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Geomorphology and sedimentology of hummocky terrain, south-central Alberta, Canada

by

Mandy J. Munro-Stasiuk ©

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

Department of Earth and Atmospheric Sciences

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ABSTRACT

The landscape in south-central Alberta, Canada, is dominated by a suite of landforms that formed beneath the Laurentide Ice Sheet. This thesis explores the origins of those landforms, specifically hummocky terrain. Sediments in the hummocks, hummock form, and associations with other landforms are examined to determine hummock genesis. Sediment was examined from over one hundred exposures through the "Buffalo Lake Moraine" at Travers Reservoir, McGregor Reservoir, and the Little Bow River. This belt of hummocky terrain (like most hummocky terrain regions) is traditionally interpreted as forming at, or near, the stagnating margins of the Laurentide Ice Sheet by supraglacial letdown. However, hummocks in south-central Alberta contain a complex variety of sediments and materials atypical of supraglacial letdown: *in situ* bedrock, thrust bedrock, lodgement till, melt-out till, sorted sand and gravel, rippled sand, rhythmically-bedded sand, silt, and clay, and pervasively sheared beds. All sediment types and deformation structures were deposited, or formed, subglacially. Also, the deposits make up *in situ* stratigraphies that record the history of initial Laurentide Ice Sheet advance into the area (lodgment till and thrust bedrock), the extensive accumulation of water at the bed (glaciolacustrine beds), and ice stagnation (melt-out till).

Regardless of the genesis of sediments in hummocks, sedimentary units and structures are abruptly truncated by the surface that represents the hummock and trough morphology, demonstrating that the hummocks are erosional forms and that they represent a landscape unconformity. Subglacial sediments predating the erosion and subglacial eskers overlying the erosion surface strongly suggest that hummock erosion was subglacial. Also, hummock morphology, lithostratigraphy correlated from hummock to hummock, abrupt truncation at the land surface, and widespread boulder lags support meltwater erosion for hummocky terrain in the region. Well-developed longitudinal and transverse trends in hummocks suggest that these landforms are giant erosional bedforms. Palaeoflows determined from surface trends are approximately from the northwest to the southeast. These are transverse to the flow directions preserved in the youngest unit in the hummocks, a basal melt-out till, further supporting an erosional origin for the hummocks. Hummocks are transitional from fluted terrain and surface trends are the same for both landform types. Fluted terrain is also erosional as remnant ridges are composed of *in situ* bedrock and fluvial gravels deposited by rivers flowing from the Rocky Mountains before Laurentide Ice Sheet invasion of southern Alberta. Consistent trends in hummocky terrain and fluted terrain suggest that the meltwater flow responsible for eroding flutes and hummocks was about 120 km wide.

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CHAPTER 1: INTRODUCTION

INTRODUCTION AND PROBLEM TO BE ADDRESSED

Hummocky terrain in previously glaciated regions is composed of hillocks and depressions of variable size and shape. It is extensive in North America (e.g., Clayton and Moran, 1974; Shetsen, 1987; 1990; Klassen, 1989), Scandinavia (e.g., Hoppe, 1952; Aario, 1977; Lagerbäck, 1988), and elsewhere in Europe (e.g., Benn, 1995; Boulton and Caban, 1995). Hummocky terrain patterns can be entirely chaotic (e.g., Gravenor, 1955), though distinct longitudinal and transverse patterns are commonly present (e.g., Aario, 1977). These types are referred to in the literature as "uncontrolled" and controlled" respectively (e.g., Gravenor and Kupsch, 1959; Rains and Shaw, 1981). Regardless of pattern, hummocky terrain tracts are characterized by hummocks of similar size and shape in any one area (Rains et al., 1993).

Among the hypotheses of hummocky terrain formation, the traditional and most popular view is that it represents the final stages of ice-stagnation. Supraglacial sediments are thought to be slowly lowered by ablation in ice-marginal zones, resulting in a topography dominated by hillocks and depressions (e.g., Gravenor, 1955; Gravenor and Kupsch, 1959; Clayton and Moran, 1974). Consequently, extensive hummocky zones on the Canadian prairies have been mapped as recessional positions of the Laurentide ice sheet (e.g., Stalker, 1977; Christiansen, 1979; Clayton and Moran, 1982; Clayton et al., 1985; Dyke and Prest, 1987; Klassen, 1989; Stalker and Vincent, 1993), and they are commonly referred to as *hummocky moraine*, *ice-stagnation moraine*, and *disintegration moraine*. However, observations on exposures at McGregor and Travers Reservoirs, south-central Alberta (Fig. 1.1) indicate that erosion, rather than deposition, was the main mechanism of formation. Since hummocky terrain may not represent depositional moraines, I use the non-genetic term ***hummocky terrain*** throughout this thesis. The main aim of this thesis is to develop a model of hummocky terrain genesis that accounts for both the hummock form and the sediments within the hummocks.

IMPORTANCE OF STUDY

The study area, north of Lethbridge, south-central Alberta (Fig. 1.1), contains to the best of my knowledge, the most extensive exposures in hummocky terrain in the world. At best, exposures in most other areas are usually restricted to minor road and river cuts. The damming of the Little Bow River and McGregor Lake in the 1960s raised lake levels up to 40 m, resulting in extensive

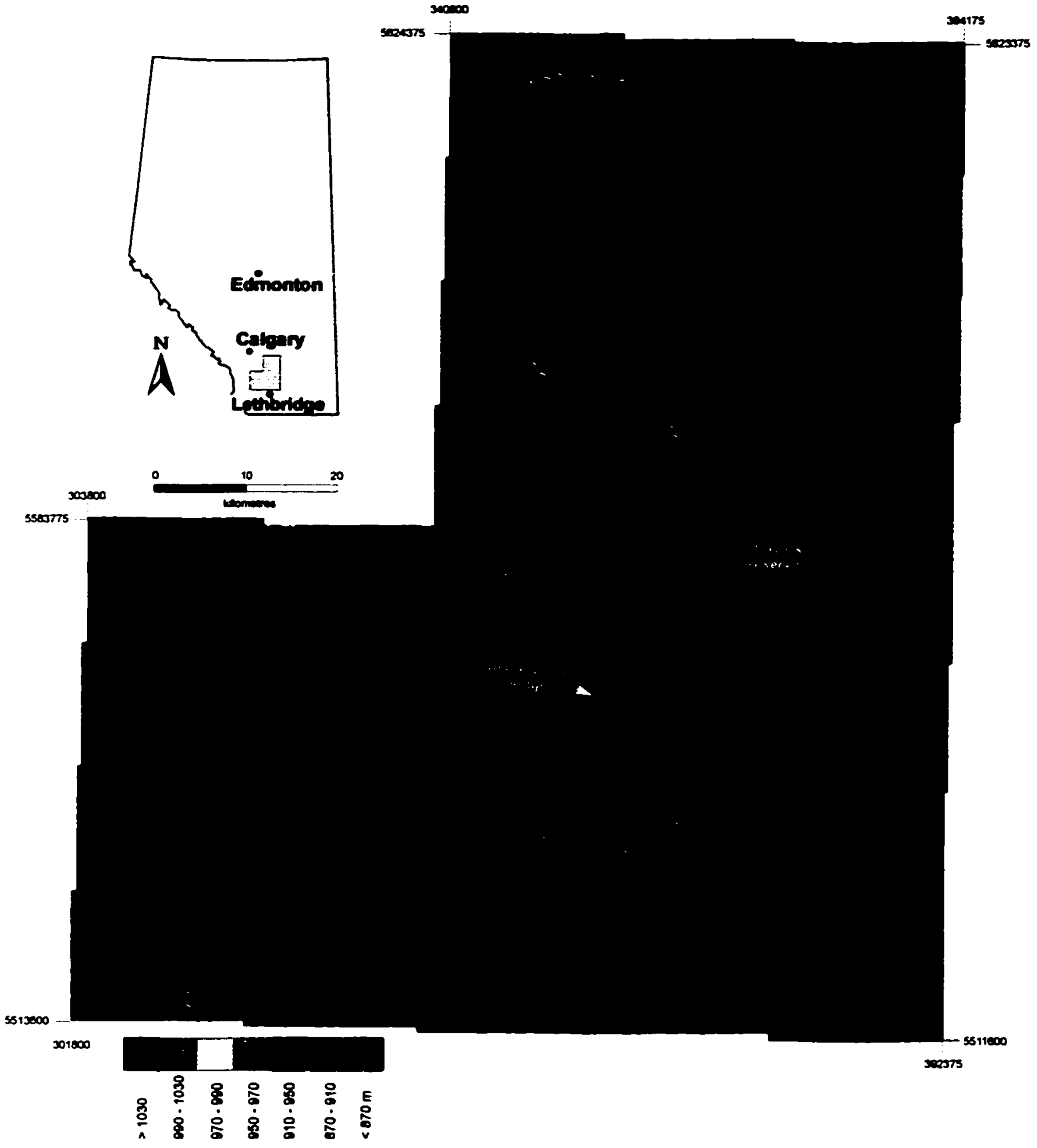

Figure 1.1: Classed Digital Elevation Model (DEM) of the study area in south-central Alberta, Canada. Location of study area is shown on inset map.

renewed shoreline erosion. The result is over 100 exposures between 2 and 25 m high in hummocks along the shores of McGregor and Travers reservoirs. In addition, other exposures up to 60 m high are also present in non-hummocky terrain. These exposures offer an exceptional internal view of hummocks and adjacent landforms, an opportunity unavailable elsewhere on this scale. When first viewed, the sedimentary sequences appear chaotic, but it is quickly apparent that the sediments do not support the supraglacial let-down model most readily accepted for this region. That is, these hummocks are not composed of "flow" tills and slumped glacial lake deposits. This observation is important because, if the hummocks are not composed of materials released at the ice surface, then the accepted model of hummocky terrain formation must be seriously challenged. In addition, if these hummocks are not composed of supraglacially released sediments, then belts of hummocky terrain may not be large recessional moraines associated with the melting of the Laurentide Ice Sheet. If these belts are not recessional moraines, then reconstructions of the deglacial pattern of the Laurentide Ice Sheet (e.g., Dyke and Prest, 1987) must be reconsidered.

PRINCIPLES

Four basic geological principles are used consistently throughout this thesis. Each principle is governed by set rules and must be followed in order to reconstruct spatial and temporal events in the correct chronological order. These principles are:

1. Superposition: the principle of superposition states that if one sediment bed overlies another sediment bed, then the upper bed formed after the lower bed, unless disturbance occurred. In the context of this thesis, the disturbance would be due to glaciotectonic action, or mass movement. This may result in the repetition of sequences due to thrusting, overturned beds due to pushing, and disruption of sequences due to slumping.

2. Stratigraphy: the principle of stratigraphy deals with the composition, sequence, spatial distribution, classification, and correlation of stratified units. In this thesis, the concepts of lithostratigraphy are applied: that is, those aspects relating to the physical characteristics of particular units. If the physical characteristics of a particular unit are the same as the physical characteristics at another site then they may be stratigraphically correlated. These characteristics include sedimentary structures, presence or absence of fossils, lithology, grain size, fabric, contacts, and overlying and underlying sediment type.

3. Unconformities, truncation surfaces and erosion: unconformities in sedimentary sequences indicate a time lapse in sedimentation between two units or an interruption in deposition, or when weathering, erosion or denudation occurs between two depositional events. Unconformities are easily observed in sediment where structures and dipping beds are truncated by overlying units. If units are abruptly cut at the ground surface then that surface is a truncation or erosion surface.

4. *Cross-cutting relationships*: cross-cutting relationships are important both stratigraphically, and topographically. First, in sedimentary sequences, if a dike or diapir intrudes or cross-cuts strata, then that feature is younger than the sediments that it cuts through. The intruded sediments may be older than the sediments through which they intrude if they were deposited *stratigraphically* below those sediments (*superposition*). Second, if one particular landform overlies another, then the lower landform is the oldest. For example, if an esker overlies a hummock, then the hummock is older than the esker. If one feature truncates another feature, then the truncated feature is older. For example, if a meltwater channel, cuts through a belt of hummocky terrain, then the hummocky terrain had to pre-date the formation of the channel and hence, the meltwater channel is younger.

THESIS OUTLINE

This thesis is written in paper format, and appears here as six papers (eight chapters):

Chapter 2: Hummocky terrain genesis: a critical review. The first paper in this thesis presents a critical evaluation of existing literature on hummocky terrain genesis. There are many theories of hummocky terrain formation and this provides a fundamental core for all material to be discussed in later papers.

Chapter 3: McGregor and Tee-Pee preglacial valley fills, south-central Alberta: a reconstruction of Late Wisconsinan glacial events. This paper presents a detailed analysis of the preglacial valley fills in the study area. This includes both the hummocky and non-hummocky zones, and discusses the stratigraphic relationships between the two zones. The history of sedimentation and the events that led to sedimentation are discussed.

Chapter 4: Rhythmic till sedimentation: evidence for repeated hydraulic lifting of a stagnant ice mass. This paper (Munro-Stasiuk, in press a) concentrates on the youngest sediment in the hummocks, a subglacial melt-out till. Detailed sedimentology and a sedimentation model are presented. The paper explores the importance of water storage and release during till deposition and discusses conditions at the base of the ice sheet prior to hummock erosion.

Chapter 5: Evidence for water storage and drainage beneath the Laurentide ice sheet, south-central Alberta, Canada. This paper (Munro-Stasiuk, in press b) examines glaciolacustrine sediments deposited in preglacial valleys in the study area. Using stratigraphic, topographic, and spatial relationships, a case is presented that the lake sediments represent subglacial, rather than proglacial sedimentation. Hence, by inference, the sediments represent subglacial water storage.

Chapter 6: Hummocky terrain in south-central Alberta, Canada: an erosional origin. The theme of this paper is to demonstrate the erosional origin of hummocky terrain in the study area. Hummock morphology and pattern are classified, and it is demonstrated that the hummock surfaces represent bedforms. It is also demonstrated that the hummock surfaces are cut into all preexisting materials. Hence there is a strong emphasis placed on the architecture of sedimentary units and their relationship with the landform surfaces.

Chapter 7: Evolution of a subglacial landscape, south-central Alberta. This last paper brings together information provided in the previous papers. It explores the evolution of glacial conditions and subglacial hydrology across the study area and examines those as a series of depositional or erosional events that took place beneath the ice.

Chapter 8 at the end of the thesis summarizes the research and discusses areas of possible future work.

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CHAPTER 2: HUMMOCKY TERRAIN GENESIS : A CRITICAL REVIEW

INTRODUCTION

Hummocky terrain is composed of hillocks and depressions of variable size and shape and occurs in regions that have been previously glaciated. This terrain has been recognized extensively in North America (e.g., Clayton and Moran, 1974; Shetsen, 1987; 1990; Klassen, 1989), Scandinavia (e.g., Hoppe, 1952; Aario, 1977a; Lagerbäck, 1988), Europe (e.g., Benn, 1992; Boulton and Caban, 1995), and Antarctica (e.g., Rains and Shaw, 1981). Although there are numerous theories of hummock formation (Table 2.1), hummocks are traditionally, and most commonly, believed to represent the final stages of ice-stagnation. According to those hypotheses, sediments that accumulated on the surface of a glacier or ice-sheet were slowly lowered as the ice melted near its ice margins, thus forming hillocks and depressions (e.g., Gravenor, 1955; Gravenor and Kupsch, 1959; Clayton and Moran, 1974). Consequently, extensive hummocky zones are recognised and mapped as major recessional positions of ice sheets and glaciers (e.g., Stalker, 1977; Christiansen, 1979; Clayton and Moran, 1982; Clayton et al., 1985; Dyke and Prest, 1987; Klassen, 1989; Stalker and Vincent, 1993). Most workers refer to this type of landscape as *hummocky moraine* which implies genesis by direct deposition from glacial ice. As there are many hypotheses of hummocky topography formation, I choose to use the non-genetic term *hummocky terrain*.

HUMMOCKY TERRAIN CLASSIFICATION

Hummocky terrain generally occurs in tracts up to tens of kilometers wide (Rains et al., 1993; Johnson et al., 1995) and, in any one area, the height and shape of hummocks are similar (Rains et al., 1993; Munro and Shaw, 1997). Hummocks in these tracts can be chaotically distributed with no obvious patterns, but usually distinct longitudinal and transverse trends are present. These two distribution types are referred to as "uncontrolled" and "controlled" respectively (e.g., Gravenor and Kupsch, 1959). Outlined below are the five main mound types that researchers identify (Figs. 2.1 and 2.2). The terminology chosen for each hummock type avoids any genetic connotations inherent in geomorphological nomenclature.

1. Mounds with no discernible orientation or shape patterns (also known as stagnation moraine, disintegration moraine, and uncontrolled moraine). Prior to extensive aerial photograph use, most regions of hummocky terrain were considered to be in this category. This type of hummocky terrain is actually the least common of all hummocky terrain types, as pattern is usually

TABLE 2.1: Summary of the characteristics and origin of hummocky terrain

Author	Location	Terminology/ Morphology	Landform Associations	Sedimentology	Genesis
Let-down theories					
Gravenor, 1955	east-central Alberta	circular mounds with central depressions "prairie mounds"	n/a	clayey till containing contorted lenses of sand, silt and clay	supraglacial let-down by topographic inversion
Gravenor and Kupsch, 1959.	western Canada	moraine plateaux, closed and linear ridges	meltwater channels lead away from moraine plateaux. Moraine commonly superimposed on drumlins and flutings	clayey till covered in some places by a thin cover of lacustrine silts and clays	letting down of ablation till and/or squeezing up of till into openings at the base of the ice
Clayton, 1973	south-central Alaska compared with North Dakota	prairie mounds, circular disintegration ridges	ice-walled outwash plains, ice-walled lake plains	ablation till	glacial karst features, infilling of sink-holes, caves, tunnels, and roofless channels
Marcussen, 1973	Denmark	fields of small hills	n/a although other authors have interpreted the features as drumlins or recessional moraines	stratified and laminated diamicton interpreted as flow till	flow of debris originating on the surface of the ice
Eyles, 1983	*theorietical with examples from Norway, Iceland, and Scotland*	hummocky high relief surfaces	lateral moraines, medial moraines	"surpaglacial" diamict	concentration of debris in marginal zone due to compression and subsequesent letdown by topographic inversion and/or melting of ice blocks
Johansson, 1983	northern Sweden	dead-ice moraine	flutes, isolated ridges, terraces	loose coarse-grained ablation till	deposited on or by dead ice
Paul, 1983	*theoretical with numerous locations including Norway, Britain, Alaska, Minnesota*	hummocky morainic complexes	overlies and obscures fluted lodgement till	interbedded outwash and flow till, subglacial till.	exposure of debris bands at ice surface and subsequent deposition by topographic inversion
Johnson and Mickelson, 1983	northern Wisconsin	hummocky topography	n/a	subglacial melt-out till	melting out of unevenly distributed debris in the base of the ice
Clayton et al., 1985	central north America	prairie landforms, collapse hummocks, hummocky topography	drumlins and eskers	supraglacial flow till	let-down of debris brought to the ice surface by ice-sheet thinning after surging
Möller, 1987	Åsnen, Sweden	isolated and grouped hummocks	n/a	flow till and melt-out till	subglacial, englacial and supraglacial melt-out during ice stagnation

Author	Location	Terminology/ Morphology	Landform Associations	Sedimentology	Genesis
Lagerbäck, 1988	northern Sweden	moraine plateaux surrounded by rim ridges "Veiki Moraine"	drumlinization of moraine plateaux	high content water-laid sediment in plateaux, till	supraglacial letdown
Benn, 1992	Isle of Skye, Scotland	"hummocky moraine", rim-ridges, flat topped hummocks, composite hummocks (chaotic)	commonly associated with recessional moraines and drumlins and fluted moraines	reworked debris flows and glaciofluvial sands and gravels. Dewatering structures and faults common	melting of stagnant or slow moving ice (last stages of deposition)
Attig and Clayton, 1993	northern Wisconsin	hummocky glacial topography, non-oriented	braided stream plains lie adjacent to hummocky zones, drumlins nearby	lodgement and melt-out till, debris flows,	topographic inversion, melting out of thrust debris-rich bands, melting of buried ice
Ham and Attig, 1993	north-central Wisconsin, USA	hummocky glacial topography, rim ridges	ice-walled lake-plains, linear-to arcuate ridges and meltwater channels	hummocks composed of uniform sandy sediment overlying lacustrine sediments; rim ridges composed of sand	letdown of lacustrine sediment
Kemmis et al., 1994	Iowa, USA	hummocks	n/a	n/a	melting of debris-rich ice containing extensive tunnels
Johnson et al., 1995	western Wisconsin, USA	hummocks, hummock tract	ice-walled lake plains	melt-out till, meltwater stream sediment	combination of subglacial and supraglacial melt-out
Andersson, 1998	southwest Sweden	hummocky moraine, low relief terrain	sandar, eskers, kame fields, small deltas	stratified diamictons (sediment flow deposits	hummocky moraine resulted from melt-out of material high in ice, and low relief hummocks from melt-out of basal/near basal debris
Ice-pressing theories					
Hoppe, 1952	northern Sweden	rim ridges, moraine/plains plateaux, Veiki plateaux	glaciofluvial erosion is common	till and glaciofluvial accumulations	subglacial squeezing
Stalker, 1960	central Alberta	rim ridges, moraine/plains plateaux	commonly associated with eskers and drumlins	"basal till" with local pockets of sand and gravel	pressing/squeezing by the weight of the overlying ice of thawed material into holes/crevasses at the base of the ice
Parizek, 1969	Northern Great Plains	ice contact rings and ridges	many meltwater channels	lacustrine silt and clay, "till", fluvial outwash	primarily dead-ice stagnation with some ice-pressing
Aartolahti, 1974	southern Finland	ring ridges, elongate ridges, mounds	ring-ridge fields border glacial meltwater channels	predominance of sand and gravel at surface overlying till	letting down of supraglacial material and subglacial squeezing
Eyles et al., 1999	central and southern Alberta	hummocky moraine, humdrums	associated with fluting and drumlins on lower ground	homogenous basal deformation till	squeezing of deformable sediment by stagnant ice blocks

