proglacial lake deposits to the west by a topographic high of hummocky terrain eliminates the catastrophic drainage from a proglacial lake as the source of the flow. Alternatively, the required conditions of flow could have been produced by the release of a reservoir of meltwater from under the ice sheet. Such a flow moving toward the ice margin, under conditions of high pressure and high velocity, would be expected to be highly erosive. Upon reaching the ice margin, the meltwater would continue unrestrained in a jökulhlaup-type of flow. Sharpe and Cowan (1990) described comparable conditions in their interpretation of stratified end moraines in northwestern Ontario where widespread outbursts of subglacial meltwater are hypothesized to have flowed into glacial Lake Agassiz, depositing broad and coalescing subaqueous lacustrine fans.

The source of the meltwater flow that deposited the gravel lobes in the Wolverine and Viscount is difficult to determine due to the lack of geomorphological evidence. Such evidence would not necessarily exist if the source of the water was subglacial or englacial. The erosive activity of the water, however, would be expected to be in evidence in areas adjacent to the zone of intense scouring and subsequent deposition. The variation in the character of different zones of hummocky terrain upflow of the gravel lobes may also be due to the subglacial meltwater flow. The tract of hummocky terrain immediately west of the gravel lobes is characterized by a dense, poorly integrated network of small-scale, rudimentary channels and a larger groove and ridge morphology at its northern margin. The overall orientation of the channels and the groove is generally from west to east. More significantly the tract truncates a zone of higher elevation and higher relief hummocky terrain to the north that has prominent north-south trending lineations. The truncation of the northern zone of hummocky terrain suggests that the landscape was produced by erosional processes. The development of the rudimentary channels and the relationship between the hummocky terrain and the zone of scouring and gravel deposition suggests that fluvial processes were also responsible for the formation of the hummocky terrain. There are no sedimentological data available from the hummocky terrain in this portion of the study area to confirm that the hummocks are in fact erosional features. Investigations in other regions (Rains et al., 1993; Munro et al., 1996) as well as observations from the North Battleford area, however, also suggest that subglacial fluvial erosion was a possible formative agent of hummocky terrain.

The surface on which the gravel lobes were deposited provides further support for the occurrence of turbulent sheetflows of subglacial meltwater. The gravel lobes are superimposed on a north-south trending tract of eroded till plain. The plain is very flat and almost featureless with the exception of very low relief, slightly arcuate transverse ridges and shallow, circular scours. The scours are preferentially located within swales between subparallel ridges. The ridges are interpreted to be remnants resulting from the erosion of the intervening swales. The dense network of small, shallow, generally circular scours are paved with boulders indicating a very high energy, turbulent formative flow. The absence of surface sorted sediments indicates that the eroded material was completely removed from the area.

The only significant subsequent modification of the till plain was the incision of a series of small-scale, shallow, subparallel meltwater channels that trend northeast to southwest. The meltwater channels cross cut the transverse lineations and therefore formed at some time after the ridges. The meltwater channels contain modern lakes and ephemeral streams that generally do not drain out of the area. The development of the meltwater channels may be associated with deglaciation and a progressively westward retreating ice lobe as interpreted by Edmunds (1962) and Greer and Christiansen (1963). A subglacial flow of meltwater, however, cannot be discounted as a possible origin for the channels. Regardless of the process that incised the meltwater channels, their development occurred prior to the event that scoured the terrain to the west and deposited the gravel lobes. The gravel lobes are superimposed on portions of the meltwater channels, disrupting the southwestward flow of water. Reincision of the channels did not occur subsequent to the deposition of the gravel lobes.

The formation of the Plunkett Channel represents the progressive channelization during the waning flow stage of the initial subglacial sheet flow event. Shoemaker (1992a, 1992b) hypothesized the transition of sheet flows to tunnel channels due to the instability of sheet flows induced by lateral pressure gradients. Sjogren and Rains (1995) describe a network of integrated channels in east-central Alberta that they interpreted to have formed in a subglacial environment under hydrostatic pressure by a single, highly erosive, meltwater flow. The channels are characterized by varying degrees of anabranching and highly variable sizes, shapes, and orientations. Longitudinal grooves, abundant boulder deposits, composite and residual streamlined hills indicate formation by the flow of highly turbulent water. The position of the channels on top of a modern drainage divide, evidence of reverse gradients, and localized glaciotectonic features induced by pressure from overlying ice are used as evidence for a subglacial origin for the channels.