Author	Location	Terminology/ Morphology	Landform Associations	Sedimentology	Genesis
Thrusting at or near the ice margin					
Bishop, 1957	Baffin Island	shear moraines	n/a	bands of mixed debris	shearing up of debris towards ice surface and melting out leaving upstanding ridges of debris
Weertman, 1961	Baffin Island, and Thule, Greenland	Thule-Baffin moraine	n/a	n/a	Freezing on of debris to basal ice and then thrusting up onto ice surface to be melted out
Souchez, 1967	south Victoria Land, Antarctica	shear moraines	n/a	debris	Shearing up of debris onto the ice surface followed by melting
Rains and Shaw, 1981	south Victoria Land, Antarctica	controlled moraine consisting of hummocks and transverse moraine ridges	n/a	coarse, angular, supraglacially transported debris	transverse thrust blocks subsequently melted out from ablation cusps on the ice surface
Kruger, 1985	south Iceland	push moraine	marginal moraine ridges, fluted ground moraine, hummocky dead-ice moraine, meltwater channels, outwash plain	deformed glaciofluvial sand and fine gravel,	small-scale pro-glacial thrusting and folding of unfrozen glaciofluvial deposits and lodgement till
Kulig, 1985	central Alberta, Canada	"hummocks"	meltwater channels	glaciolacustrine sediments and bedrock-cored	englacial melt-out and glaciotectonism
Bennet and Boulton, 1993	Scotland	hummocky moraine	flutes (down valley radial elements), ice-marginal kames, fed by meltwater channels, kettleholes,	sands, bouldery gravels and diamictons, homogenous diamictons, typically show shear-folding	ice-push marginal moraines overlying flutes to give the hummocky appearance
Hambrey et al., 1997	Svalbard, Sweden and Britain	hummocky moraines	outwash plains	Diamicton, sandy gravel, gravelly sand, muddy gravel, sand, mud, sand-mud lamnites.	mainly thrusting of subglacial material into an englacial or supraglacial position prior to melting out.
Bennett et al., 1998	Svalbard and Scotland	moraine mound complexes hummocky moraine	flutes and outwash plains	sandy to muddy diamictons, gravels and muds glaciotectonically stacked on top of each other	proglacial thrusting and englacial thrusting near the ice margin (material is subsequently let down during melting
Subglacial moulding and/or deposition					
Aario, 1977	Finland	hummocky disintegration moraine, hummocky squeezed-up moraine, hummocky active ice moraine	transitional from fluted, drumlinized and Rogen terrain	"till"	depending on form - subglacial sqeezing, subglacial moulding, and supraglacial letdown

Author	Location	Terminology/ Morphology	Landform Associations	Sedimentology	Genesis
Lundqvist, 1981	Sweden	moraine plateaux with rim ridges - "Veiki Moraine", drumlinized hummocky moraine	commonly associated with drumlins. Hummocky moraine often drumlinized	high content water-laid sediment	supraglacial letdown and subglacial squeezing - likely subglacial formation dominant "like drumlins"
Menzies, 1982	*theoretical*	hummocks	n/a	lodgement till	localized basal freezing, increasing shear strength, causing debris accretion
Sutinen, 1985	northern Finland	hummocky moraine, transversal morainic hummocks, radial morainic hummocks	associated with eskers	basal melt-out till, glaciofluvial sediments, mass-movement sediments	subglacial sedimentation of melt-out till
Subglacial meltwater erosion and/or deposition					
Holden, 1993	central Alberta, Canada	"hummocks", hummock chains	many meltwater channels and some eskers superimposed on the hummocks	glaciofluvial sediments	meltwater erosion and deposition
Rains et al., 1993	Alberta, Canada	hummocky terrain	drumlins and flutings occur in lower lying areas	n/a	primary meltwater erosion followed by deposition and deformation
Munro and Shaw, 1997	south-central Alberta, Canada	hummocky terrain	drumlins and flutings have same orientation, subglacial eskers overlie the hummocks	subglacial till, lacustrine debris flows and rhythmic beds, sorted beds; all units truncated by erosion surface marking the hummock morphology	subglacial meltwater erosion
Sjogren, 1999	east-central Alberta, Canada	hummocky terrain	glaciofluvial channels cross-cut hummocks,	in-situ and displaced bedrock, diamicton, and lacustrine beds	subglacial meltwater erosion
Subsurface diapirism					
Zelcs, 1993	Latvia	hummocks	n/a	n/a	rising diapirs of subglacial debris
Boulton and Caban, 1995	*theoretical with examples from Poland and Saskatchewan, Canada*	extrusion moraine	n/a	n/a	release of glacially generated subsurface overpressure
Vogt, 1997	Norway Basin and Eastern Iceland Plateau	hummock fields	n/a	glacigenic sandy clys	sediment diapirism due to instabiliteis arrising from thick dense sediments overlying less dense muds
Periglacial theories					
Henderson, 1952 (described by Gravenor, 1955), 1959	Alberta, Canada	till mounds	n/a	till overlain by thin bands of silt	ice-wedge polygons

Author	Location	Terminology/ Morphology	Landform Associations	Sedimentology	Genesis
Bik, 1968	prairies North America	prairie mounds	n/a	primarily till and colluvium	pingos
Flemel, 1972	north-central Illinois, USA	Dekalb mounds	adjacent outwash plains and ground moraine	glaciolacustrine deposits,	pingos
Mathews, 1973	northeast B.C., Canada	Elliptical to flat-topped mounds	occur within a lake basin	folded and faulted lake sediments occasionally overlying till	stratigraphic relationships suggest the mounds are the result of postglacial pingo formation

Figure 2.1: This aerial photograph illustrates the transitional nature of the hummocks within individual hummock tracts. Numbers refer to the classification as outlined in the text.

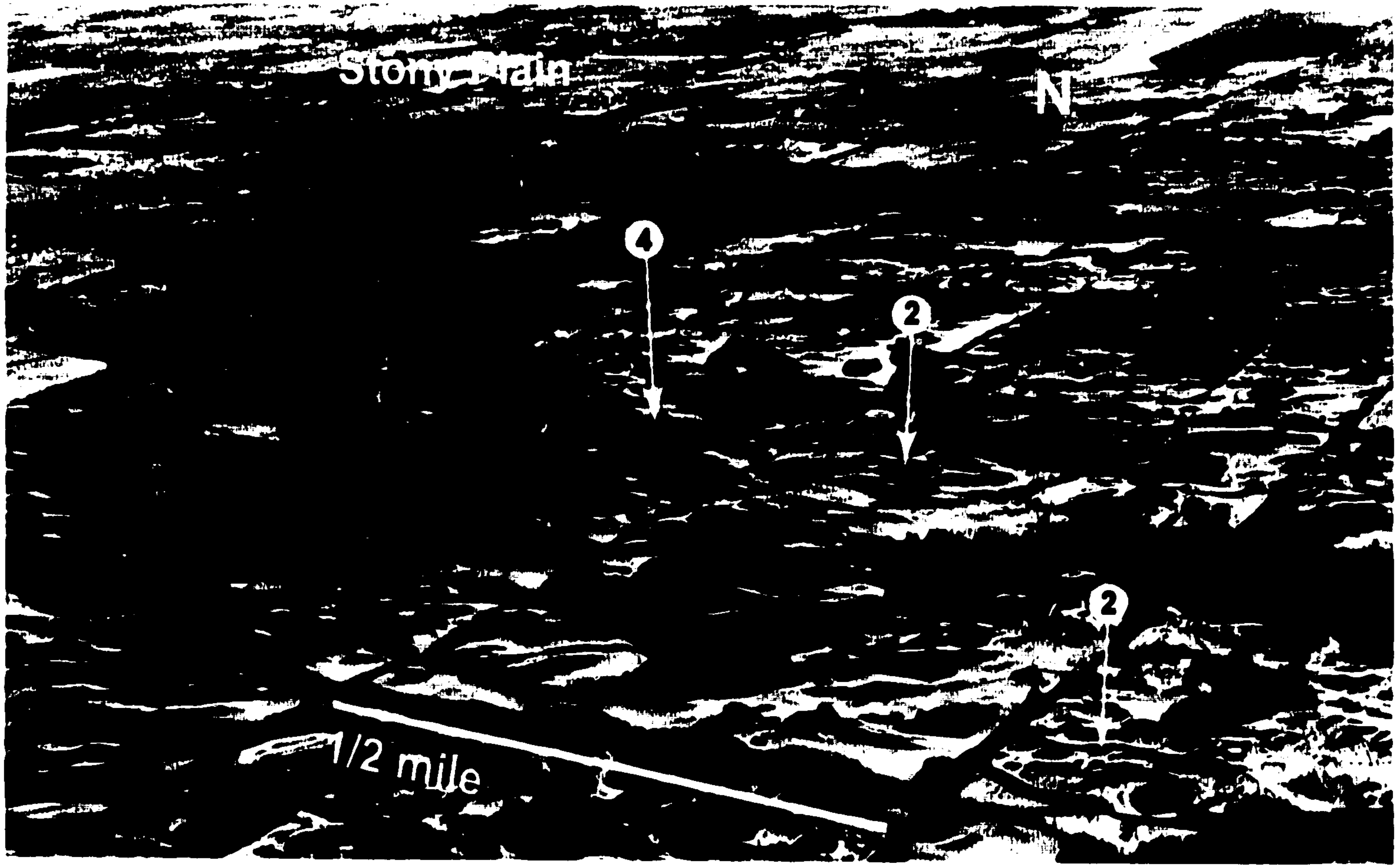

Figure 2.2: Oblique photograph of typical hummocky terrain, near Stony Plain, Edmonton. Numbers refer to hummock types as outlined in the text.

evident in hummock distribution.

2. *Mounds with central depressions* (also known as prairie doughnuts, rim/ring ridges, and uncontrolled moraine). These are circular mounds with shallow depressions in their central areas. Their relief is generally lower than other types of hummocky terrain (< 5 m). Some researchers have compared these to pingos (e.g., Bik, 1968), periglacial rather than glacial phenomena. Often several mounds are linked, giving the appearance of a chain (also known as hummock chains, rim ridge chains, donut chains, and both controlled/uncontrolled moraine).

3. *Ridged mounds* (also known as cross-valley ridges, transverse ridges, transversal morainic hummocks, and controlled moraine). These are common hummock types and they often resemble Rogen moraine. They are commonly thought to have formed transverse to local ice flow directions.

4. *Elongate mounds* (also known as drumlinized hummocky moraine, corrugated moraine, humdrums, and controlled moraine). These usually occur in small groups within hummocky terrain, and there is a distinct elongation in their shape. This elongation is generally thought to have formed parallel to local ice flow directions, like drumlins.

5. *Moraine plateaux* (also known as ice-walled lake plains and Veiki plateaux). Moraine plateaux are present within any type of hummocky terrain. They are higher than surrounding mounds and can range from a few metres to several kilometres across. The surface is generally flat to undulating, and is commonly surrounded by a discontinuous rim.

THEORIES OF HUMMOCKY TERRAIN FORMATION

Existing theories of hummocky terrain formation are not discussed at any great length in the later chapters of this thesis. To provide a framework for the thesis, the main theories are discussed here, and summarized in Table 2.1. Table 2.1 does not contain a comprehensive list of all papers discussing hummocky terrain. Rather, it contains a list of those papers that discuss hummocky terrain genesis. Additional tens, perhaps hundreds, of papers and reports accept the theories outlined here and reconstruct past glacial conditions based on these. The hypotheses are discussed in the following order:

1. Ice-marginal sedimentation
2. Letdown and/or melt-out during ice stagnation
3. Ice-pressing
4. Thrusting at, or near, the ice margin
5. Subglacial moulding and/or deposition

6. Subglacial meltwater erosion and/or deposition
7. Subsurface diapirism
8. Periglacial theories.

Ice-marginal sedimentation

I discuss the ice-marginal hypothesis first as many of the following theories expand upon this. Hummocky terrain in North America was originally considered as morainal deposits in the 1770's when researchers first realized that thick sequences of sediment bordered the sides of glaciers (lateral moraines), looped around the snouts of glaciers (terminal moraines), and was present in the central areas of glaciers (medial moraines) (Charlesworth, 1957). The term "ablation moraine", that is, a moraine that was deposited because of melting ice, was first introduced by Tarr (1909). Tarr observed debris on Alaskan valley glaciers which seemed to be associated with the melting of those glaciers after they had advanced rapidly (surged) and subsequently melted *in situ*. Some researchers noted, however, that not all glaciers were covered in debris. As early as 1914, Tarr and Martin (referring to glaciers in Alaska, the Himalayas, and the Alps) stated that "the clear glacier ice is the normal, and the moraine-covered glacier the exception". They indicated that sediment-covered glaciers were restricted to narrow steep-sided valleys, where debris supply from the steep valley sides was high. The larger glaciers that spread beyond the hilly zones and ice caps were generally devoid of debris. In spite of these early observations, irregular topography ("hummocky moraine") in valley and continental settings came to represent ice margins in regional reconstructions in North America (e.g., Coleman, 1909; Johnson and Wickenden, 1931, Rutherford, 1941; Bretz, 1943; Bayrock, 1955; Dyke and Prest, 1987), Scotland (e.g., Sissons, 1961; 1967), England (e.g.,Yates and Mosely, 1967), and Scandinavia (e.g., Virkalla, 1952). Modern studies do illustrate that debris exists on the surface of some glaciers (e.g., Boulton, 1967; Rains and Shaw, 1981; Lawson, 1982; Paul, 1983; Sharp, 1985), either in the form of sediment deposited directly on the ice surface, or material thrust up onto the top of the ice.

Letdown and/or melt-out during ice stagnation

Supraglacial letdown and/or melt-out during ice-stagnation is the common theory of hummocky terrain formation. Terms such as "ablation moraine", stagnation moraine" and "disintegration moraine" all refer to processes inherent in this hypothesis.

In spite of early observations that many glaciers were not covered by debris, and Hoppe's

(1952) study demonstrating that many hummocks are actually composed of subglacial till (see next section), a supraglacial origin for hummocky terrain was accepted wholeheartedly by the majority of researchers, and it is now considered to be the primary process responsible for many hummocky areas in Scandinavia, Europe, and North America. The theory explaining supraglacial letdown was first discussed in detail by Gravenor (1955) who studied what he termed " prairie mounds" in east-central Alberta, Canada. These mounds were in the "Viking Moraine" named by Warren (1937). In Gravenor's (1955) hypothesis, letdown of debris was based on the following assumptions: glacial ice was stagnating, sediments on the surface of the ice were unevenly distributed, and differential ablation of underlying ice occurred. It is implicit in the hypothesis that this terrain represents the position of (at, or close to) ice-margins during periods of stagnation. Gravenor summarized the process in the following way. If large quantities of debris existed on the surface of an ice mass, then where the debris cover was thickest, surface ice melting would be reduced by insulation of the overlying debris (Fig. 2.3). Where debris cover was thin, melting of the underlying ice would be rapid, creating holes which would then be filled with sediment by supraglacial wash and/or mass movement. Once melting was completed, hummocks would have formed at the site of the last sediment-filled depressions. If ice was still present in the core of the resulting hummock, it would eventually melt and leave a central depression, forming a doughnut-shape (prairie doughnut or rim/ring ridge). He did not provide a detailed sedimentary analysis of the hummocks he discussed, but he did indicate that most mounds were composed of clayey till and also of some slumped, stratified silts and clays. He felt that this fitted with washing and mass movement into depressions in the ice.

Four years later, this hypothesis was modified by Gravenor and Kupsch (1959) to include features which they believed inherited characteristics from ice flow (controlled moraine/hummocky end moraine). As well as the irregular-shaped features discussed in Gravenor's (1955) paper, Gravenor and Kupsch (1959) also attributed linear ridges, which, in places formed diamond or box patterns, and washboard ridges (ridges believed to have formed transverse to local ice flow direction) to ice-stagnation and letdown. They suggested that the ice-flow characteristics were mainly crevasses which opened both from the top, and from the bottom, of the ice. They also suggested that as well as supraglacial material slumping into crevasses on the surface of the ice, some material was also squeezed up into crevasses at the base of the ice. When ice finally melted, the concentrations of debris were melted out of the ice and let down.

A modification of the let-down theory relates to the development of "karst-like" caves and

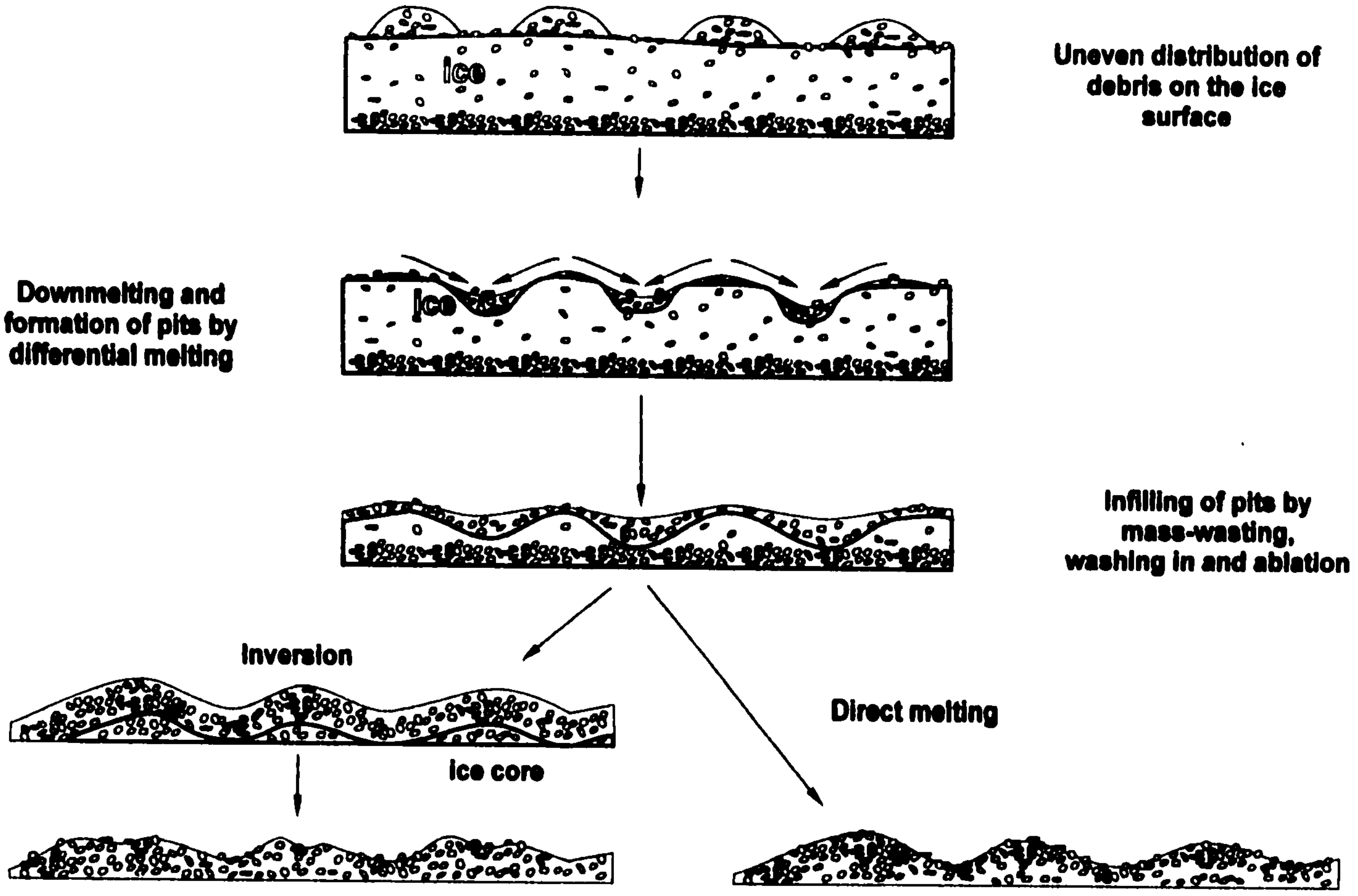

Figure 2.3: Summary of the topographic inversion hypothesis of hummocky terrain formation (modified from Gravenor, 1955).

depressions in stagnating ice (Clayton, 1973). He observed that many large sink-holes, up to 370 m across, developed on the surface of Martin River Glacier, south-central Alaska. Most were filled with small lakes. He suggested that when ice melted, the resulting features should be broad, relatively flat-topped plateaux: moraine plateaux. He suggested that this process could account for the inferred ice-walled lake plains (moraine plateaux) observed across the Prairies in North America. This suggestion was supported by subsequent studies that suggested that the rims on moraine plateaux were composed of shore-worked sand (e.g., Lagerbäck, 1988). Johnson et al. (1995) also demonstrated that moraine plateaux rims were filled with stream and wave-sorted sand and gravel. The plateaux centres were filled with lake sediment and the bases were filled with local till. Although this supported Clayton's (1973) inference, not all moraine plateaux have formed in this way. Hoppe (1952) demonstrated that the Veiki moraine rims in Sweden were composed of basal till, and hence that it was impossible for those to have formed in a supraglacial environment.

Many studies demonstrated that large quantities of debris existed on the surface of some modern glaciers (e.g., Boulton, 1967; Rains and Shaw, 1981; Lawson, 1982; Paul, 1983; Sharp, 1985), and hence lowering of this debris to the ground surface during stagnation is inevitable. Therefore letdown is a plausible mechanism for forming hummocks. However, it is only be plausible in certain environments. As Tarr and Martin (1914) stated: "clear glacier ice is the normal, and the moraine-covered glacier the exception". For example, while it is relatively easy to feed and maintain large volumes of debris from surrounding mountains onto an alpine glacier, it becomes far more problematical when considering large continental ice sheets. Those ice sheets are generally deficient in supraglacial debris, as they overtop the majority of topographic highs. Hence, before letting down sediment, a mechanism must first be considered to get the debris up on top of the ice. Clayton and Moran (1974) suggested that material can be brought to the surface of the front of an advancing glacier by thrusting, due to intense decelerating and compressive flow. This was based on the earlier work of Weertman (1961) on the Thule Baffin moraines, and Souchez (1967) on thrust moraines in Antarctica. A thrust origin for hummocky terrain is considered later. Clayton et al., (1985) suggested that ice-lobe surging would result in significant thinning of an ice sheet, resulting in the exposure of large accumulations of debris on the ice surface, which could then be let down during stagnation. If all hummocky belts were the product of this mechanism, it would require that the ice was active immediately prior to each stagnation event and, hence, the margins of the ice sheet must have surged and stagnated on several occasions. They also indicated that supraglacial melt would result in reworking of any originally subglacially-derived debris, and therefore, any subglacial characteristics would be lost.

This introduces the next question: do the internal sediments in hummocks support the letdown hypothesis? That is, are the sediments "flow tills" or debris flows, and reworked glaciolacustrine beds? Some researchers argue that lake sediments may be preserved during letdown if the process is very gradual. However, at least some normal faults would be present due to the removal of supporting ice walls. Also, some researchers have attributed melt-out till to the letdown of englacial sediments with little modification of properties inherited from glacial ice. For instance, Kulig (1985) suggested that many of the hummocks south of Edmonton, Alberta, were the result of melt-out of englacial sediment. He suggested that sedimentary structures characteristic of debris banding in ice were preserved in the sediment. However, it is expected that such processes would result in the deposition of a relatively regular blanket of sediment, that may result in gently undulating topography. It is difficult to envisage such a process forming steep-sided hummocks. If this were the case, then sediment within the basal portions of the ice would have to be concentrated into zones of similar lateral dimensions as the deposited hummocks. Although debris concentration may occur over kilometres, it is unlikely that thick concentrations of debris in discrete bands in the ice would be present over a distance of only tens of metres, the scale required to account for these landforms.

Other workers suggested a combination of subglacial, englacial, and supraglacial melt-out or letdown, since various sediment types are present in the mounds (e.g., Möller, 1987). Johnson et al., (1995) documented hummocks with well-preserved melt-out till in their bases. Clast fabrics from the melt-out till were strong, preserving local ice flow directions (Fig. 2.4). They interpreted the sequence as representing stagnating ice where debris melting out at depth maintained englacial structure. However, they indicated that surface debris continued to be released as flow till, or was deposited as lake or stream sediment.

Generally, in the letdown/melt-out hypothesis, "flow tills", sorted sands and silts, and glaciolacustrine silts and clays, are used by researchers to infer supraglacial letdown as the landforming agent. Where melt-out till is recognised, subglacial, and englacial melt-out, and englacial let-down are assumed.

A fundamental question is: do the sediments in hummocks actually support letdown or topographic inversion? Evidence at ***many*** sites in continental settings precludes this hypothesis. In many areas, *in situ* undisturbed subglacial lodgement and melt-out tills (e.g., Hoppe, 1952; Stalker, 1960a; Aario, 1977a; Menzies, 1982; Kulig, 1985; Munro and Shaw, 1997), undisturbed

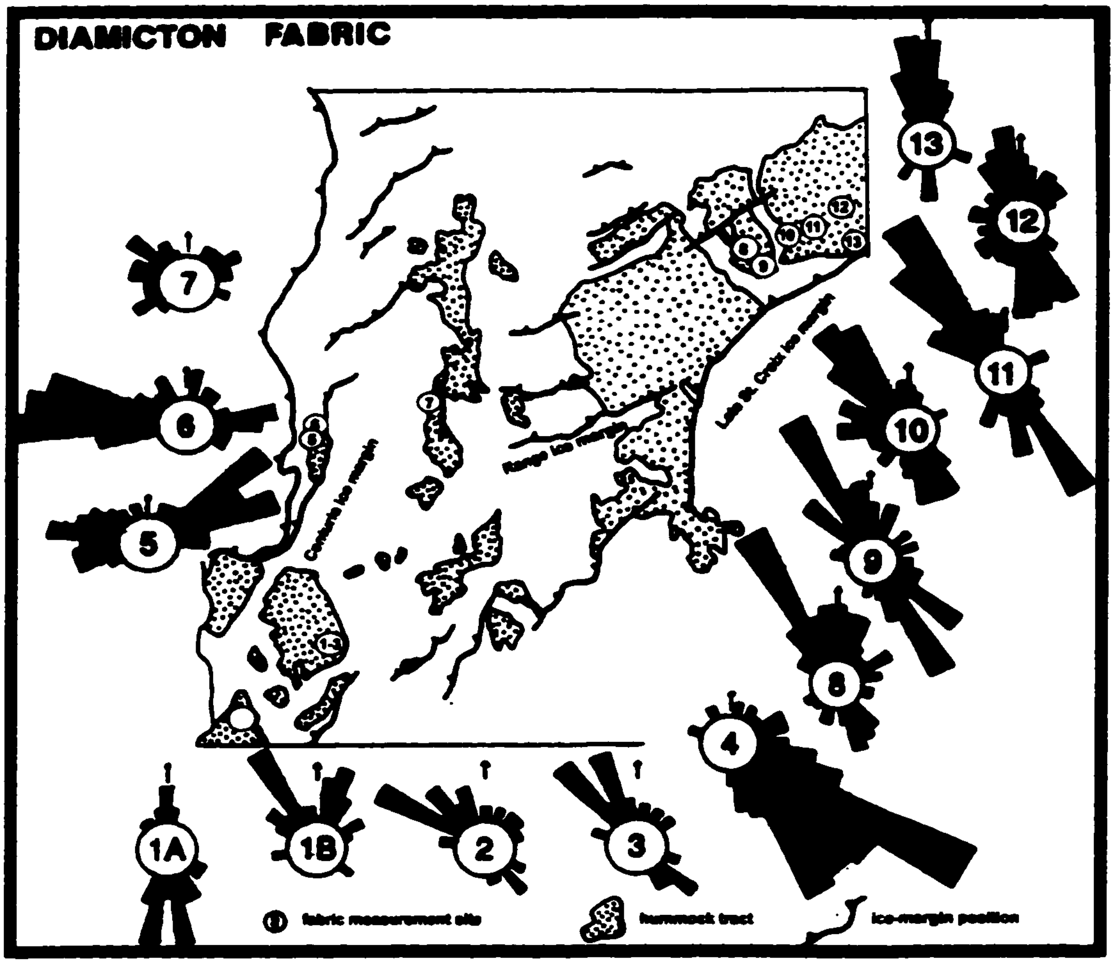

Figure 2.4: Fabric data from hummock tract in western Wisconsin. Fabrics generally have dominant orientations along the NNW - SSE axis. These fabrics, and sand strata within the diamicton, led Johnson et al., (1995) to interpret the diamicton in the hummocks as melt-out till (modified from Johnson et al., 1995).

lake sediments (Klassen, 1989; Munro and Shaw, 1997), and bedrock (Kulig, 1985; Tsui et al., 1989; Munro and Shaw, 1997; Beaney, 1998; Sjogren, 1999) are observed. These materials could not have been deposited on the ice surface. Hence, topographic inversion, a process observed at some modern glaciers, does not account for all sediments in hummocky terrain, and as a result cannot account for all hummocky terrain types.

Ice-pressing

The ice-press hypothesis was mentioned in early literature (e.g., Erdtman and Lewis, 1931), and it was more fully developed by Hoppe (1952) and Stalker (1960a). The theory evolved as researchers noted subglacial tills, rather than "let-down sediments" inside hummocks. The fact that only a few glaciers in the modern environment were covered by debris prevented Hoppe (1952) from accepting that supraglacial letdown could explain all hummocky belts. He excavated several Veiki plateaux and noted that the varying till types were solidly packed, suggesting basal deposition. Orientations preserved in the fabrics from the tills were consistently transverse to the rim ridges (Fig. 2.5). In contrast, fabrics within the central plateaux areas and within the depressions between plateaux (termed dead-ice hollows by Hoppe, 1952) were highly variable and displayed no strong alignments. This would be expected if most squeezing occurred in the region of the rims. His preferred explanation was that till below stagnant ice blocks was squeezed outwards toward the edge of the Veiki plateaux, due to the weight or movement of the overlying ice block, thus orienting the pebbles at right angles to the ridges along the plane of maximum strain. He was satisfied that this explanation was correct, because similar features were observed when ice melted away after Sefström glacier, Spitzbergen, had surged and deposited an end moraine (Lamplugh, 1911). Hoppe also indicated that it is possible that the plateaux represent parts of an uneven, basal till surface below the ice that existed prior to the formation of the rim ridges. Some researchers were reluctant to accept the ice-press hypothesis as Boulton (1967) demonstrated that supraglacially-derived flow tills can be as consolidated as subglacially-deposited till.

Stalker (1960a) also believed that compact, unsorted diamicton in hummocky terrain in Alberta was subglacial in origin. He referred to Hoppe's (1952) fabric results that suggested shear was always outwards from major hollows towards the ridges. Stalker (1960a) extended these results to explain "prairie doughnuts" (small hummocks with central depressions). He believed the irregular pattern observed in many hummocky zones was due to stagnant ice, and that subglacial sediment was completely saturated, allowing deformation and squeezing. He assumed that

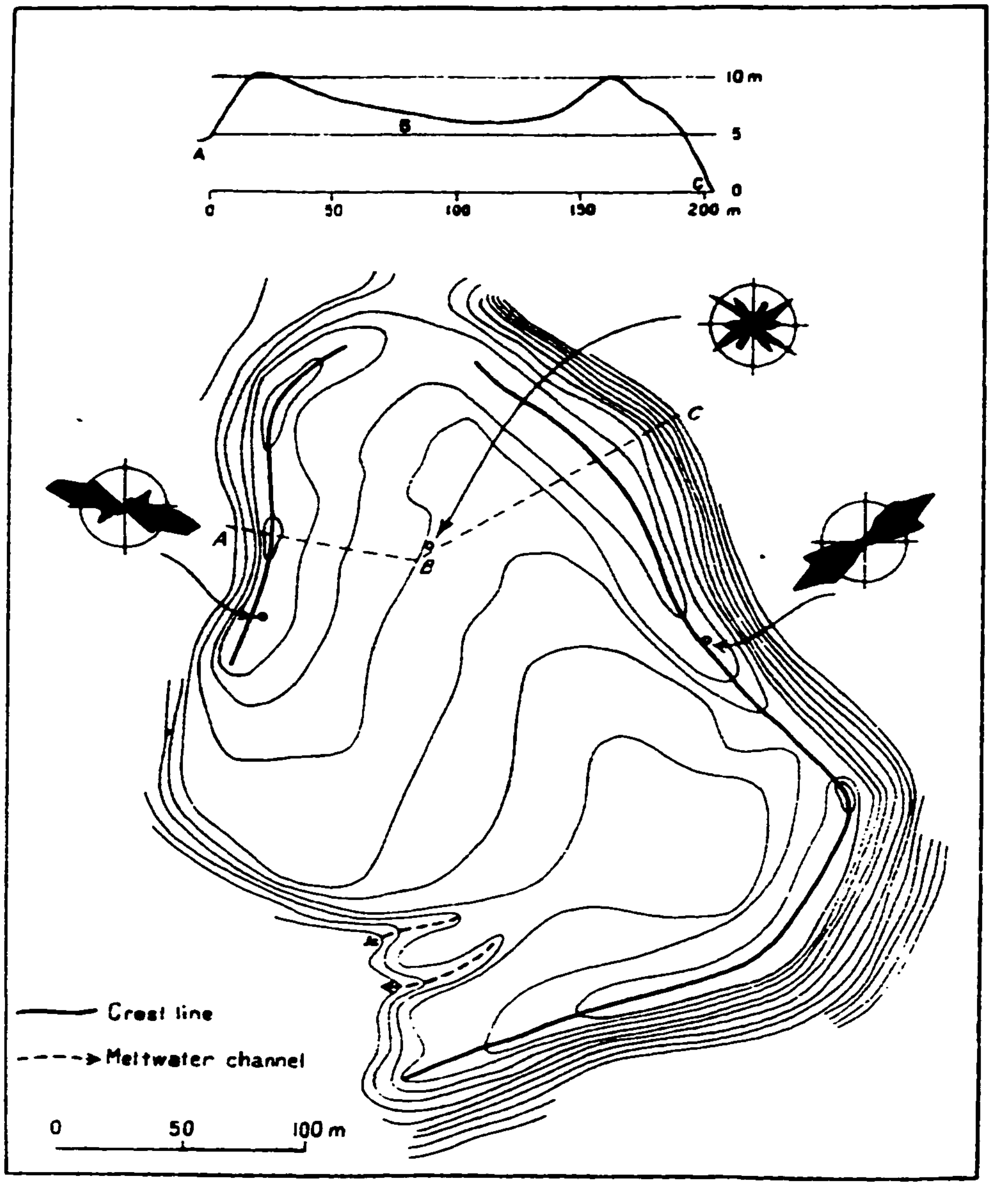

Figure 2.5: Map and profile of a single hummock in the Veiki area, Sweden. The contour interval is 1 m (from Hoppe, 1952).

subglacial cavities and crevasses were present at the base of the ice, although he did not address the origin of those cavities. He stated that where the holes were large, material would only be pressed in at the edges, producing a circular ridge (a "doughnut"), rather than a mound. Holden (written communication) pointed out that the ice-press hypothesis cannot adequately explain the presence of rim-ridge chains (doughnut chains). The theory assumes that debris is squeezed into a cavity from all directions beneath the ice walls, yet it would be impossible for two fully connected rim-ridges to form when there is no ice at the cavity connection to create the ridge.

Both Hoppe (1952) and Stalker (1960a) assumed that ice was stagnant during the pressing process, although Hoppe (1952) did state that where attenuated ridges occur, some ice movement was necessary to explain the pattern. Stalker (1960a) also suggested that some drumlins and eskers were formed by the ice-press process because they are spatially related to the hummocks, and because some eskers contain diapirs of diamicton. He invoked the presence of cavities at the base of the ice to produce "ice-press landforms", yet the origin of "irregular" shaped cavities, drumlin-shaped cavities, and esker-shaped cavities is unaccounted for. Although Stalker (1960a) did not explain how the cavities originated, more recent research does explain why an esker tunnel may eventually become filled with diamicton rather than sorted sediment. If flow in the tunnel was fast, it is possible that the water pressure in the tunnel was relatively low in comparison to the porewater pressure in underlying saturated till. Till could therefore preferentially move into the tunnel (e.g., Boulton and Hindmarsh, 1987). Depending on the rate of sediment migration, sediment may be partially removed, but the tunnel may eventually become plugged by the till.

More recently Eyles et al., (1999) developed a conceptual model which expanded upon the ideas of Hoppe (1952), and more specifically the ideas of Stalker (1960a). This model takes into account the deforming bed paradigm. Eyles et al., (1999) noted that hummock tracts border a zone of low-lying fluting in southern Alberta, Canada. Their conceptual model proposes that ice surged through low-lying areas because of the presence of easily deformable shale bedrock (Fig. 2.6). During the surge event, deformation and moulding of clay-rich till, derived from the bedrock, resulted in flute and drumlin formation. Where the ice was thinner on the higher ground, the result was stagnation. These higher areas, which they indicate are also dominated by clayey till, were the subject of ice pressing by dead ice blocks (Fig. 2.7), resulting in hummocky terrain.

Eyles et al.'s (1999) model is based on the following assumption: hummocks in southern Alberta are filled with clay-rich till. They state that Stalker (1960a) demonstrated that the entire glacial topography in central and southern Alberta is underlain by fine-grained till (regionally known

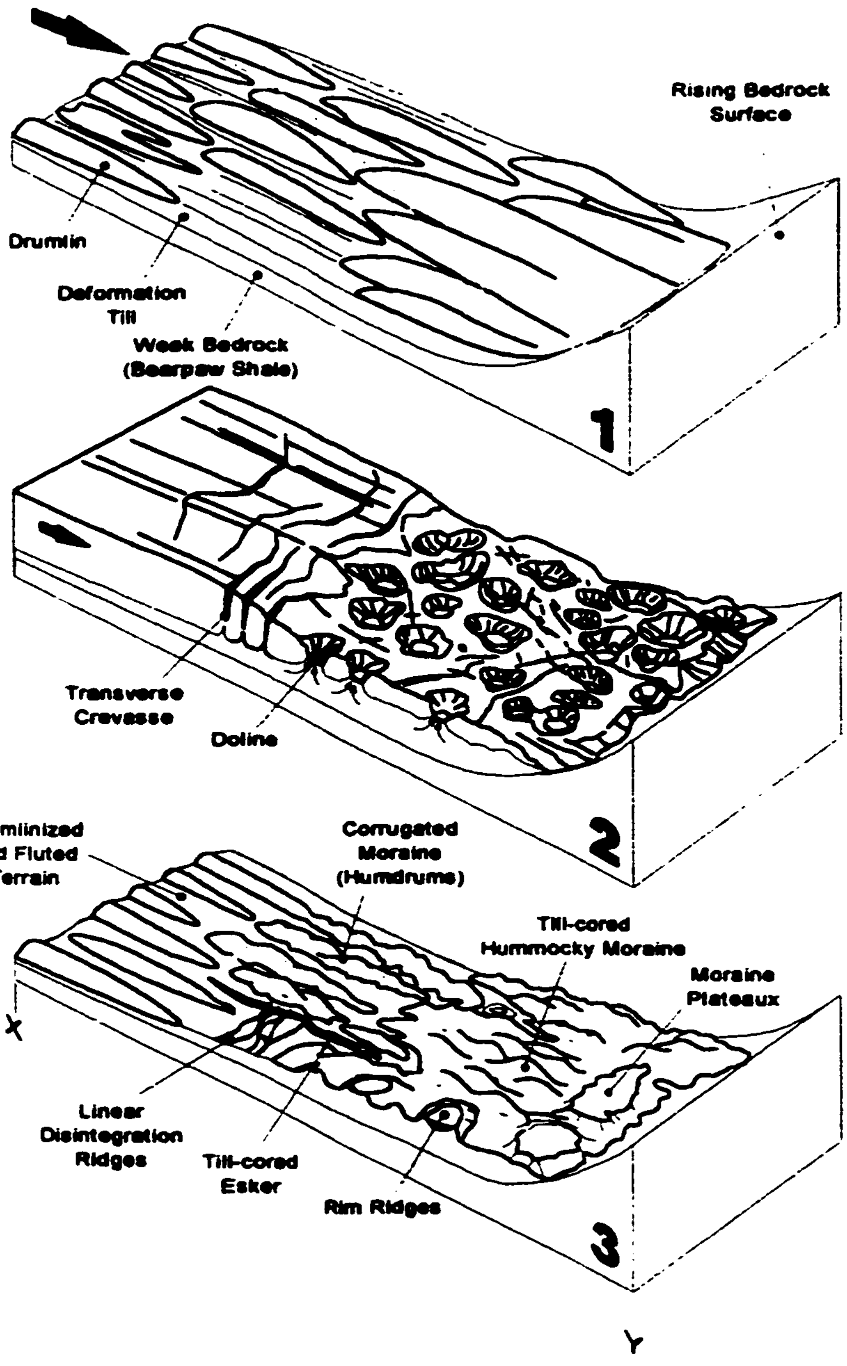

Figure 2.6: Conceptual model of "soft bed terrain" with till-cored hummocky moraine and corrugated moraine on the margins of the topographic highs, and drumlinized topography in the lows (from Eyles et al., 1999).

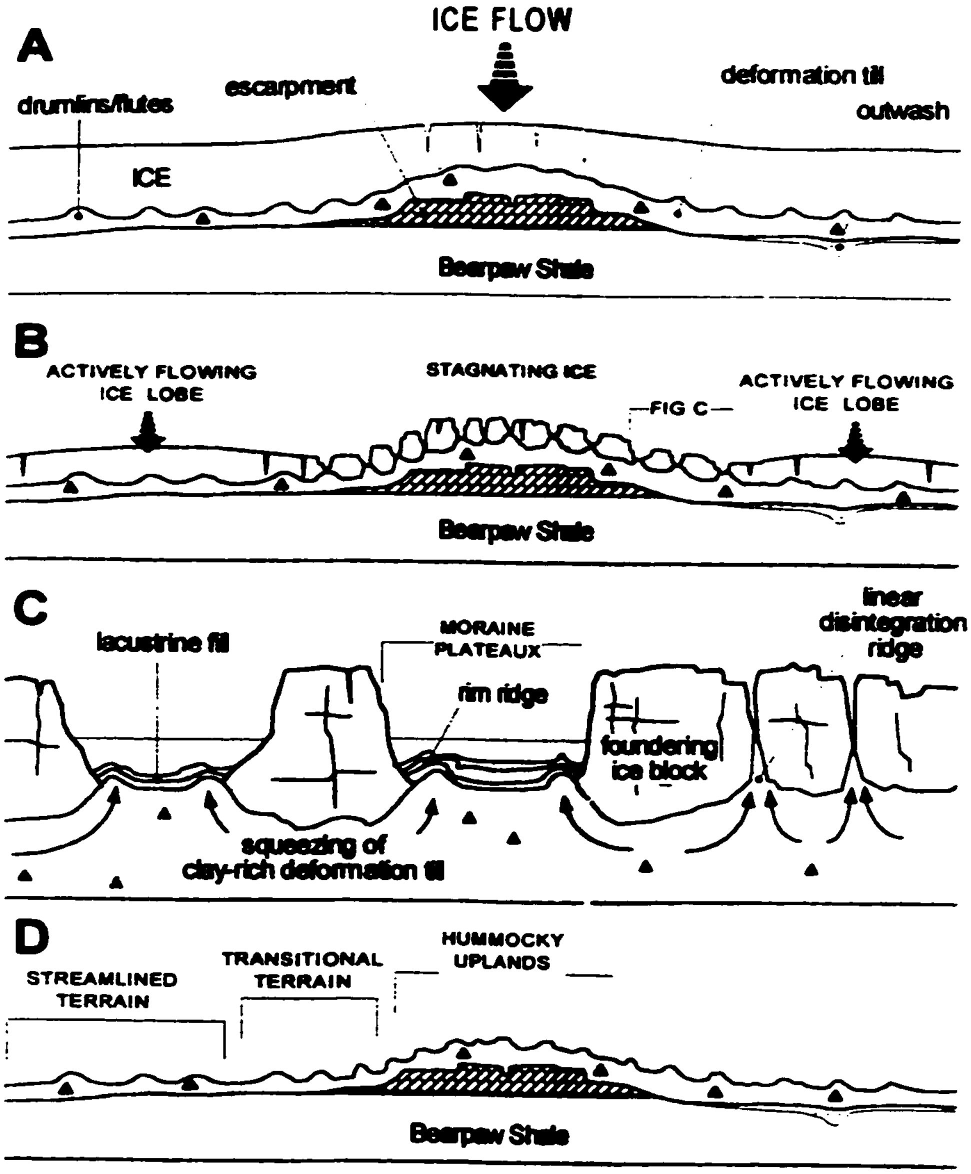

Figure 2.7: Schematic diagram showing sequence of events proposed by Eyles et al., (1999). A. Active ice phase with erosion of drumlins in topographic lows and accumulation of thick deformation till over the more resistant bedrock escarpments (areas of reduced ice velocity) B. During regional deglaciation, hummocky moraine forms at the margins of ice lobes by pressing below stagnant ice stranded on the uplands. Drumlins record continued active ice flow in the topographic lows during deglaciation. C. Formation of rim ridges and linear disintegration ridges by pressing; moraine plateaux form where rim ridges are filled by lacustrine sediment. Anticlinal arching of lacustrine sediments over rim ridges is the result of till diapirs. D. Soft bed terrain consisting of drumlins and fluted terrain in shale-floored low-lying area pass laterally into a transitional zone of ice-pressed drumlins ("humdrums"), and washboard moraine and thick hummocky moraine on the upland areas.

as the Labuma till) derived from the clay-rich Bearpaw Shale. This is important in their conceptual model, as this is the driving mechanism for fast flow in the low-lying areas. However, Stalker (1960a) actually reported this till as the oldest in the region, occurring at the base of the glacigenic stratigraphic sequence. While the proposed lobe does lie over the clay-rich Bearpaw Shale, little "deformation till" or other sediments (apart from postglacial lacustrine beds) underlie this zone (Rains et al., 1993). The flutes and drumlins, reported to be filled with deformation till, are, predominantly composed of undisturbed local bedrock. Munro and Shaw (1997: Appendix A) reported over 100 exposures within Eyles et al.'s (1999) western margin of their "Lethbridge Lobe" that were filled with thick glaciolacustrine beds (debris flows, sorted units, and rhythmically-bedded units), bedrock, and melt-out till. Only at a few locations are there thin deposits of the clay-rich till that Eyles et al. (1999) discuss. However, they argue against the presence of "melt-out tills" in hummocky terrain, supposedly "interbedded with glaciotectonically-deformed strata" reported by Munro and Shaw (1997; Appendix A). Munro and Shaw (1997) actually reported melt-out till as the youngest unit in the region which conformably overlies glaciolacustrine sediments, and did not report that the till was "interbedded with glaciotectonically deformed strata" (Eyles et al., p. 172), or that the till possess the properties "crude banding, faults, or rafts of underlying strata" (Eyles et al., 1999, p.171). Munro and Shaw (1997; Appendix A) actually reported a diamicton with continuous sorted strata, scours below boulders (see their Fig. 6), and 27 fabric samples with high principal eigenvalues, low plunge angles, and consistent mean orientations (see their Fig. 7; Table 1). These are all properties of melt-out till (e.g., Lawson, 1979), and not deformation till. Eyles et al. (1999) also state that the good clast orientations reported by Munro and Shaw are more probably of deformation till. However, Hart (1995, p. 123) stated that if clasts "are not aligned or indicate evidence of clast rotation in the till then this is good evidence of deformation". Variable or weak fabric strengths from deformation tills are also reported by Dowdeswell and Sharp (1986), Hicock and Dreimanis (1992), Benn (1994), Benn and Evans (1996), and Hicock et al., (1996). Also, fissility, rotation of clasts and, most importantly, sediment deformation are not present in the unit described by Munro and Shaw (1997). Hence this unit displays none of the characteristics of deformation till as described in the above literature, but it is compatible with the interpretations of melt-out till as described in detail by Harrison (1957), Lawson (1979), and Shaw (1982).