The Plunkett Channel is a short, relatively broad meltwater channel which was formed by the same event that deposited the gravel lobes. The indistinct head of the channel is separated from lacustrine deposits to the west by a topographic high that does not appear to be breached at any point along its length. The flow that eroded the Plunkett Channel, therefore, was likely initiated in a subglacial or englacial environment. In contrast to the head of the channel, the distal portion is deeper and has better defined margins. The floor of the channel in all areas, however, is characterized by densely spaced hummocks and depressions and smaller, poorly defined subchannels that indicate zones of more intense erosion. The Plunkett Channel widens abruptly at its mouth and diverges into a series of more distinct subchannels that are separated by large, streamlined erosional remnants and a narrow zone of gravel deposition. The gravel deposits are superimposed on the northeast to southwest trending meltwater channel that was previously incised into the adjacent till plain. The gravel deposits at the mouth of the channel quickly terminate where they are superimposed on the eroded till plain. These characteristics of the mouth of the Plunkett Channel coincide with comparable aspects of the scoured zone and gravel lobes to the north.

The gravel lobes in the Rural Municipalities of Wolverine and Viscount represent a depositional event that is related to the larger scale erosion of the immediate upflow landscape by a turbulent sheet flow and the erosion of the laterally adjacent Plunkett Channel by a highly turbulent channelized flow. The sediments in the lobes indicate a depositional environment of high velocity and rapid sedimentation. The sources for the gravel were the glacial sediments immediately upflow. The most intense erosion occurred at the western margin of the lobes that resulted in large elongate scours that are paved with boulders. Less intense erosion produced the hummocky terrain at least as far as the higher ground that separates it from the hummocky terrain and lacustrine deposits approximately 25 km to the west. The width of the sheet flow that eroded the landscape was at least as wide as the zone of gravel deposition. The gravel lobes appear to mark the northern extent of the sheet flow as indicated by its relationship to the immediately adjacent tract of older hummocky terrain to the north. The southern limit, however, is more difficult to discern. It may correspond to the Plunkett Channel or the Plunkett Channel may have been incised into a portion of the landscape that was influenced by the sheet flow. South of the Plunkett Channel the effects of the sheet flow may grade imperceptibly into the surrounding hummocky terrain. The Plunkett Channel represents channelized flow that would be expected to occur during the waning flow of the sheet flood.

The geomorphological relationships between its various elements indicate the likely sequence of events that shaped the landscape. The fluvial erosion of the till plain upon which the gravel lobes and mouth of the Plunkett Channel are superimposed occurred when ice covered the region. Subsequent to the creation of the eroded till plain, very little further geomorphic activity shaped the landscape until the deposition of the gravel lobes. The northeast to southwest trending meltwater channels are very shallow and narrow and were likely formed as meltwater drained along a retreating ice margin or at some time under the ice prior to the deposition of the lobes. The lobate form of the gravel deposits indicates a very abrupt change in the flow conditions that eroded the hummocky terrain and the scours. They likely represent conditions of sudden flow expansion and a consequent reduction in the capacity for the flow to transport its sediment load. Such conditions might be expected to develop as water driven under hydrostatic pressure in a subglacial environment issued from the ice front into a subaerial or subaqueous environment. Given this interpretation, the position of the ice front would, therefore, correspond to the position of the zone of intense scouring and the proximal end of the gravel lobes. Similarly, the flow through the Plunkett Channel was highly erosive through the portion that was incised in a subglacial environment. Erosional remnants, differential scouring and a dense boulder lag throughout the channel with minimal deposition were caused by a highly turbulent flow. As the channelized flow reached the ice margin, abrupt flow expansion caused a reduction in velocity and the deposition of the coarsest fraction of the sediment load. The finer material was transported away from the area by the meltwater flow event.

Conclusion

The lobate gravel deposits, the associated scour zones, and the Plunkett Channel in the southeast portion of the study area were formed by a highly turbulent, subglacial sheet flow of meltwater that issued from the margin of a receding glacier. Though a much smaller scale event than the sheet flow that formed the North Battleford fluting field, these features indicate that highly turbulent, subglacial, fluvial processes were a powerful and recurring geomorphic agent on the prairies. Significant subglacial sheet flows occurred at different times, at different scales, and with different effects on the landscape. The formative flow of the North Battleford fluting field and its associated features was a regional-scale event with effects on the landscape that were almost entirely erosive. The formative flow that produced the landscape features in the Rural Municipalities of Wolverine and Viscount was also highly erosive but with a more localized effect that also resulted in significant deposition of sediments as well. The common feature of both areas is that the formative agent was the catastrophic drainage of subglacial meltwater in short-lived sheet flows.