Also, in the region discussed by Eyles at al., (1999), Munro and Shaw (1997) demonstrated that hummocky terrain is the product of erosion into many different sediment types (see their Figs. 3, 4, 5, 8 and 9; Appendix A). Although pressing of pre-existing sediments may account for the variety of sediment types in hummocky terrain, it does not account for erosion of hummock surfaces, the preservation of *in situ* stratigraphies, or the presence of undeformed sediments.

Thrusting at, or near, the ice margin

Recently, many areas of hummocky terrain have been ascribed to thrusting of sediment or bedrock at the front of, or near, the margins of a glacier or ice sheet (e.g., Kulig, 1985; Tsui et al., 1989; Hambrey et al., 1997; Bennett et al., 1998). These areas are often referred to as thrust moraine, and individual ridges are interpreted as forming transverse to the ice flow. Hence thrust moraine is also considered to be controlled moraine. Most of the thrusting ideas have their roots in the early work undertaken in Antarctica and the High Arctic. Bishop (1957) initiated the work, examining what he termed shear moraines. He indicated that where the ice sheet or glacier was cold-based at its margin, active ice behind the margin may ride up over the dead ice by shearing, and hence also incorporate debris from the bed. This debris could then be transported to the surface of the ice sheet along shear planes. The debris on the surface could then protect the underlying ice from extensive ablation and hence, ice-cored upstanding ridges would remain: shear moraines.

Weertman (1961) disagreed with the mechanism of shearing and, hence, also disliked the name *shear moraine*. He preferred the term *Thule-Baffin moraine,* after the regions that the moraine type occurs in. He suggested that the number of debris bands and the thickness of the debris bands (millimetres thick) could not be accounted for by shearing. Weertman (1961) also indicated that "only slightly dirty ice" could not be accounted for by such a "scraping action". He believed, however, that the freezing of water onto the base of the ice sheet could account for the dirty layers. Weertman's (1961) model is based on the assumption that ice is frozen to the bed at its toe, and melting and refreezing occur at the bed up-glacier from this. These assumptions are corroborated by measurements at the Thule Ice Lobe on Baffin Island. The melting area is divided into two zones (Fig. 2.8). The zone furthest from the frozen toe experiences basal melting. The meltwater is forced by the pressure gradient towards the front of the glacier, where it moves into a zone where the temperature gradient in the ice conducts away more heat than is produced by sliding or geothermal heat. Hence the water refreezes to the base of glacial ice. Any shift upglacier of the 0°C isotherm, coinciding with the base of the ice sheet, would result in the freezing of debris bands into the base of the ice. As this process would be continuous, numerous debris bands could be incorporated into the ice. In the marginal zones of a glacier, where the flow lines are upwards toward the surface, debris layers eventually become exposed in the ablation area, and can therefore form the Thule-

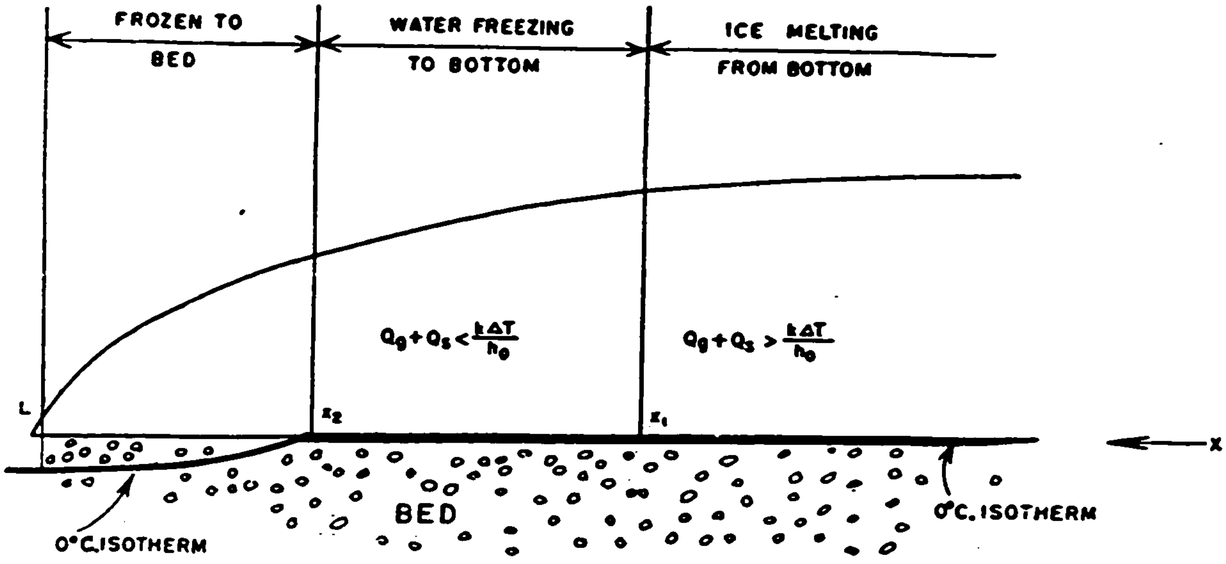

Figure 2.8: Weertman's (1961) freezing model. This shows a hypothetical cross-section of an ice sheet, where the edge of the ice sheet is frozen to its bed, and the 0°C isotherm reaches the bottom of the ice sheet up ice from its edge.

Baffin moraines.

Rains and Shaw (1981) considered Antarctic "shear moraines" (they do not use this terminology) to result primarily from debris reaching the surface via thrust blocks, and then melting in a pattern related to the development of ablation cusps. They noted two different types of controlled moraine (Fig. 2.9), depending on the volume of supraglacial debris. The largest volumes of debris occur where thrust planes are best developed. Where these larger volumes exist, downwasting is generally due to sublimation. Rains and Shaw (1981) suggested that material would eventually be let down as a series of transverse ridges relating to the spaces between thrust planes in the ice, and hence also to the spacing of ablation cusps (areas of debris concentration) developed between thrust planes. They also noted that in the areas where debris cover is thin, ablation rates are significantly higher. The exception is at the immediate margin of glaciers, where ice is protected by scarp debris. The greater thickness of debris in this region would result in significantly larger ridges, with many smaller controlled and uncontrolled hummocks forming behind that.

Several papers have related Scottish hummocky moraine to thrusting (e.g., Bennett and Boulton, 1993; Bennett et al., 1998). Bennett and Boulton (1993) revisited some of the hummocky landforms believed to have been deposited during the Younger Dryas re-advance (Loch Lomond Stadial) in the Scottish Highlands. While previous researchers indicated that these landforms were chaotic in their distribution (e.g., Sissons, 1976), Bennett and Boulton (1993) noted a distinct order of cross-valley and down-valley lineations, with only a few patches of unordered terrain. The downvalley components were interpreted as flutes, while the cross-valley components were interpreted as recessional moraines. The presence of shear folding in the sediments was believed to document the pushing up of the moraines at the ice front. Hambrey et al., (1997) and Bennett et al., (1998) examined "hummocky moraine" in Scotland and Svalbard. Both suggested that hummocks resulted from thrusting up of debris either englacially or proglacially, followed by subsequent melt-out and letdown of that debris.

Subglacial moulding

Subglacial moulding, as a theory of hummocky terrain formation, attempts to explain patterns in hummock distributions, and also the presence of subglacial till in hummocks. Aario (1977a) actually suggested the term "active-ice hummocks", because many hummocks contain sediment similar to drumlins (although there tends to be more sorted material). He also indicated that the upper parts of many hummocks contain shear planes. Significantly, Aario (1977a) noted

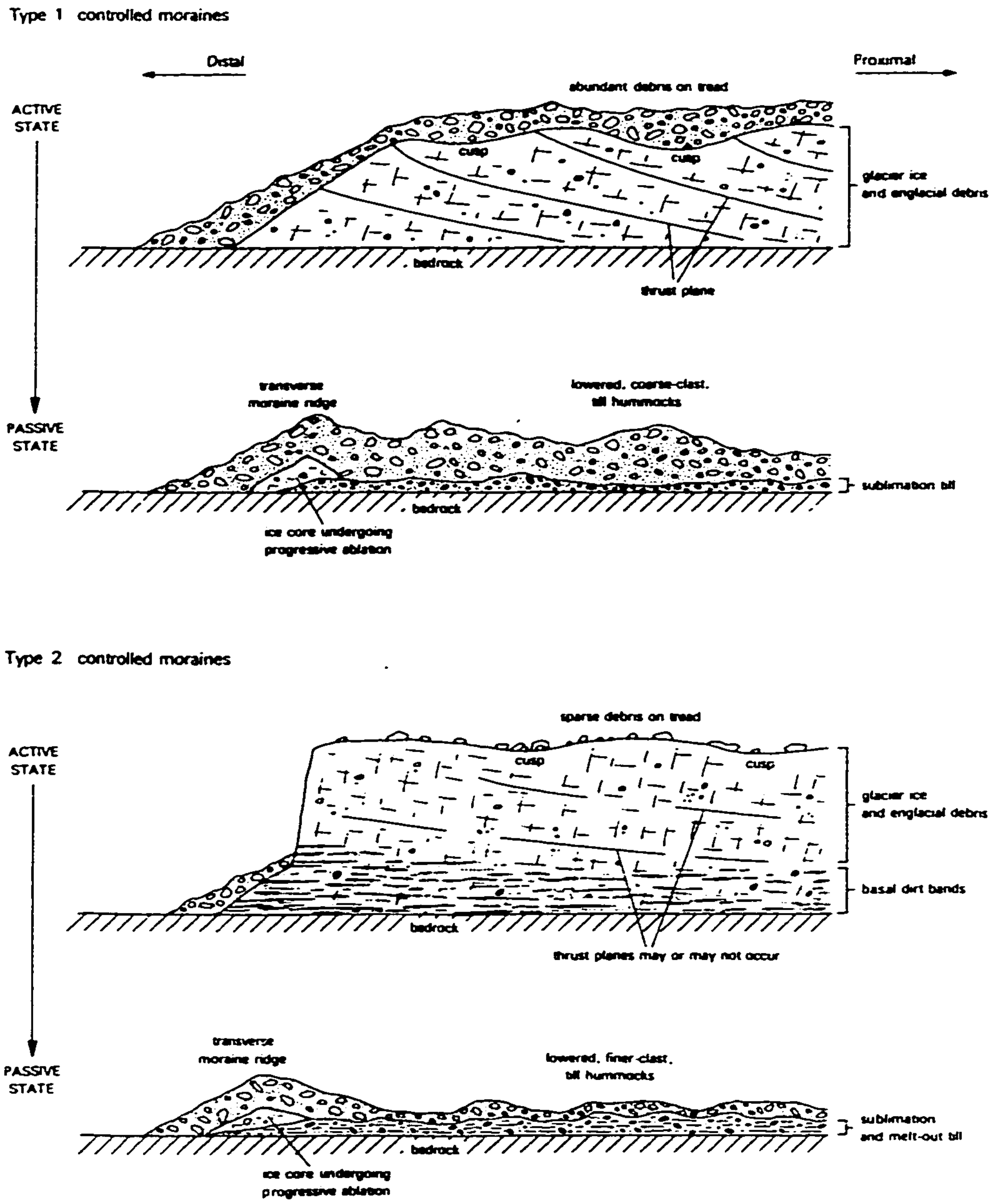

Figure 2.9: Model illustrating the development of controlled moraine in Antarctica (from Rains and Shaw, 1981).

that the surface trends often resemble that of Rogen moraine, i.e., ridges believed to have formed transverse to local ice-flow directions (Fig. 2.10). Where distinct ridges were not observed, hummocks were aligned in transverse rows (Fig. 2.10). Aario (1977a) suggested that an up and down forward wave motion of the ice was responsible for the hummocks and Rogen moraine formation. Importantly, he also noticed the resemblance between these landforms and rippled surfaces, and noted that hummocks are transitional to flutes and drumlins (Fig. 2.10). Hence, he believed that there was a link in genesis between these landform types.

Lundqvist (1969) discussed what he termed "hummocky active-ice moraine" because of the transition and comparison between hummocks and Rogen moraine. Later, Lundqvist (1981) noted the resemblance between some hummocky regions in Sweden and drumlins. He also noted that hummocks were filled with lodgement till (the common contemporary interpretation of drumlin till). He suggested three possible origins for the drumlinized hummocks: 1. hummocks were formed subglacially like drumlins; 2. drumlins formed subglacially and were then overlain by dead-ice morphology; and 3. an existing hummocky topography was slightly drumlinized during possible reactivation of the ice. He conceded, however, that he was unsure of the exact origin of the topography.

Menzies (1982) considered some hummocks to be the precursors of drumlins. He suggested that various geotechnical changes between subglacial ice and the bed may result in localized accretion of lodgement till. These changes include dissipation of porewater into the substrata or conduits, resulting in areas of higher strength material; the sudden removal of a lubricating layer, resulting in local grounding; and local porewater freezing, resulting in increased shear strength of material. Menzies (1982) stressed that if wholesale agglomeration occurred at the bed, the necessary conditions for creating till nuclei would not be met, hence agglomeration had to be localized. Sufficient agglomeration would result in the formation of a till hummock (a proto-drumlin). Menzies suggested that these may act as nuclei for drumlin formation. Once material begins to agglomerate, the stress field placed on the material will be such that the sediment at depth will be mostly unaffected by basal shear stresses, because of stress dissipation in the sediment (Fig. 2.11). This area would therefore act as a nucleus around which deforming sediments (sediments subjected to shear stress) would move. The Menzies (1982) model is not supported by field evidence, and indeed when sedimentary data from other papers are examined, the theory seems largely unsubstantiated. Most importantly, many, if not most, hummocks are not composed of lodgement

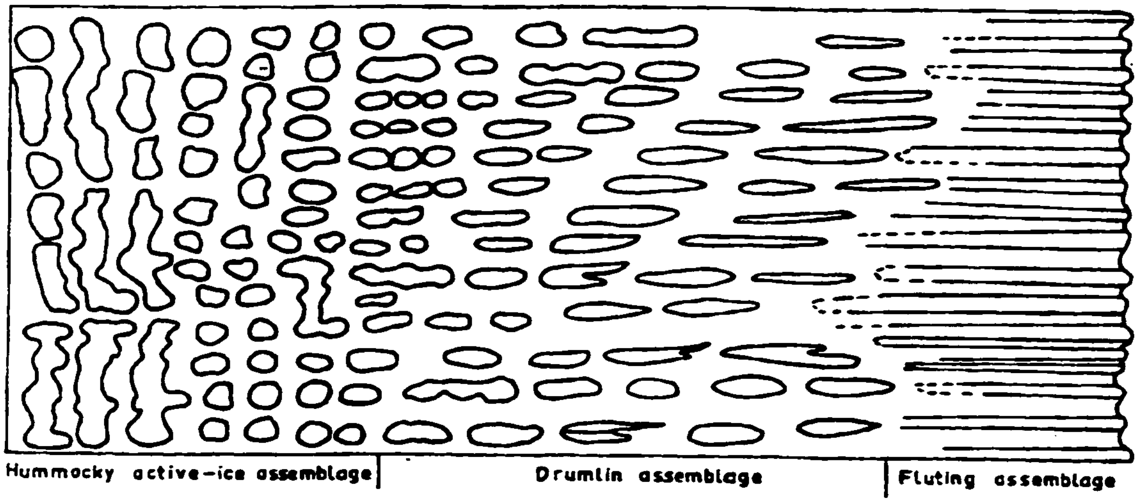

Figure 2.10: Diagram demonstrating the transitional nature of active-ice assemblages: the fluting assemblage, the drumlin assemblage, and the hummocky assemblage. Flow was from left to right. Spiral flow in the ice predominates in the formation of flutings and linear drumlins, whereas up and down movement predominates in the formation of the hummocky terrain. Between end members, combinations of these patterns occur (From Aario 1977a).

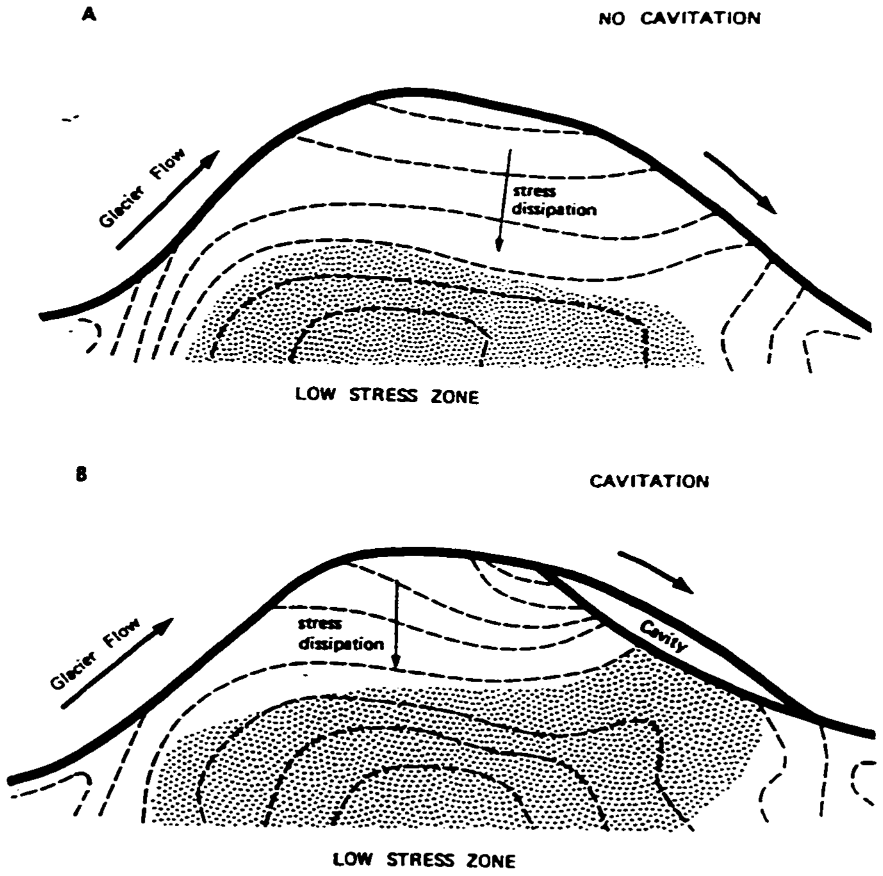

Figure 2.11: Theoretical distribution of stresses in a till hummock (from Menzies, 1982).

till or deformation till[1].

Subglacial meltwater erosion and/or deposition

Some researchers have proposed that hummocky terrain is the product of erosion by subglacial meltwater sheetfloods moving below glacial ice (Rains et al., 1993; Shaw et al. 1996; Munro and Shaw, 1997; Sjogren, 1999). The terrain therefore represents erosional remnants. Rains et al., (1993) suggested that moraine plateaux, which commonly occur several metres above hummocks, are the remnants of a preflood, subglacial surface composed of variable sediment types. The hummocky zones are believed to represent overspill diversion of more extensive water sheets that produced drumlins and flutings in low-lying zones. These are the same drumlins and flutings that Eyles et al., (1999) later ascribe to subglacial deformation. Less efficient water erosion of the higher zones resulted in hummock formation rather than streamlined landforms.

Munro and Shaw (1997; appendix A) demonstrated that hummock surfaces were erosional, as those surfaces cut through both undisturbed and pervasively deformed sediments of several types and bedrock (Fig. 2.12). They also demonstrated that the erosion occurred in a subglacial environment, as the youngest unit in the hummocks is subglacial, and subglacial eskers overlie the erosion surface. With no evidence of ice advance and retreat between these two depositional events, they concluded that the erosion was most likely subglacial also. Both ice and deformation were discounted as the erosion agent, as the erosion surface is abrupt, boulder lags (the result of winnowing) overlie that surface, no deformation till lies directly below the surface or is associated with that surface, and there are no moraines or deposits behind the ice margin or at the ice margin, which account for the volume of erosion required. Munro and Shaw (1997) preferred a meltwater origin for the erosion as this better explained the abrupt truncation surfaces, the lack of deformation of underlying sediments, and the presence of boulder lags overlying hummock surfaces, which they attributed to fluvial transport. Also, sediment eroded by meltwater can be transported over very long distances, even as far as the Gulf of Mexico (Shaw et al., 1996), hence explaining the lack of moraines as depositional products. Sjogren (1999) also demonstrated that hummock surfaces were eroded into a variety of sediment types and bedrock. Beaney (1998) noted hummocks eroded into undisturbed bedrock only. Both authors noted the resemblance between the hummock topography

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[1] The lodgement hypothesis of drumlin formation has largely now been replaced by the deforming bed hypothesis (e.g., Hart, 1995)

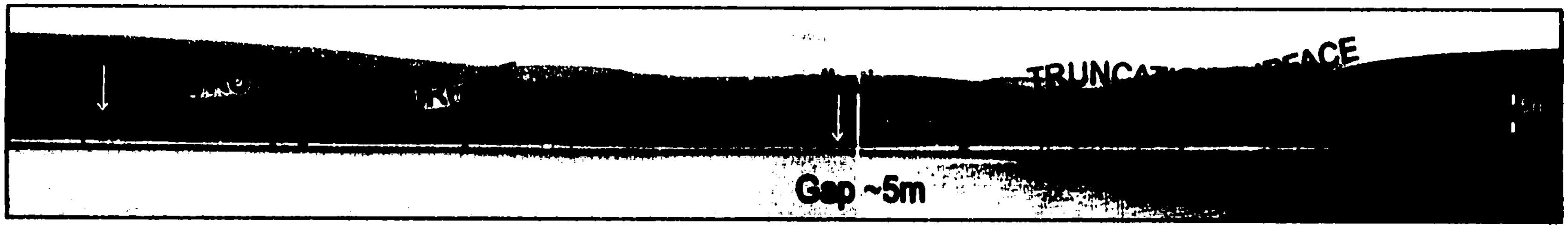

Figure 2.12: Stratigraphy can be traced between hummocks at McGregor Reservoir, south-central Alberta, indicating that at that location, hummock form is the result of erosion into preexisting sediments. The thin dashed line shows where the contact between the lower light unit and upper dark unit would have been, had erosion not occurred (from Munro and Shaw, 1997).

and ripples, and considered the hummocks to be giant bedforms.

Holden (1993) interpreted hummocks in the Duffield sand and gravel complex, ~30 km northwest of Edmonton, Alberta, as infilling of subglacial cavities by meltwater flow. Thermal and mechanical erosion of the ice bed by meltwater is believed to have produced inverted scallops on the underside of the ice, which subsequently filled with sediment transported by subglacial sheetflow water.

Shaw and Ashley (1988) proposed that hummocks are related to Rogen moraine and drumlins, just as Aario (1977a) and Lundqvist (1981) had. However, they favoured the meltwater mechanism for hummock formation. Shaw and Ashley (1988) indicate that cavities could have formed in basal ice due to subglacial meltwater flow, and sediment was then squeezed into the cavities forming the hummocks (ice-pressing). For instance, in flume experiments, they showed that relatively low-velocity flows produced scallops in plaster of Paris, which look like hummocky terrain and Rogen moraine in reverse relief.

A meltwater origin for hummocky terrain is supported by more detailed work than most other hypotheses, and better explains the wide range of sediments in the hummocks. That is, the erosional mechanism does not require that the internal structure and composition of the moraines be directly related to the morphology. However, the meltwater ideas are highly controversial in the field of glacial geomorphology. If a meltwater origin is to be accepted for the formation of hummocky terrain, more sedimentological work must be undertaken.

Subsurface diapirism

Boulton and Caban (1995), suggested that over-pressurization of groundwater in the proglacial zone may be responsible for some hummocky terrain. The idea is that upward flow of water in the proglacial zone will result in high porewater pressure beneath overlying clay-dominated layers or permafrost (Fig. 2.13). The presence of surficial water bodies such as lakes or rivers results in the local thawing of permafrost, hence developing an escape route to the ground surface for confined over-pressurized groundwater. Similarly, loading from ice sheets could cause hydrofractures which would act as points of weakness to rising water. Boulton and Caban (1995) suggest that the rims on "prairie doughnuts" and moraine plateaux in areas such as Saskatchewan, Canada, are likely the result of diapirism of underlying sediments. Hence Boulton and Caban (1995) term hummock fields, "extrusion moraine".

While sediment diapirs are fairly extensive in thick glacigenic sediments, their architecture,

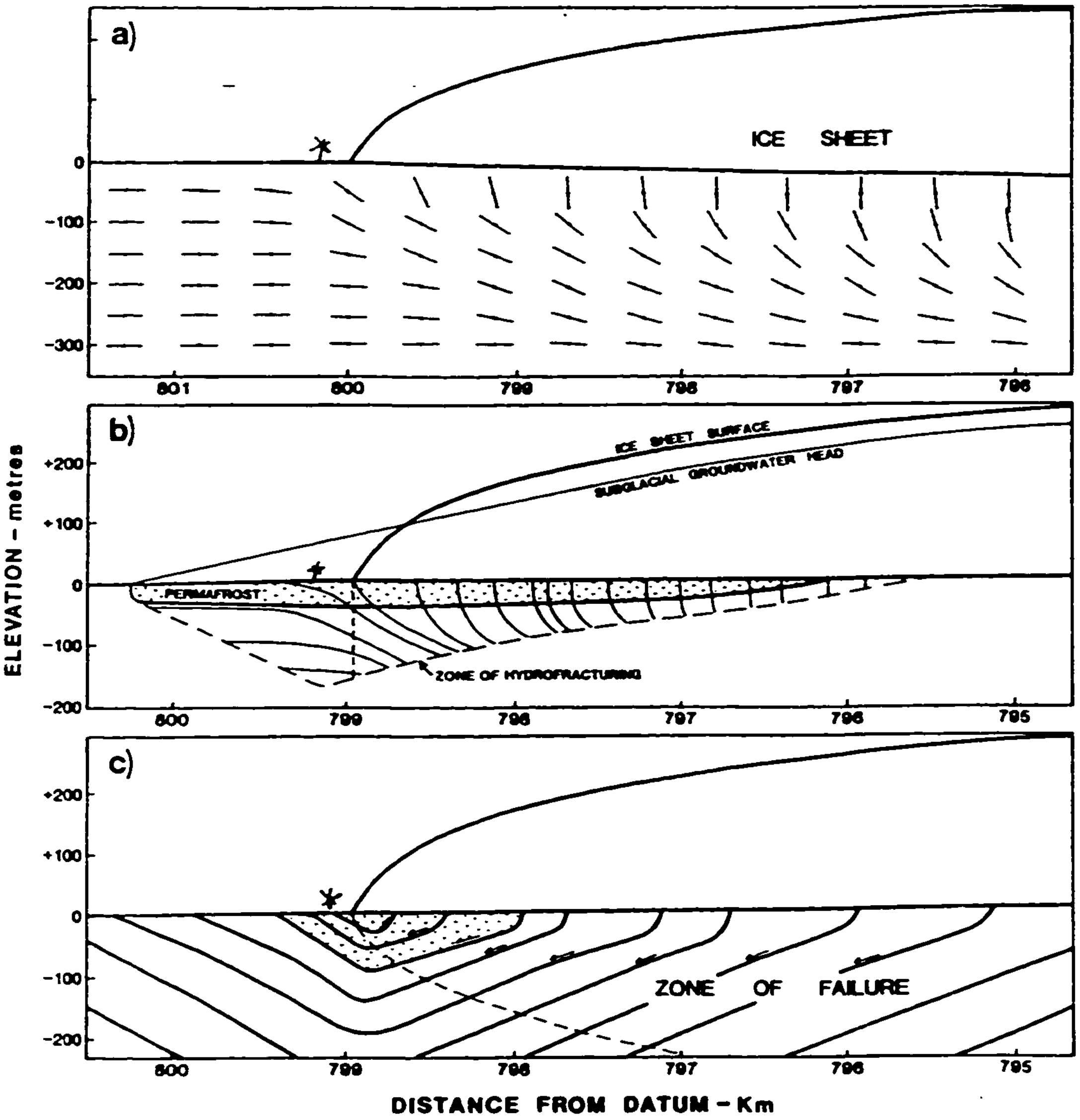

Figure 2.13. A. Calculated orientations of subsurface principal stresses (after Boulton et al., 1995). B. Modeled distribution of permafrost. C. Modeled planes of shear. Failure is assumed to occur in the proximal parts of all planes. Importantly, the area where water escape occurs to the surface is the area where "extrusion moraine" would form (marked by an asterisks) (from Boulton and Caban,1995).

their location relative to hummock surfaces, their sedimentology, and the sedimentology of adjacent beds must be considered before establishing that hummock surfaces are related to diapirism of underlying sediments. Boulton and Caban's (1995) model is conceptual and arose from the mathematical model of Boulton et al., (1995), that examined the movement of glacially derived groundwater flow. Conceptual models are extremely important in geomorphology, but available evidence must be considered. This model fails to do this. Fundamental flaws are:

1. Boulton and Caban (1995) discuss an example of sediment diapirism from Poland, and then suggest that this diapirism may explain hummocky features in Saskatchewan, Canada. First, they do not demonstrate whether the diapir from Poland is in a belt of hummocky terrain. Although they don't actually state it, all indications point to the diapir forming a single, 80 m high, hill. This is higher than documented in any other hummocky areas. It is therefore inappropriate to take this single example of diapirism and suggest that this process was responsible for wide tracts of hummocky terrain in Saskatchewan, Canada.
2. Boulton and Caban (1995, p.584) discuss hummock relief as "primarily made up of diapiric structure ......(or) the result of uplift of liquefied material along pipes". However, many diapirs will collapse or flow along the ground surface if that surface is penetrated (Fig. 2.14), resulting in minor or no relief. This is not addressed. The hypothetical type and the shape of the diapirs that Boulton and Caban (1995) suggest, indicate that these features should have never penetrated the ground surface. Hence, an essential element missing from the model is a mechanism that would exhume the features (Fig. 2.14). That is, most of the overlying sediment would have to be stripped away by large scale erosion. This is not addressed.
3. If hummocks were the result of water escape to the ground surface, it is extremely difficult to imagine how this would produce large fields of hummocks. If an escape feature has already formed, by default, overpressurized water would not seek an alternative escape route tens of metres away; rather it would follow the same route. This mechanism should result in a few dispersed hills rather than many closely-spaced hills. This would explain Boulton and Caban's (1995) large diapiric hill in Poland, but not the wide tracts of hummocks in Saskatchewan.

Vogt (1997) suggested that many hummocks on the sea floor in the Norway Basin, previously attributed to bottom currents, may have actually been the result of sediment instabilities. He suggested that the superposition of 50 - 100 m of glacigenic sandy clays over several hundred metres of biosiliceous oozes resulted in the sandy deposits sinking into the muds and, the muds

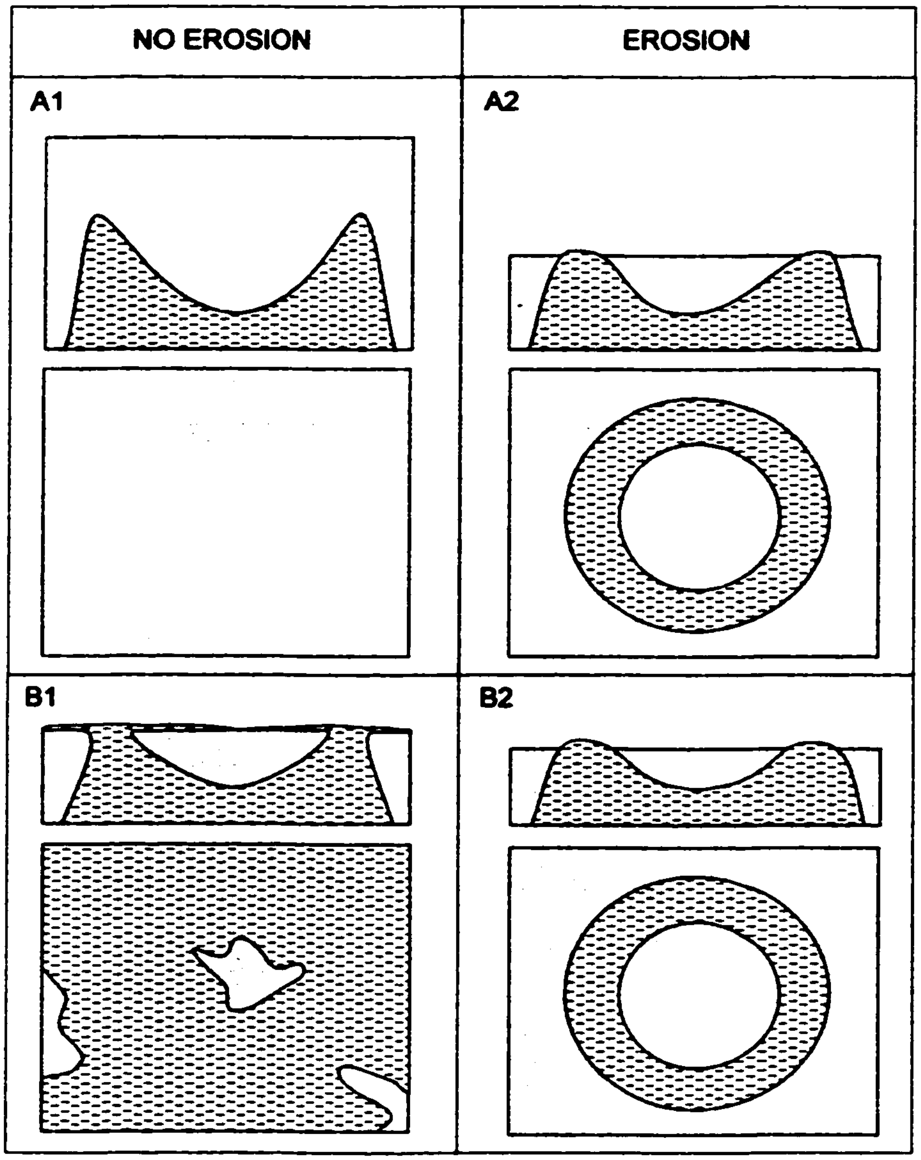

Figure 2.14: Hypothetical cross-section and map of finer-grained material diapirically intruding through coarser -grained material. A. The diapir never penetrates the ground surface; B. The diapir penetrates the ground surface and flows along that surface. In both cases the surface expression of the diapir is unobserved. However, in either case, if erosion post-dates the diapir formation (A2 and B2), then a ring of sediment can be observed on the ground surface.

rising as diapirs into sands. The rising muds are well-documented in seismic profiles and their surfaces do coincide with hummock surfaces. This process may explain some hummock fields but it is imperative to first demonstrate that the sediments in the hummocks were laid down in a subaqueous environment.

Periglacial theories

Many of the periglacial theories were developed to explain why morphologically identical landforms, in close proximity to each other, could form in such widely different parent materials (Jennings, 1982). Henderson (1952; discussed by Gravenor, 1955), proposed that "prairie doughnuts" were the remnants of large ice-wedge polygons. Gravenor (1955; p. 478) summarized Henderson's (1952) theory in the following way:

1. Frozen ground contracts and polygonal tension cracks are formed.
2. Water enters the cracks and on freezing forms ice wedges resulting in crack enlargement.
3. Water migrates to the cracks resulting in their further enlargement.
4. The centres of polygons bulge due to lateral pressures exerted by the growing ice wedges.
5. Ice lenses form under the bulged centres of the mounds, and when these melt, a central depression is left in the mounds.
6. Melting of the ice wedges accentuates the relief of the mounds.
7. Thin silts over the till in the intermound spaces are the result of recent drainage.

Gravenor (1955) dismissed Henderson's (1952) work for several reasons. First, he felt that the ice wedge hypothesis did not account for stratified sediments within the mounds; however, the presence or lack of silts is irrelevant to Henderson's (1952) hypothesis as the sediments predate the formation of the ice wedges. Gravenor (1955) also indicated that the clayey tills that Henderson reported from the mounds would be relatively impermeable to water migrating to the ice wedges. However, while ice wedges occur most commonly in sorted sediments, they are not exclusive to sorted sediments (Washburn, 1973). Gravenor (1955) also suggested that Henderson's mounds had no analog of comparable size in the Arctic examples; however, subsequent work discusses features up to ~50 m across in Alaska (Washburn, 1973). Gravenor (1955) also indicated that if the mounds were formed by lateral displacement of till due to ice wedge expansion, then the frost wedges would have to have been ~ 150 m wide and 5 m deep to account for an average prairie mound of ~ 100 m diameter. While Gravenor (1955) is correct that the ice wedges would have to be large (large modern ice-wedges are usually no more than 2 or 3 m wide), his estimates are grossly overestimated, especially since most of the displaced material would be at the edge of the mounds, and displaced material is not a requirement to account for the depression in the centre of the mound. Gravenor's strongest argument against the ice wedge hypothesis is the lack of ice wedge casts in exposure in hummocky zones, hence demonstrating that Henderson's (1952) hypothesis is unlikely. However, the idea does have much merit as it recognizes that materials have to predate the hummock form. In Henderson's later (1959) memoir, he demonstrated that many symmetrical mounds with relatively flat tops and central depressions are composed of disturbed silt and till. He attributed the disturbance to periglacial convolutions, and indicated that only two processes could account for their formation. The first is upheaval of fluid material induced by freezing of a thawed layer over a frozen substratum. The second is the formation of a polygonal system of vertical ice wedges that grew in place. He favoured the ice-wedge hypothesis as it better explains the regular distribution of the features (Fig. 2.15).

Many authors have likened "prairie doughnuts" to pingos, which are ice-cored hills that grow in a permafrost environment (e.g., Bik, 1969; Flemal,1972; Seppala, 1972). The central depression resulted from the collapse of the pingo. Flemal (1972) believed that these related to injection of groundwater through a proglacial permafrost zone. This water froze near the ground surface lifting the surface up into a pingo mound (Fig. 2.16). The process is somewhat similar to Boulton and Caban's (1995) model, resulting in what they termed "extrusion moraine". Here, however, water never penetrates the surface until late in the mound-forming process. It is hard to envisage how the process documented in Figures 2.16A, B, and C would result in a well-developed mound such as shown in Figure 2.16D. Also, it is not explained why sand becomes concentrated towards the edge of the mound and silts and clays in the centre.

DISCUSSION AND CONCLUSIONS

All theories discussing hummocky terrain have a general disadvantage: the lack of detailed sedimentary analysis. There are good reasons for this. Generally, hummocky terrain is considered inhospitable and hence it is rarely cropped (hence there are no drainage ditches with exposures). Also, roads are usually constructed in adjacent flatter regions. Consequently, most exposures are restricted to minor road cuts and river banks. Most researchers mention the main sediments in studied hummocks. Often, where this appears to be basal till (an interpretation often based on compactness or clast fabric), an ice-press or subglacial ice-moulding hypothesis is assumed. Where "flow till" or sorted sand and gravel are noted, a supraglacial origin is commonly assumed.

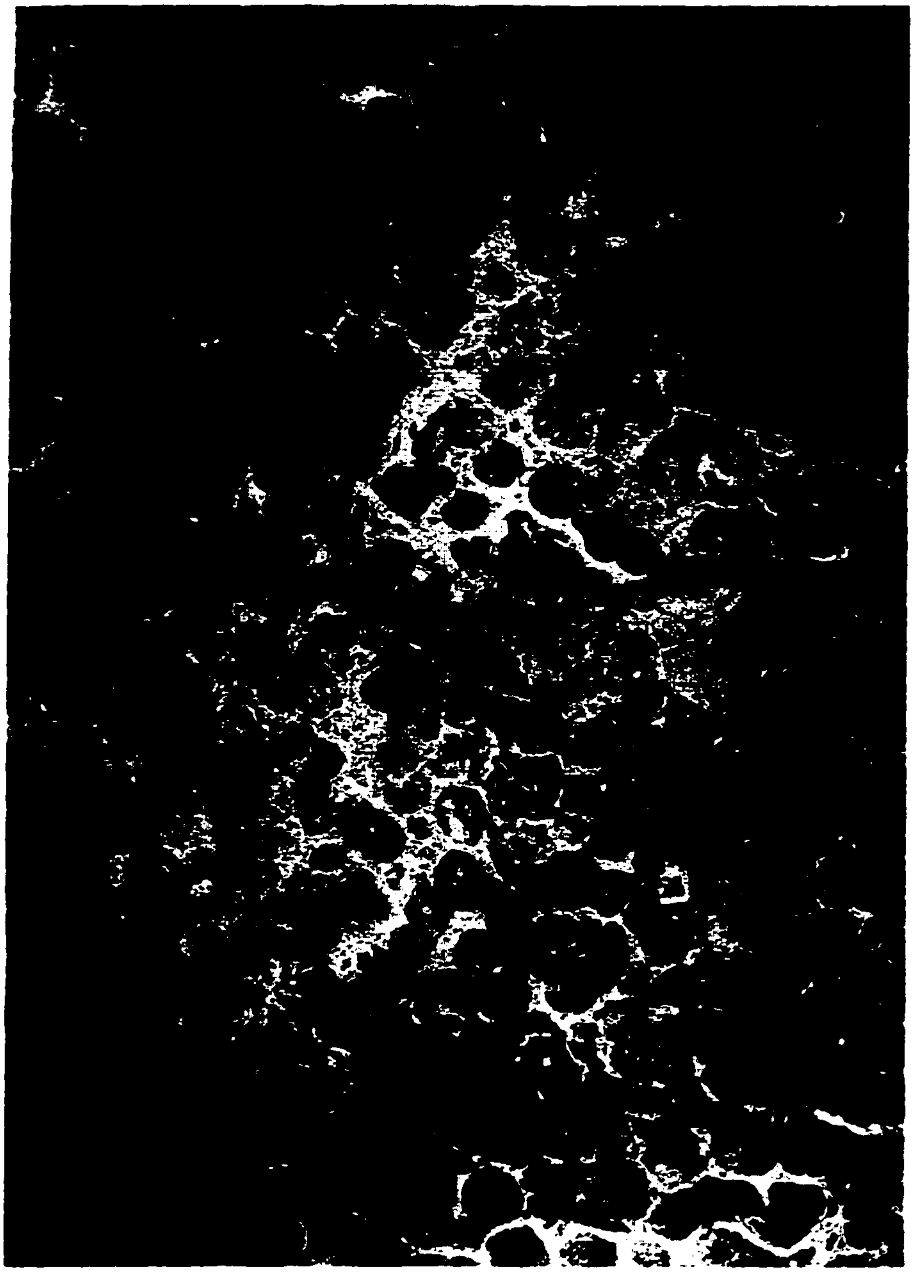

Figure 2.15: Hummocky terrain, northwest Alberta. The light coloured areas between mounds are interpreted by Henderson (1959) as representing ice wedge casts.