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Appendix A. Grain Size Analysis Results

Weight (grams) per sample										
	NB-SO1	NB-SO2	NB-SO3	NB-SO4	NB-SO5	NB-SO6	NB-SO7	NB-SO8	NB-SO9	NB-S10
-8ϕ/25.0mm	726.80	-	175.90	479.40	386.13	-	-	-	462.37	-
-6ϕ/6.1mm	1084.50	-	589.50	1778.00	1303.50	-	-	-	1010.60	29.03
-2ϕ/4.0mm	264.28	2.44	129.25	498.44	458.12	-	-	-	229.53	57.97
-1.5ϕ/2.8mm	204.89	2.01	192.23	437.85	560.43	-	-	-	207.08	20.46
-1.0ϕ/2.0mm	221.93	3.47	233.35	459.70	651.42	0	0	0	177.76	25.69
-0.5ϕ/1.4mm	306.03	5.89	331.80	514.56	785.58	0	0.11	0.10	201.73	41.90
0.0ϕ/1.0mm	458.59	13.76	423.66	478.85	612.34	0.22	0.33	0.52	280.25	61.68
0.5ϕ/0.710mm	643.22	39.03	739.37	421.19	310.08	0.92	0.80	0.97	555.16	143.14
1.0ϕ/0.5mm	581.51	57.36	1163.99	281.95	129.96	2.14	1.94	1.79	861.02	424.06
1.5ϕ/0.355mm	218.41	35.16	575.88	103.54	36.75	2.64	3.34	2.84	530.73	798.39
2.0ϕ/0.25mm	72.70	34.42	213.82	34.73	12.72	46.80	12.68	19.23	228.26	809.57
2.5ϕ/0.18mm	39.22	57.82	104.23	15.47	8.28	173.35	118.35	161.86	119.36	1281.93
3.0ϕ/0.125mm	31.46	32.60	51.01	8.66	6.42	45.68	109.48	73.00	58.98	608.55
3.5ϕ/0.09mm	41.64	8.76	21.59	5.30	5.25	9.99	25.73	19.89	29.78	139.70
4.0ϕ/0.063mm	57.17	3.53	15.12	4.87	7.23	5.98	11.24	9.97	24.78	48.76
>4.0ϕ/0.063mm	65.34	2.55	15.40	4.54	12.72	4.33	5.50	8.57	33.50	25.96
TOTAL	5017.69	298.80	4976.10	5527.05	5286.93	292.05	289.50	298.74	5010.89	4536.7
Start Weight	4988.20	299.51	4998.70	5519.50	5248.20	292.46	290.09	299.45	5039.50	4530.50

	Weight (grams) per sample									
	NB-S11	NB-S12	NB-S13	NB-S14	NB-S15	NB-S16	NB-S17	NB-S18	NB-S19	NB-S20
-8ϕ/25,0mm	186,34	-	548,20	-	-	-	143,71	172,96	660,80	1021,60
-6ϕ/6,1mm	756,70	-	840,40	235,17	-	3,25	917,80	398,82	1566,70	2401,40
-2ϕ/4,0mm	388,86	-	262,19	301,23	1,38	4,27	204,83	219,60	474,05	327,54
-1,5ϕ/2,8mm	318,75	0,62	402,31	198,59	1,42	4,99	246,71	136,30	476,20	295,59
-1,0ϕ/2,0mm	359,35	0,81	461,41	239,00	1,84	7,08	203,12	137,52	340,02	257,62
-0,5ϕ/1,4mm	411,54	0,75	508,29	329,14	2,71	11,01	240,30	141,31	235,80	243,71
0,0ϕ/1,0mm	463,85	1,05	480,21	475,97	3,51	18,68	297,89	161,09	159,54	199,01
0,5ϕ/0,710mm	498,61	2,53	424,57	609,29	6,21	33,31	416,59	241,83	125,67	148,34
1,0ϕ/0,5mm	496,04	9,45	340,84	673,98	11,19	50,60	595,12	395,84	97,71	109,52
1,5ϕ/0,355mm	299,23	24,76	228,81	516,68	18,29	53,18	640,40	482,31	62,35	46,41
2,0ϕ/0,25mm	175,22	47,63	156,54	298,46	29,61	50,82	462,14	525,18	48,37	31,22
2,5ϕ/0,18mm	100,96	80,36	89,02	230,13	78,24	42,89	292,26	610,56	50,88	36,51
3,0ϕ/0,125mm	48,53	56,95	35,00	468,35	87,74	17,01	135,72	391,07	48,07	33,83
3,5ϕ/0,09mm	26,70	25,89	12,21	97,84	37,99	4,90	54,05	142,04	30,91	19,74
4,0ϕ/0,063mm	25,12	20,06	9,72	67,02	18,86	2,65	40,44	77,55	29,43	19,25
>4,0ϕ/0,063mm	49,99	13,71	11,02	52,63	13,16	2,86	55,36	71,81	48,74	31,10
TOTAL	4605,79	284,57	4810,74	4493,48	312,15	307,50	4946,44	4301,79	4455,24	5222,39
Start Weight	4623,10	284,74	4841,70	4530,50	311,28	307,77	4979,70	4325,50	4425,60	5231,10