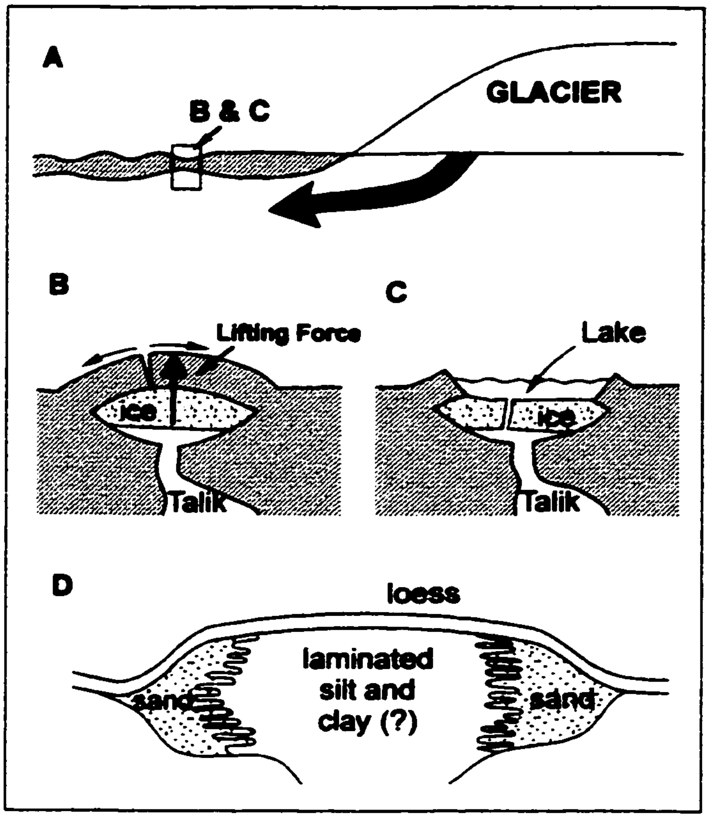

Figure 2.16: Sequence of development of Dekalb mounds. A. Groundwater flow from beneath glacier into permafrost region; B. Segregation and injection of ice layers into permafrost; C. Breaching of ice lens and formation of pingo lake; D. Generalized cross-section of resultant mound (redrawn from Flemal, 1972).

However, sediment type appears to be highly variable (Table 2.1) and while there is great consistency in morphology, there is no consistency in sediment or inferred processes. This, therefore, questions the importance of sediment and morphology relationships. The ice-press hypothesis, erosion by meltwater, the periglacial theories and, to a certain extent, the thrusting theories, all involve reworking or erosion of pre-deposited sediments, and hence all these hypotheses explain the variety of materials observed in hummocks. Supraglacial letdown of sediment would result in a single facies association and not the variety of sediment types observed. Hence, the supraglacial letdown hypothesis least explains the variety of sediments observed, especially in continental settings. The following questions therefore arise: Are all hummocks formed by the same process? Can similar features be formed by different processes? Do different hummocks represent different processes? These questions can only be answered by further analysis of hummock form, internal sediments, and relationships between hummocks and other landforms.

It also becomes apparent when evaluating the different hypotheses of hummock formation, that each type is associated with a specific geographic region. This is most apparent with meltwater erosion which appears to be restricted to the Canadian Prairies, ice-pressing, also restricted to the Canadian Prairies, and to Sweden, and thrust ridges generally restricted to modern cold environments. There are several reasons why this geographic distinction may exist. The most obvious, in glaciological terms, is that ice sheet conditions may have been (are) different in different regions. For example, thrusting near or behind the ice-margins requires cold-based conditions. In contrast, ice-pressing requires warm-based conditions. Therefore using this logic, it may be determined that the margins of modern and ancient glaciers were cold-based due to the presence of thrust moraines. The near-marginal areas of the Laurentide Ice Sheet in the plains area of North America may have been warm-based, and underlain by wet sediment if ice pressing was the main process of hummock formation there. The geographic distribution may have a simpler explanation. For example, proponents of the meltwater hypothesis have worked mainly in the Canadian Prairies and hence meltwater-eroded hummocks are primarily reported from the Prairies. Similarly proponents of the ice-thrust hypothesis have mainly worked in cold regions; therefore ice thrust hummocks are generally reported from those regions.

An important issue is whether or not it is possible to develop a single model of hummocky terrain formation that explains all hummocks. The answer is likely "no". Hummocks are clearly polygenetic. For example letdown hummocks are observed forming in modern environments (e.g., Paul, 1983; Sharp, 1985). Conversely, hummocks containing subglacial sediments have been noted in a variety of environments (e.g., Hoppe, 1952; Munro and Shaw, 1997). Of all the hypotheses discussed in this paper, each has it merits as each can explain certain characteristics of hummocky terrain. Hence, it is unlikely that a single model of hummocky terrain formation will ever be established, and perhaps a far more realistic goal is to develop a landform classification scheme which will relate specific hummock types to specific processes (e.g., let-down, erosion, glaciotectonics).

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CHAPTER 3: McGREGOR AND TEE PEE PREGLACIAL VALLEY FILLS, SOUTH-CENTRAL ALBERTA: A RECONSTRUCTION OF GLACIAL EVENTS

INTRODUCTION

All sediment and exposures discussed in this paper occur within the preglacial valley system in south-central Alberta (Fig. 3.1). Preglacial valleys are defined as those valleys that were incised prior to the Laurentide Ice Sheet invasion, and they are estimated to range in age from the Late Tertiary (the end of the Miocene) to ~ 22,000 BP (e.g., Farvolden, 1963; Campbell, 1964; Young et al., 1994). No datable material was obtained from the valleys in the study area, so their absolute ages cannot be determined. However, since they are deeply incised into the underlying bedrock, most are assumed to be relatively "young" (Farvolden, 1963). Older valleys and preglacial sediment are generally on higher erosional remnants of ancient plains, formed during the uplift of the Rocky Mountains in the early Tertiary (e.g., Farvolden, 1963). Some preglacial valleys in the study area are incised up to 200 metres (Campbell, 1964) into upper Cretaceous Horseshoe Canyon Sandstone and Bearpaw Shale (Jackson, 1981). These valleys were preferred areas of sediment accumulation prior to, and during, continental glaciation. Unlike the surrounding plains, the valleys were also protected from extensive glacial and glaciofluvial erosion (e.g., Rains et al, 1993). As a result, the preglacial valleys of south-central Alberta now contain a complex sequence of preglacial deposits and glacigenic sediment recording the regional glacial history from initial Laurentide Ice Sheet advance to deglaciation.

Three areas are discussed in this paper: 1. Carmangay in the Tee Pee Preglacial Valley; 2. Travers Reservoir also in the Tee Pee Preglacial Valley; and 3. McGregor Reservoir in the McGregor Preglacial Valley (mapped and named by Geiger, 1967; Farvolden, 1963) (Fig. 3.1). Extensive riverbank and reservoir shoreline erosion exposes up to 70 m of sediment at each site. The Carmangay exposure lies within an area of fluted terrain, draped by Glacial Lake Carmangay sediments. Sediment at Travers and McGregor Reservoirs are exposed in erosional hummocky terrain (Munro and Shaw, 1997; Appendix A).

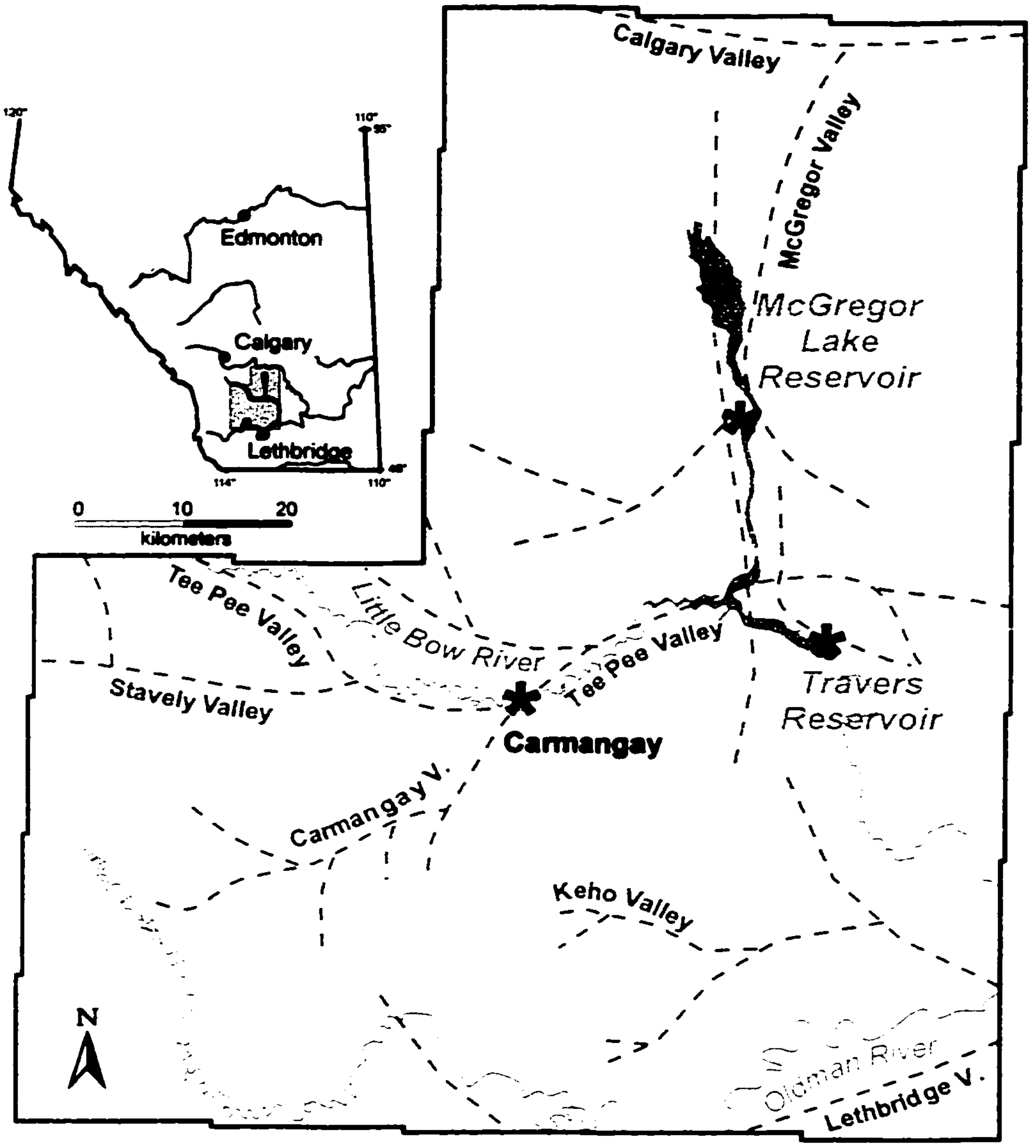

Figure 3.1: Preglacial valley drainage network within the study area. Preglacial valleys are shown as red dashed lines while the modern drainage is shown as solid grey lines. The asterisks mark sites discussed in this paper. Inset is a map of Alberta showing the location of the study area. Preglacial valleys are mapped from Farvolden (1963) and Geiger (1967).

FACIES DESCRIPTIONS AND INTERPRETATIONS

Sediment observed and interpreted in this paper is discussed as a series of lithofacies. Each facies is recognized by a set of physical characteristics that makes it distinct (e.g., sedimentary structure, grain size, colour, fabric). The sixteen facies are recognized in the preglacial fills of south-central Alberta are briefly described and interpreted below.

Facies A - moderately sorted pebble/cobble gravels with Shield clasts absent

Description

Facies A is composed of up to 5 metres of moderate to well sorted granules, pebbles, and cobbles, with some discontinuous beds of sand (Fig. 3.2A). This gravel rests on a fluted bedrock surface (Fig. 3.2B) and in some places flutes contain clasts that are cemented into the depressions. Larger clasts sit within a loose matrix of sand and fine granules. Units, which may fine or coarsen upwards, range from a few centimetres to up to a metre thick. Clasts are mainly quartzites (> 80%), with occasional limestone, and local sandstone and siltstone. They are rounded to well-rounded (cf. Folk, 1955) and are predominantly rollers with some spheres (cf. Zingg, 1935). Clast imbrication is common (e.g., Fig. 3.2C). The dip orientation of imbricated clasts is generally parallel or near parallel to the preglacial valley trends.

Interpretation

Well-rounded and imbricate clasts, and moderate to well-sorted beds, demonstrate that these gravels were transported and deposited by flowing water. This flow removed the smaller sizes, while rolling larger clasts were deposited on approximately horizontal beds with imbricate fabric. Palaeoflow directions obtained from imbricate clasts indicate flow directions between 0° and 135°. Thus flow was generally down the regional gradient and parallel to the preglacial valley axes. The change from coarse cobble beds to sand beds probably indicates lateral migration of braided channels. The gravels are devoid of clasts from the Canadian Shield and, therefore, they predate Laurentide glaciation in the study area (Stalker, 1968). Since quartzites from the Rockies are the dominant lithology, gravels were most likely deposited by streams flowing from the mountains to the west.

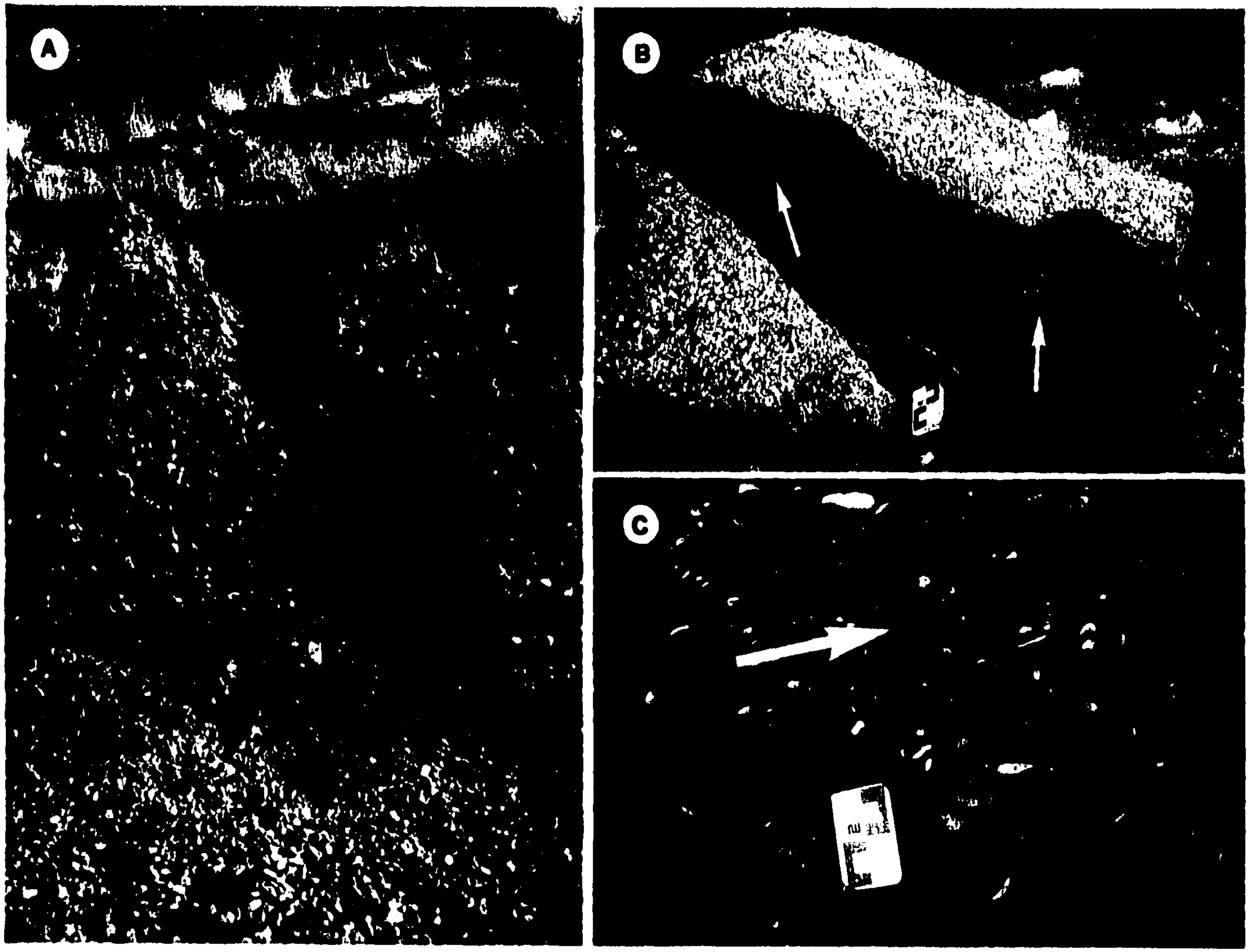

Figure 3.2: A. Typical bedded appearance of sorted beds in Facies A; B. Fluted bedrock surface - the arrows mark the flutes (this bedrock block is upside down and was moved from the floor of the gravel pit by the pit operator); C. Rounded pebbles and cobbles in a granular matrix showing imbrication indicating flow from left to right (arrow).

Facies B - disturbed, moderately sorted pebble/cobble gravels with Shield clasts absent

Description

Texture, structures, and clast type and size, are like those in Facies A. However, the beds in Facies B are disturbed by sand and silt-filled wedges and involutions. The wedges are typically near-vertical, and range from a metre to 2 metres deep (Fig. 3.3A). They are up to 60 cm across at the top of the wedge, tapering to a point at the bottom. The wedge fills are predominantly sand and silt with some granules and show faint stratification parallel to the wedge sides. Multiple wedges at a site are usually equally spaced (Fig. 3.3A).

Involutions are "bowl-shaped" sand and silt bodies within the sorted gravels. They are up to 2 m across and 2 m deep, and appear to have subsided into surrounding gravels. Pebbles and cobbles adjacent to involutions are re-oriented close to vertical (Fig. 3.3B). Yet, immediately below the involutions, gravel clasts remain near horizontal (Fig. 3.3B). Silt and sand in the involutions are generally massive though, clasts from the adjacent gravel beds have been incorporated (Fig. 3.3B).

Interpretation

Like the beds in Facies A, these gravel beds were initially deposited by powerful rivers flowing from the Rocky Mountains. However, these beds have been significantly disturbed by cryogenic activity. The wedge-shaped features are interpreted as epigenic ice-wedge casts (cf. Washburn, 1980a), and they are typical of ice wedges found in modern environments (e.g., Péwé, 1966; MacKay, 1989), and in ancient environments (e.g., Eyles, 1977). Faint stratification parallelling wedge edges indicate that the wedges opened as cracks from the ground surface. Cracks were filled by sediment from above, producing the vertical stratification. Because casts are equally-spaced, they likely form a polygonal network like the features observed in modern periglacial landscapes (MacKay, 1989).

Involutions are secondary features that result from the relative movement and re-orientation of clasts due to frost push or pull processes (e.g., Washburn, 1980b; Anderson, 1988). Both hypotheses relate to the freezing and thawing of the surrounding soil. In the frost push hypothesis, it is assumed that ice develops below a clast due to differential freezing and that ice literally "pushes" the clast up into the overlying soil. In the frost pull hypothesis, it is assumed that clast freezes into overlying soil, and when that soil heaves due to freezing, the clast is "pulled" upward with it. In either case the clast moves upward through the soil profile. Although there is debate over which one of these processes is more likely to account for clast movement, the important issue here

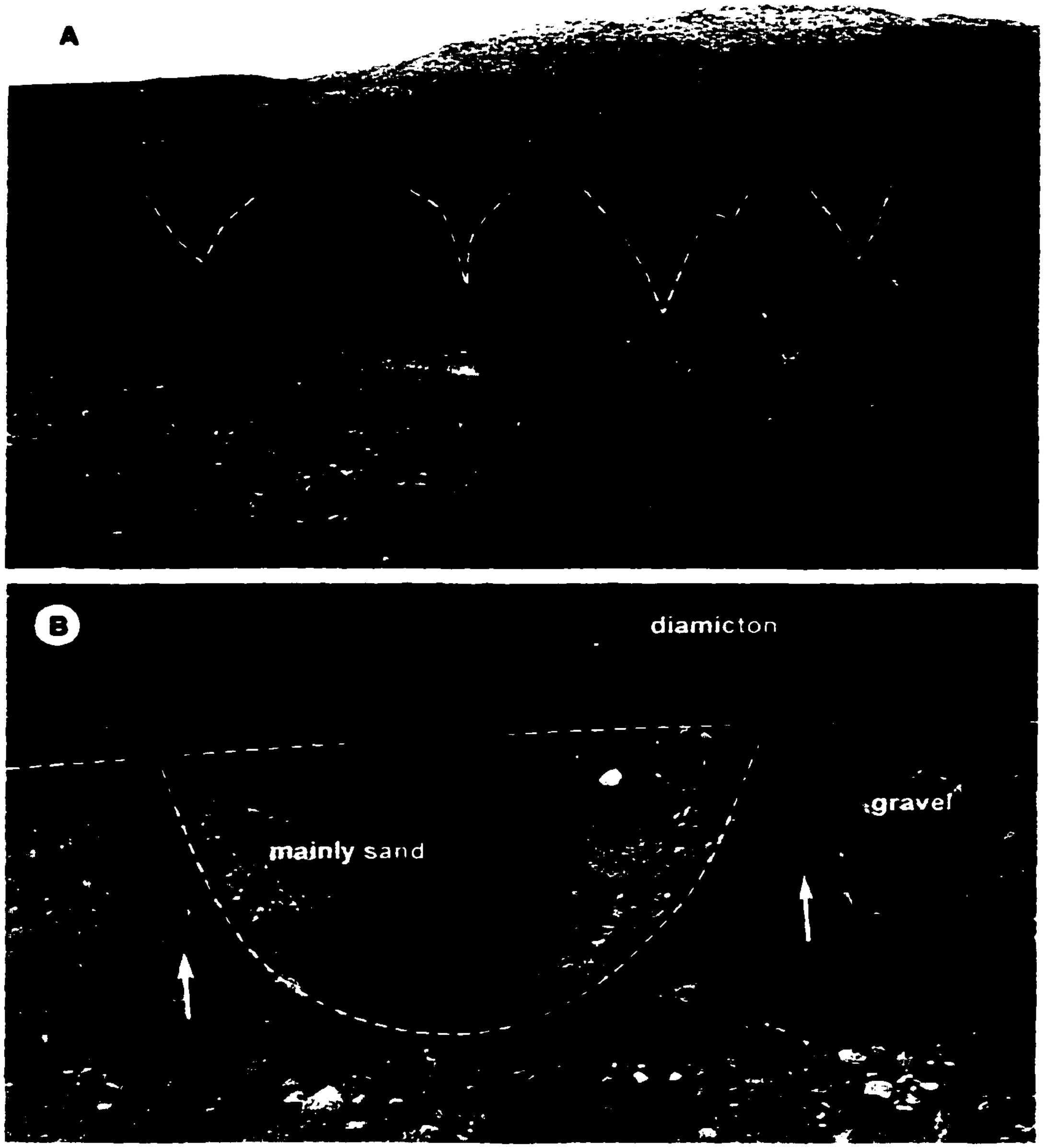

Figure 3.3: Facies B - disturbed moderately sorted pebble/cobble gravels (with no Shield clasts). A. Sorted gravel beds are cross-cut by ice wedge casts. B. Sorted gravel beds disturbed by involutions. Sand has "sunk" into the gravel, and clasts in the gravel have re-oriented themselves vertically (marked by arrows). The gravel beds are truncated and overlain by diamicton of Facies C.

is that the presence of an active layer (freezing and thawing) is necessary. Therefore, like the ice wedges, involutions are indicative of a periglacial environment. Alternatively the involutions may relate to loading of soft, saturated sediment by overlying ice.

Facies C - blue/grey clayey diamicton

Description

Facies C consists of massive blue/grey diamicton beds that disconformably overlie bedrock or beds of Facies A or B (Fig. 3.4A). The most distinguishable characteristic of the diamicton is its colour (Munsell: 2.5Y 7/2 - 2.5Y 4/1 (dry) light grey to dark grey). The diamicton is fine-grained, predominantly silt and clay, compact and, in places, fissile. It contains approximately equal amounts of Cordilleran quartzites, local sandstone and siltstone, and igneous and metamorphic rocks from the Canadian Shield. The quartzites are generally rounded to well-rounded, while local and Shield clasts are striated, faceted, and bullet-shaped (Fig. 3.4B). Clast fabrics from this diamicton are variable in strength ($0.446 < S_1 < 0.683$) with relatively inconsistent preferred orientations. However, clast plunge angles are generally low (< 10°).

Interpretation

Erosional contacts with underlying bedrock and preglacial sediments, an abundance of striated and bullet-shaped clasts, and fissility suggest these this diamicton facies is lodgement till (Dreimanis, 1982; Haldorsen, 1983; Clark and Hansel, 1989). Striated and faceted clasts indicate that abrasion played a major role during transport or after the clasts were lodged (Haldorsen, 1983). These beds are the first to contain clasts from the Canadian Shield and they probably indicate deposition by the advancing Laurentide Ice Sheet. The high content of local bedrock, Upper Cretaceous Bearpaw Shale (dark grey silty shale) (Jackson, 1981), supports the supposition that the till records local erosion and deposition together with long-distance transport of Shield erratics. This till is regionally known as the Labuma Till (e.g., Stalker, 1960). Clast fabrics from lodgement till have moderate preferred orientations (e.g., Hicock, et al., 1996). The range of orientation values from this till are not as expected for lodgement till. But, observations are limited, with samples up to 10 km apart. Thus, they may record ice flow directions governed by local topography.

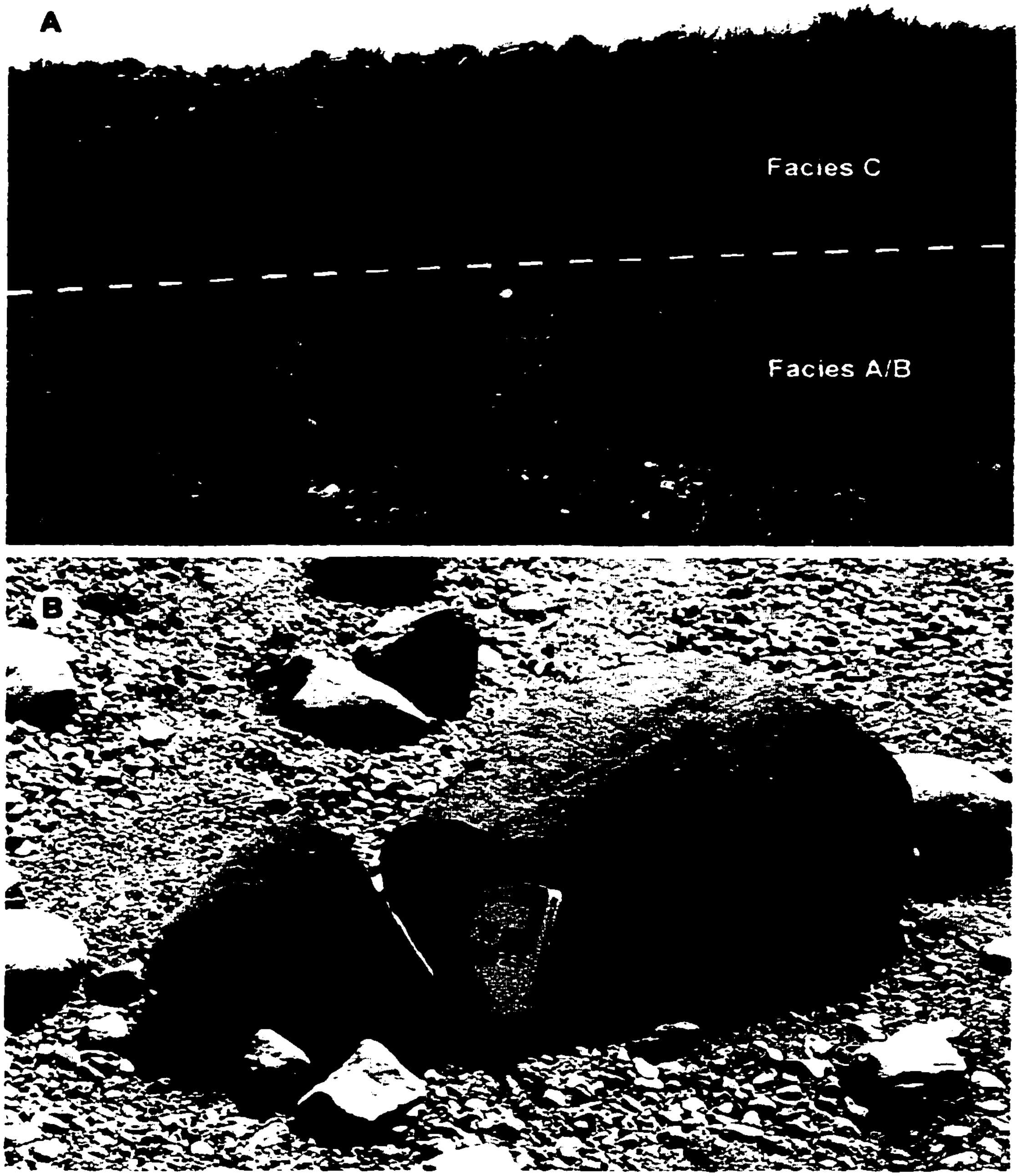

Figure 3.4: Facies C - blue/grey clayey diamicton. A. At most locations the lower contact of diamicton beds belonging to this facies is erosional. B. Clasts from Facies C beds are typically striated, faceted, and occasionally bullet-shaped.

Facies D - disturbed blue/grey clayey diamicton

Description

Beds belonging to Facies D have the same grain-size and colour characteristics as Facies C. The important difference is that the diamicton has been thrust and sheared in rafts within overlying younger beds. In places, it is folded into underlying bedrock (Fig. 3.5). Such folding is always recumbent, with fold noses pointing towards between SW and WSW (Fig. 3.5). Clast fabrics obtained from these beds are highly variable in strength, mean azimuth, and plunge.

Interpretation

Folding of the blue/grey diamicton and the underlying bedrock is considered to indicate glaciotectonism. Fold noses pointing towards SW-WSW indicate that the flow direction of the ice sheet was in a similar range of directions. Clast fabrics do not preserve the direction of ice movement as is expected of tills that are folded and thrust with relatively low total strain.

Facies E - disturbed blue/grey clayey diamicton with soft-sediment clasts

Description

Again, grain size, lithology and colour of these beds are the same as for Facies C, and hence also D. These beds are considered separately from those of Facies D because the style of disturbance is different. Deformation is primarily as diapirs and injection structures into overlying sediments. It is particularly common where beds of the blue/grey diamicton are thick (>2 m) (Fig. 3.6). Diapirs can be up to 10 m across and 10 m high (Fig. 3.6). Typically, the soft-sediment clasts are either massive silty diamicton (Facies F) or rippled sand beds (Facies M). They are up to 5 m across (Fig 3.6), angular and preserve primary sedimentary structure. At the clast edges small intrusions, up to 50 cm long, penetrate the clasts (Fig. 3.6B). These dykes typically exploit bedding planes.

Interpretation

The style of deformation in these beds is mainly as diapirs of clayey diamicton into silty or sandy sediment. This suggests that loading of the clay-rich sediment may have been the most important influence on diapirism. The blue/grey diamicton is, in places, overlain by thick beds of climbing ripple cross-lamination (see Facies M). These are the beds that are now incorporated into the diamicton as soft sediment clasts. The sand beds were likely deposited rapidly, and rapid loading

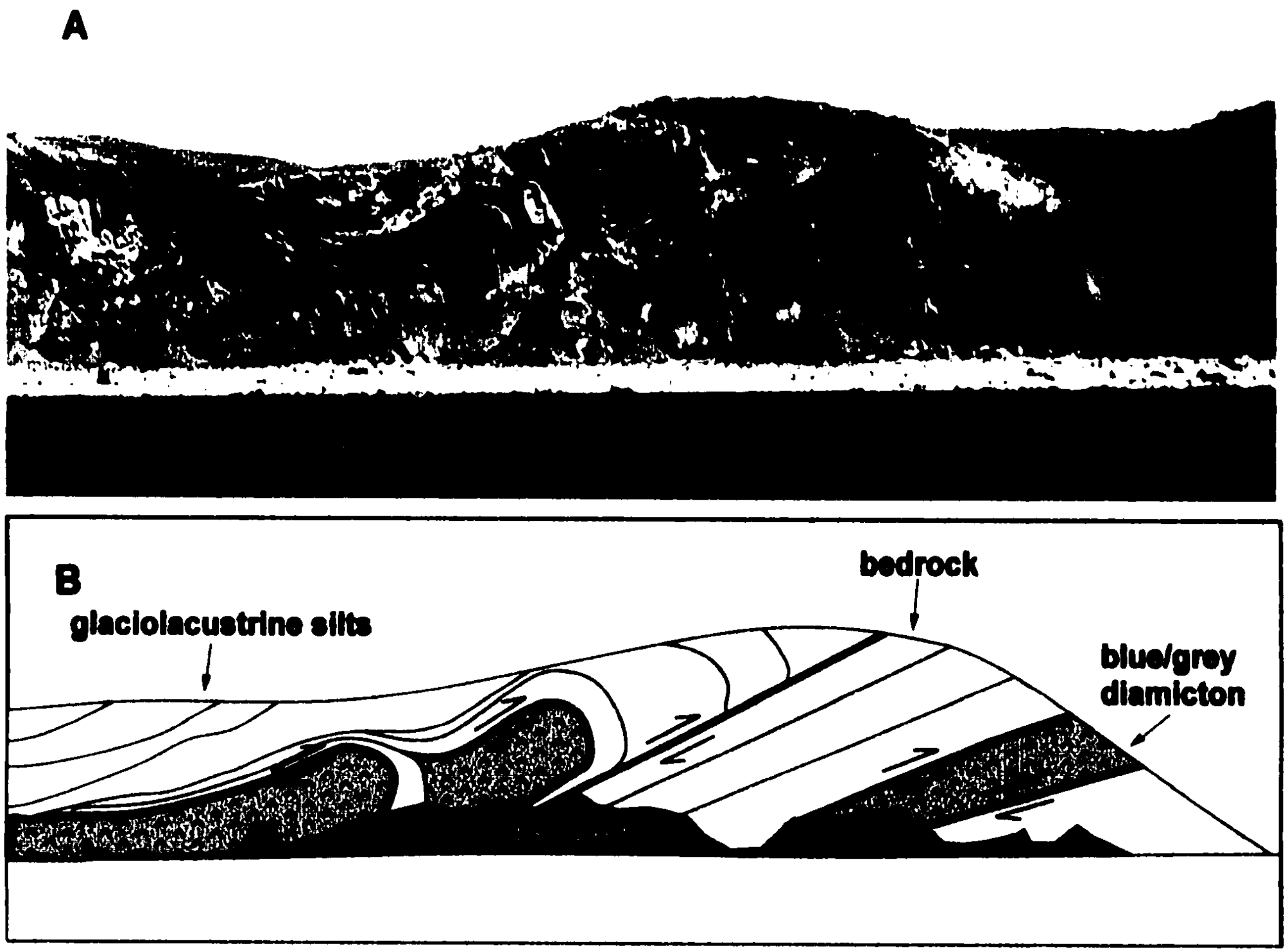

Figure 3.5: Facies D - disturbed blue/grey clayey diamicton. A. Photograph demonstrating the folding of bedrock and the blue/grey diamicton. B. Interpretive diagram of exposure in A.

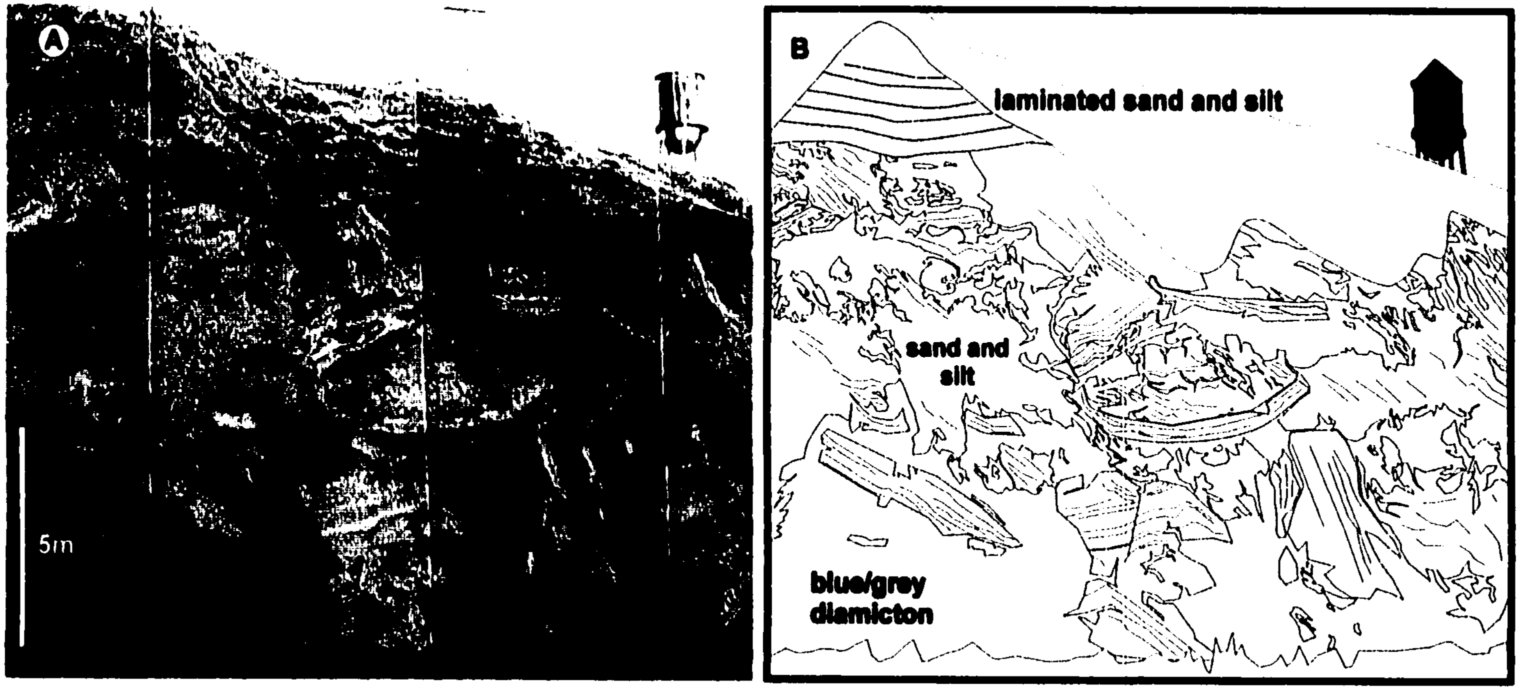

Figure 3.6: Facies E - disturbed blue/grey diamicton with soft sediment clasts. This exposure at Carmangay demonstrates how the blue/grey diamicton has diapirically intruded through overlying sorted sand and silt beds and incorporated them into the diamicton as soft sediment clasts. Many of the soft clasts maintain sedimentary structures.

may have been responsible for some of the diapirism. However, it is difficult to imagine 5 m of sand deposition causing diapirs over 10 m high. Ice loading may have influenced the diapirism. However, if it did, then the ice was not moving, as the diapirs are not overturned in the direction of loading. The cause of this diapirism is discussed later in this paper.

Facies F - massive silty diamicton

Description

Massive, silty diamicton is the most common sediment observed in the preglacial valley fills of south-central Alberta. Individual beds are up to 4 m thick, with erosional and undulating lower contacts (Fig. 3.7). Grain size analysis gives ~ 55% silt, ~ 30 % sand, and ~15 % clay. These beds are visually distinct from the diamicton beds of Facies C by their paler colour (Munsell: 2.5Y 6/4 - 10YR 6/3 (dry) light yellow brown to pale brown). Clast content is < 2 %, with clasts are of Rocky Mountain, local, and Canadian Shield origin. Clast size varies from granules to boulders, the degree of roundness varies from angular to rounded, and rollers, spheres, discs and rods are all present (cf. Zingg, 1935). At most sites, several of these beds are stacked on top of each other to create the major thickness of the sediment observed in the preglacial valleys. Individual units are commonly bound by laminated sand or silt.

Interpretation

These diamicton beds are interpreted as multiple, stacked, debris flow deposits which were deposited in an aqueous environment. Undulating erosional lower contacts, overlying silt beds, and highly variable clast fabric strengths and plunge angles support this conclusion (cf. Middleton, 1970). Also, the variety of clast shapes, and the variance of roundness suggest that the sediment in the debris flows was reworked from other beds.

Facies G - massive silty diamicton with blue/grey diamicton clasts

Description

Beds belonging to Facies G are generally uncommon in the preglacial fills. Generally, the massive silty diamicton has the same characteristics as Facies F, and the blue/grey diamicton clasts have the same characteristics as Facies C (Fig. 3.8). These beds are distinguished from Facies E, because while the blue/grey diamicton appears to be incorporated into the massive silty diamicton, Facies E displays massive silty diamicton within the blue/grey diamicton. The blue/grey "clasts"

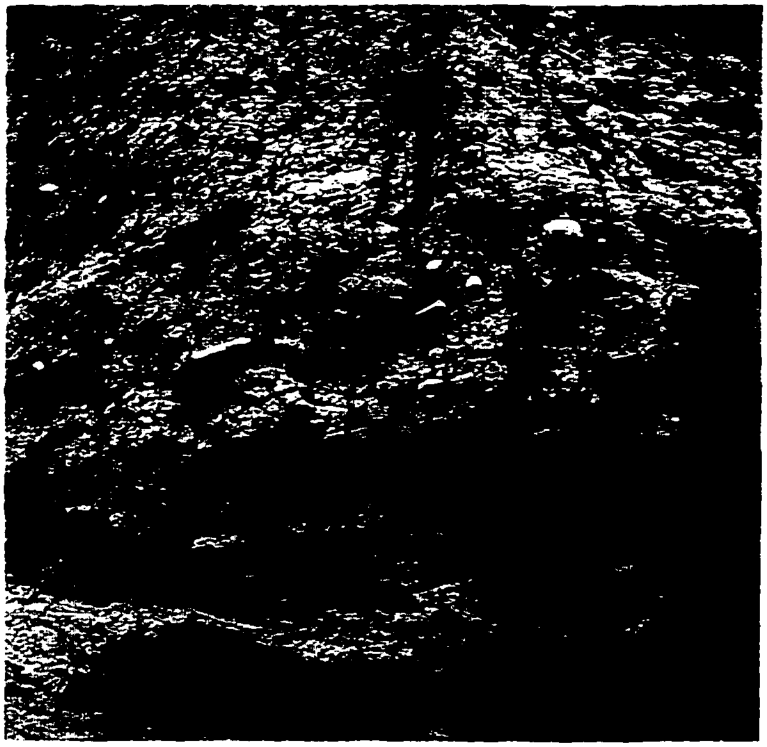

Figure 3.7: Facies F - massive silty diamicton. Massive diamicton beds are common in the preglacial valleys of south-central Alberta. Commonly, their lower contacts are erosional. Here the diamicton disconformably overlies cross-laminated sands (Facies M).

Figure 3.8: Facies G - massive silty diamicton with clasts of blue/grey diamicton. Although both diamictons are of similar grain size, the two diamictons are easily distinguishable by their colour.

appear rounded with occasional veins intruding into the surrounding silty deposits (Fig. 3.8).

Interpretation

Beds belonging to Facies G were not observed together with beds of Facies E. In spite of this, it is suggested that the blue/grey diamicton "clasts", are not actually clasts, but are dikes or diapirs intruding the massive silty diamicton. For instance, in Figure 3.8, the large grey/blue "clast" is likely a diapir that is not "rooted" in the exposure. The small veins are smaller injection structures. It is probable that beds of Facies E lie below the exposure in the preglacial valley fills.

Facies H - massive silty diamicton with some sorted beds

Description

The main silty diamicton beds in Facies H resemble beds belonging to Facies F in terms of colour, texture, and grain size. Like Facies F, clast fabrics are also highly variable. Yet, this diamicton is distinct in that it contains sorted beds a few centimetres thick (Fig. 3.9). The sorted beds are generally composed of sand or silt, and generally show cross-lamination and ripple formsets. Although many of these beds are laterally continuous over tens of metres, generally they pinch out over 2-3 m.

Interpretation

Like facies F beds, these diamictons are interpreted as multiple stacked debris flows. However, significant breaks occurred between deposition of individual debris flows. Intervening periods of low sedimentation rates are documented by traction deposition (ripples) and deposition from suspension (silt beds).

Facies I - massive silty diamicton with small (<1 cm) soft sediment clasts

Description

The diamicton in Facies I has the same physical characteristics as beds belonging to Facies F and H. However, these beds are significantly different in that small soft sediment clasts "float" within the diamicton matrix (Fig. 3.10). Soft clasts are composed of massive clay or silt (Fig. 3.10A), and primary bedding structures are commonly preserved within them (Fig. 3.10B). Laminations in the soft clasts are usually rhythmic, and mostly clay with some silt. The diamicton beds are up to 2 m thick and are usually overlain by laminated silt.