	Statistical Parameters									
	NB-SO1	NB-SO2	NB-SO3	NB-SO4	NB-SO5	NB-SO6	NB-SO7	NB-SO8	NB-SO9	NB-S10
Mean Size (M_Z)	-2,7	1,4	-1,2	-3,1	-3,0	2,3	2,6	2,5	-2,1	1,8
Standard Deviation (σ_I)	-2,7	1,1	-1,8	-3,0	-3,0	1,9	2,1	2,1	-2,4	1,3
Skewness (S_K)	-2,7	-0,05	-3,9	-0,4	-0,05	0,1	0,1	0,3	-0,7	0,1
Kurtosis (K_G)	0,6	0,8	1,9	0,6	-0,6	1,5	1,5	1,5	0,6	1,1

	Statistical Parameters									
	NB-S11	NB-S12	NB-S13	NB-S14	NB-S15	NB-S16	NB-S17	NB-S18	NB-S19	NB-S20
Mean Size (M_Z)	-2,0	2,4	2,7	0,2	2,4	1,1	-1,5	-0,1	-4,8	-5,2
Standard Deviation (σ_I)	-2,2	1,9	-2,7	-0,4	1,9	0,8	-1,9	-1,1	-3,1	-3,4
Skewness (S_K)	-0,5	0,1	-0,5	-0,1	-0,2	1,6	-0,6	-0,6	0,5	0,6
Kurtosis (K_G)	4,5	1,2	0,6	1,8	1,6	0,8	1,3	1,4	0,7	0,6

NB-S01	Exposure NB-01 at the proximal end of the fluting field
NB-S02	Exposure NB-06 9 km downflow from the proximal end of the fluting field
NB-S03	Exposure NB-06 9 km downflow from the proximal end of the fluting field
NB-S04	Exposure NB-15 at the terminus of the southern channel of the Thickwood Hills
NB-S05	Exposure NB-15 at the terminus of the southern channel of the Thickwood Hills
NB-S06	Exposure NB-09 in streamlined hummock in the Thickwood Hills
NB-S07	Exposure NB-09 in streamlined hummock in the Thickwood Hills
NB-S08	Exposure NB-09 in streamlined hummock in the Thickwood Hills
NB-S09	Surface gravel deposit in the northern channel of the Thickwood Hills
NB-S10	Channel deposit in the Thickwood Hills
NB-S11	Surface sand and gravel in southern channel of Thickwood Hills
NB-S12	Sand in hummock at margin of northern channel of Thickwood Hills
NB-S13	Gravel in hummock at margin of northern channel of Thickwood Hills
NB-S14	Exposure NB-12 in hummock on interfluve in Thickwood Hills
NB-S15	Exposure NB-12 in hummock on interfluve in Thickwood Hills
NB-S16	Exposure NB-13 at the terminus of the northern channel of the Thickwood Hills
NB-S17	Exposure NB-13 at the terminus of the northern channel of the Thickwood Hills
NB-S18	Exposure NB-14 at the terminus of the northern channel of the Thickwood Hills
NB-S19	Exposure WOL-01 in the R.M. of Wolverine and Viscount gravel lobes
NB-S20	Gravel from the northern margin of the Plunkett Channel

Most of the samples collected are from sediments that were deposited prior to or subsequent to the formation of the landforms with which they are associated. Generally, the deposits are not genetically related to the morphology of the present, predominantly erosional, landscape. The grain size data, therefore, primarily provides descriptive information. A detailed interpretation of the origin of the sediments is not directly relevant to the determination of the origin of the landforms and, consequently, is not included within the objectives of this research.