Figure 3.9: Facies H - massive silty diamicton with some sorted beds, overlain by Facies K, at Carmangay.

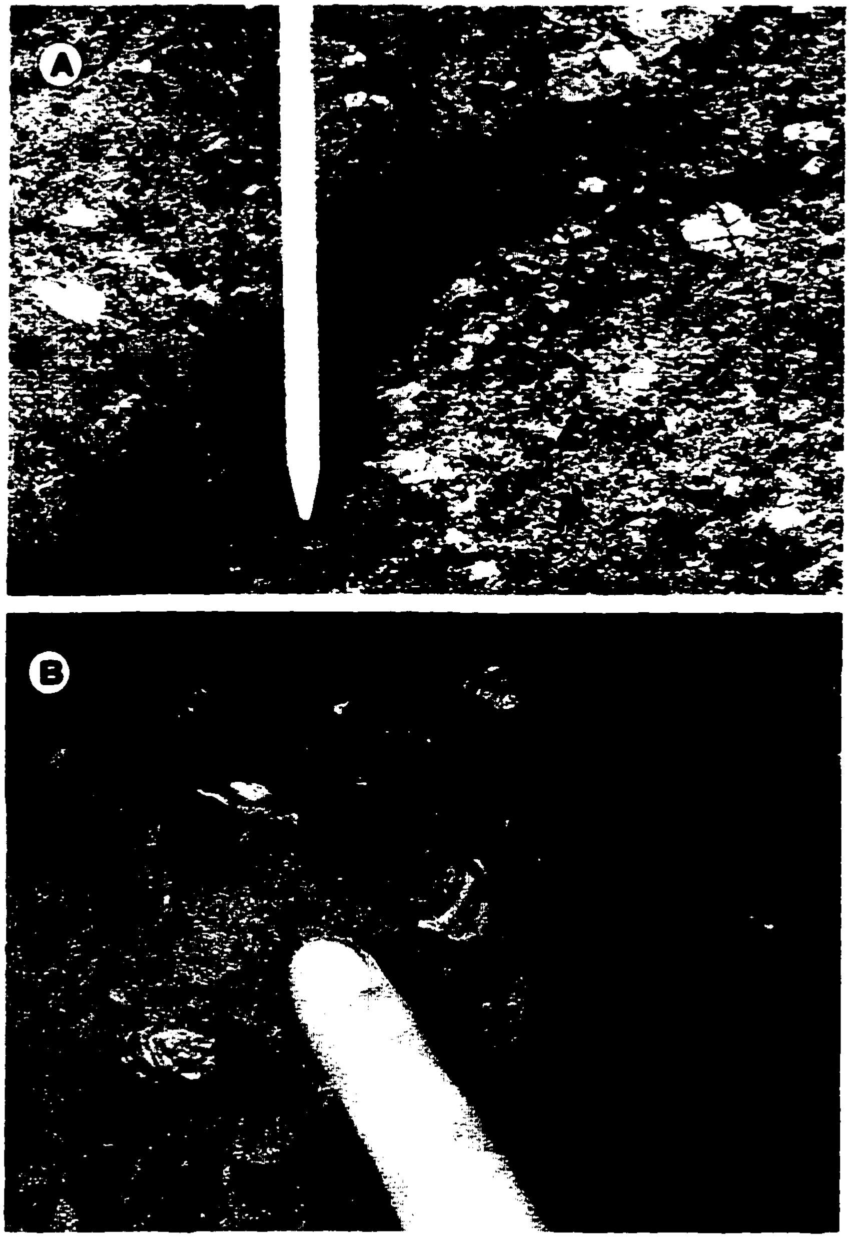

Figure 3.10: Facies I - massive silty diamicton with small soft sediment clasts. A. Soft sediment clasts are structureless. B. Sedimentary structures within soft sediment clasts are preserved.

Interpretation

The soft sediment clasts within these silty diamicton beds strongly supports a turbidite or debris flow origin for the diamicton beds (cf. Middleton, 1970). The flow was likely less cohesive than those that deposited Facies F and H beds, and may have been more representative of wetter slurry flow. The flow was of sufficient velocity to rip up bedded clay. These rip-up clasts were probably not transported over significant distances as bedding is preserved within them. Significant transport and attenuation would have destroyed the delicate structures preserved in the clasts. Diamictons with rip-up clasts are common in glacial lake sediments (e.g., Rust and Romanelli, 1975; Postma, 1984). Overlying silt beds likely represent the waning stages of deposition where silt transported in suspension above the slurry flow settled from suspension.

Facies J - diamicton/silt couplets with large (2 - 6 cm) rip-up clasts

Description

Diamicton/silt couplets typically range from 5 to 20 cm thick (Fig. 3.11). The diamicton beds comprise approximately 70 - 90% of each couplet. The composition of the diamicton beds is similar to those belonging to Facies I: massive silty diamicton with some small rip-up clasts. However, these beds are significantly thinner than Facies I diamictons. Silt beds overlying the diamicton beds are well-developed, and in some places several silt beds make up the top of the couplet. Some silt beds have minor normal faults with displacements up to 1 cm. Some are convoluted or intrude into the overlying diamicton in flame structures. These flames are usually no more than 1 or 2 cm high. Significantly, some large (2-6 cm) soft clasts were deposited within the diamicton beds and these have been rounded (Fig. 3.11). These clasts do not have primary bedding structures preserved.

Interpretation

Facies J is interpreted as the distal equivalent of Facies I. Its composition is similar, but the diamicton beds in Facies J are significantly thinner than those of Facies I. Also, silt deposition is more prominent, indicating higher deposition rates from suspension.

Convolutions and flame structures support a gravity flow origin for the diamicton beds. These features usually form when there is loading of fine sediment (in this case silt) by coarser beds (in this case diamicton) in a subaqueous environment. The disturbance is the direct result of density instabilities between liquefied and non-liquefied sediment (Allen, 1982).

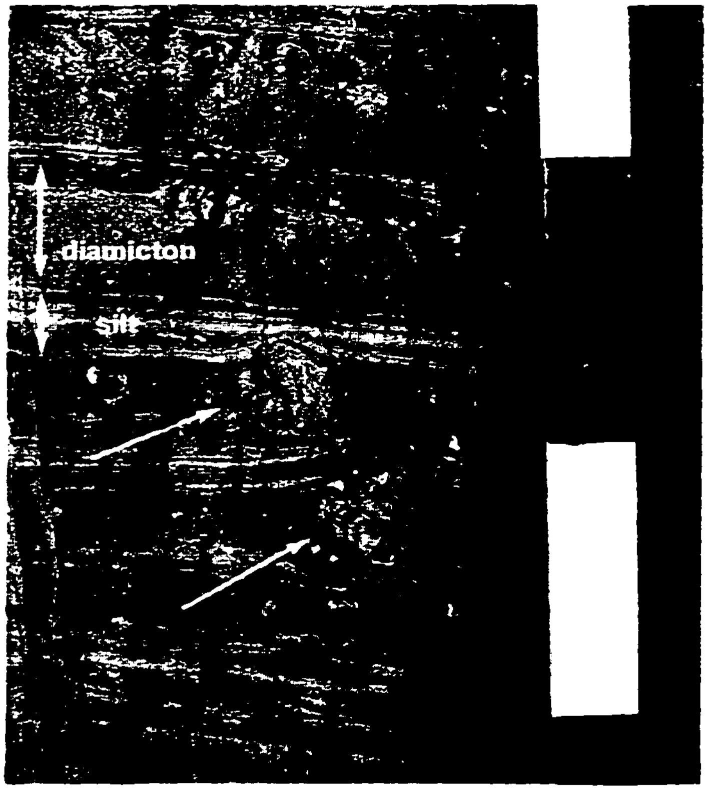

Figure 3.11: Facies J - diamicton and silt couplets with large, rounded, soft-sediment clasts (arrows).

Facies K - silt/clay couplets

Description

Facies K is composed of up to 2 metres of rhythmically-bedded silt and clay at any one site (Figs. 3.9 and 3.12). Each couplet is composed of a silt bed, up to 10 cm thick, overlain by a significantly thinner clay bed. Within a given sequence, couplets are usually thicker towards the bottom (~ 10 cm) and thinner higher in the sequence (< 1cm). These beds are generally undisturbed towards the top of exposures and they overlie most other sediment types. If they lie between diamicton beds, or where deposited in association with other facies, silt/clay couplets are commonly folded and sheared.

Interpretation

Silt and clay couplets are typical of distal glaciolacustrine sedimentation. The silt is generally attributed to higher supraglacial melt rates, and thus higher transport and sedimentation rates during the summer. Clay caps are attributed to suspension settling of fines during late fall and winter when melt rates were low. Contorted beds and folding are a direct result of loading and shear stresses from debris flows, or even glaciotectonics.

Facies L - laminated silt

Description

Laminated silt beds are extensive in all exposures. They are found at any level within the exposures, and may overlie, or underlie, other facies (Fig. 3.13). The beds range from a few centimetres to ~ one metre thick. Occasional clay or sand laminae are contained within the silts. Diapirs and flames structures are common attributes of the silt beds (Fig. 3.13B).

Interpretation

Silt beds in Facies L are interpreted to represent periods of suspension deposition in a subaqueous environment. Their close association with gravity flow deposits, and the presence of diapirs and flame structures, support subaqueous deposition for these beds.

Facies M - cross-laminated silt and sand

Description

Cross-laminated silt and sand beds are common in the preglacial valley fills of south-central

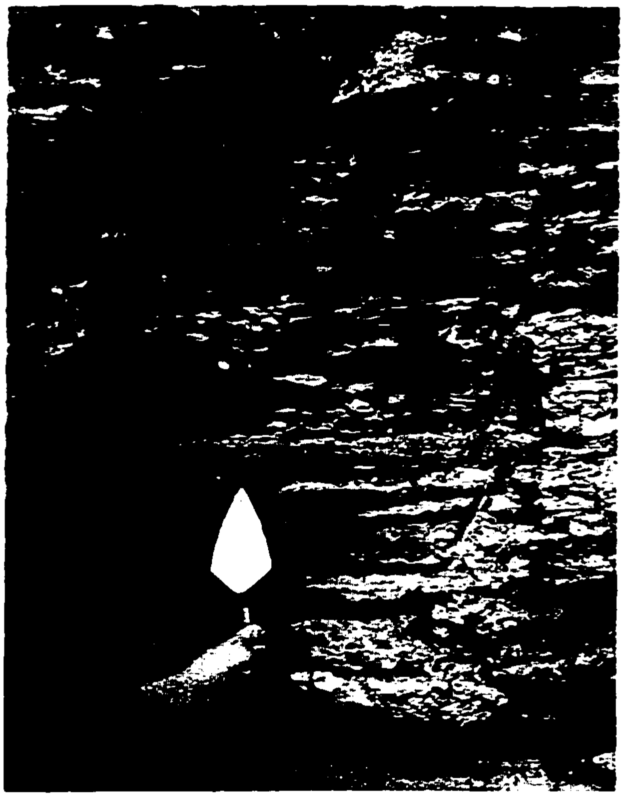

Figure 3.12: Facies K - silt/clay couplets. The light-coloured beds are silt, and the dark-coloured beds are clay. Bed thickness generally decreases upward.

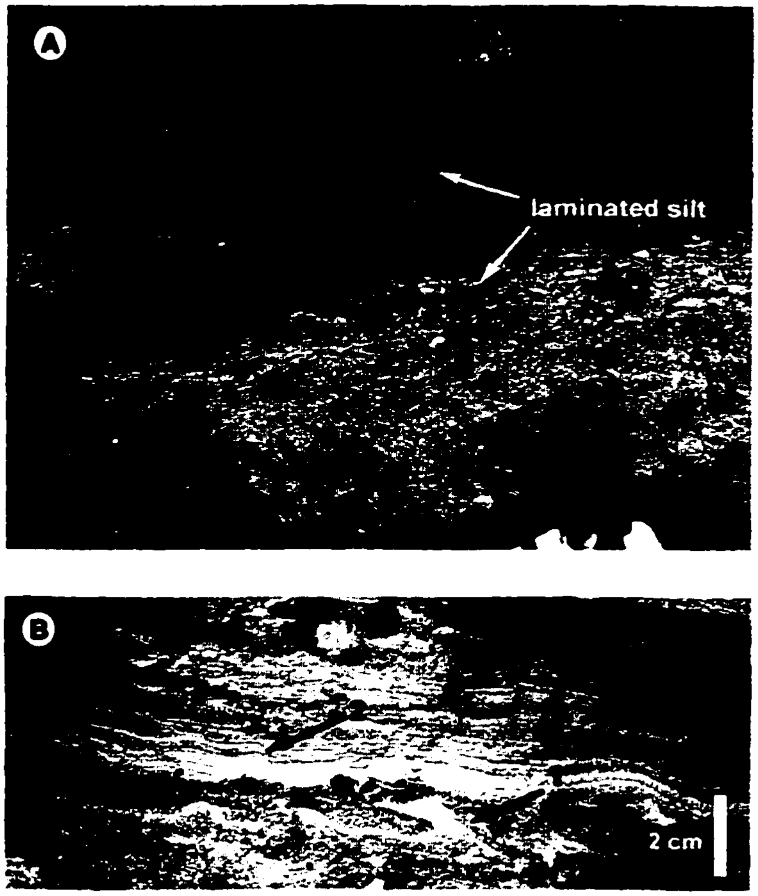

Figure 3.13: Facies L - laminated silt. Laminated silt can be bounded by any sediment type. A. laminated silt appears between Facies O beds. B. Laminated silt overlies Facies J (darker beds). Silt beds have been loaded and sheared by overlying sediment, evidenced by the flame structures (1). Normal faults (2) indicate consolidation of underlying beds.

Alberta. Beds can be as little as 10 cm thick, but they are more commonly up to 3 m thick. All three types of ripples, Type A, B, and C (erosional stoss, depositional stoss, and sinusoidal respectively) are present (cf. Jopling and Walker, 1968; Allen, 1982; Ashley et al., 1982). Types A and B climbing ripple drift (Fig. 3.14) are most common in gradational sequences. Beds are commonly disturbed. Cross-laminated beds are overlain and underlain by all facies other than Facies A, B, and C.

Interpretation

Thick cross-laminated beds are common in turbidite sequences (e.g., Bouma, 1962), deltaic environments (e.g., Williams, 1971), and ice-contact and proglacial subaqueous environments (e.g., Jopling and Walker, 1968; Rust and Romanelli, 1975; Gorrel and Shaw, 1991). Experiment has demonstrated that thick climbing ripple sequences can be deposited in only a few hours (Ashley et al., 1982). Hence, the cross-lamination observed in exposure in south-central Alberta was probably deposited in a subaqueous environment and was deposited in a matter of hours.

Facies N - sorted pebble/cobble beds with Shield clasts

Description

Gravel beds are generally less common than most of the other facies described thus far. They generally occur as discrete beds, lenses, or channel fills, and are usually no more than a metre thick. They range from moderately well-sorted (Fig. 3.15) to very well sorted. Grain size ranges from coarse sand to boulders, and beds fine both up, and down. Most clasts are rounded to well-rounded. Lithologies are mixed, with approximately 60% Shield clasts, 30% quartzites, and 10% local lithologies.

Interpretation

As the beds in Facies N are generally well-sorted and clasts are generally well rounded, these beds represent glaciofluvial transport and deposition. Because beds are generally isolated as distinct lenses, channels, or channels were likely short-lived and became plugged with sorted sediment. This suggests that the subglacial channel network was unstable, with channels opening and closing relatively rapidly.

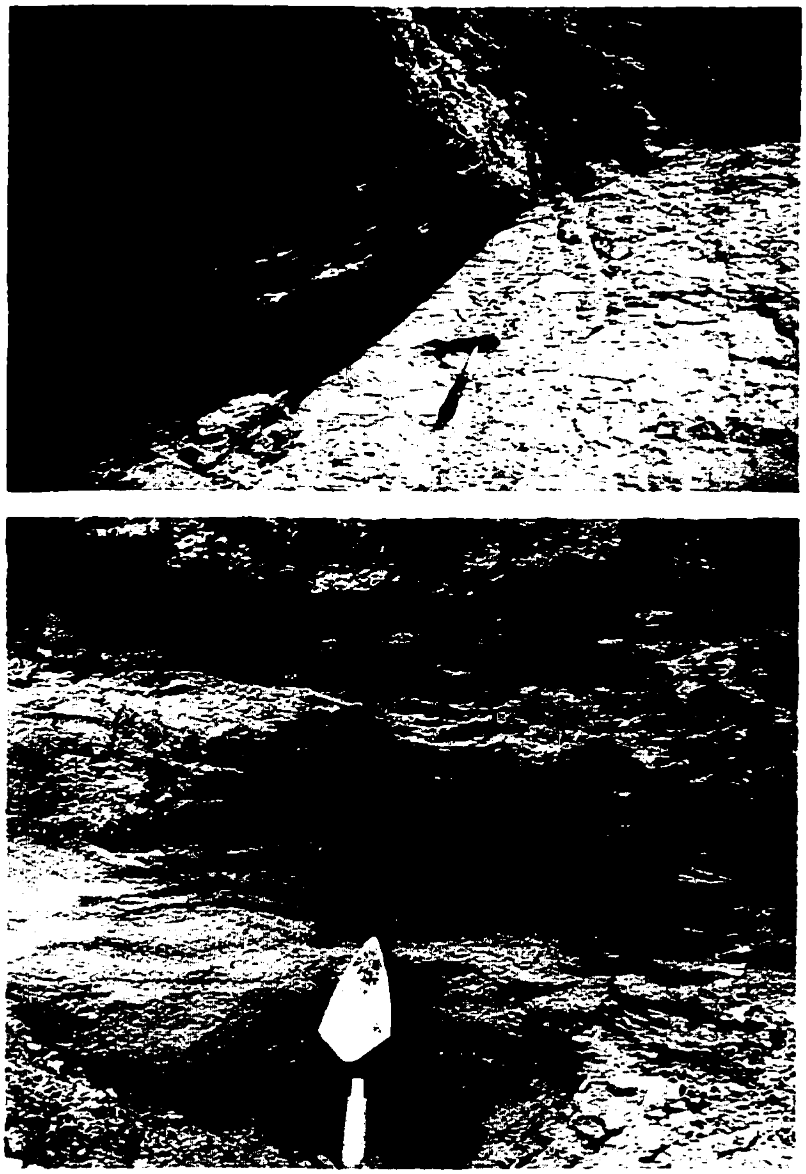

Figure 3.14: Facies M - rippled silt and sand. A. Type B cross-lamination which have been upturned and subsequently truncated by a massive silty diamicton (Facies F). B. Type A and B cross-lamination is truncated by a massive silty diamicton (Facies F).

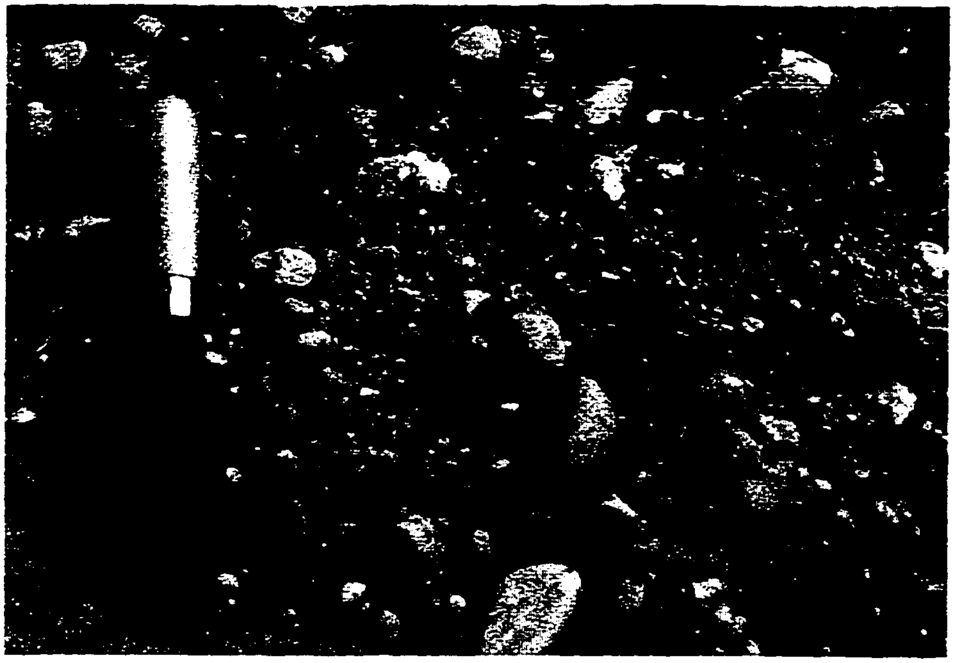

Figure 3.15: Facies N - multimodal sorted pebble/cobble beds with Shield clasts.

Facies O - silty diamicton with laterally continuous sorted beds[1]

Description

Facies O is composed of alternately bedded units of laterally extensive, massive, fine-grained diamicton, and thin, continuous beds of sand or silt (Fig. 3.16). Each diamicton bed is of similar thickness (5 - 20 cm), and each sand or silt bed is of similar thickness (millimetres to a few centimetres thick). Beds extend over tens to hundreds of meters, with little variability in bed thickness over that distance. Each diamicton and overlying silt or sand bed, is a couplet in a rhythmically-bedded sequence. The diamicton beds are moderately compact and composed of up to 30% clay and 40% silt. They are distinguished by shades of greyish brown [Munsell: 2.5Y 3/2 (moist) - 2.5Y 5/2 (moist)]. Some clasts are striated, sizes vary from granules to boulders, and shape is variable (spheres, rollers, and blades) and roundness (angular to very well rounded). Quartzites dominate the very rounded category, whereas the clasts from the Canadian Shield, as well as the local clasts, tend to dominate the subangular category. Where large boulders are observed in exposure, there are usually erosional sand-filled scours below the boulder (Figure 3.16 B and C). Thirty eight clast fabrics obtained from these beds are mostly well oriented, with high principal eigenvalues, and consistently low plunge angles. Plunge orientations are also consistently towards the ENE. All beds in Facies O are generally *in situ*, although large-scale folds do disrupt some beds.

Interpretation

Consistently well-orientated fabrics, striated clasts, preservation of sand strata, and draping of sand and diamicton strata over clasts indicate that the diamicton beds in Facies O are subglacial melt-out till (cf., Lawson, 1979; Shaw, 1982). Laterally extensive, sorted strata are interpreted to represent decoupling of the ice from its bed with water flow between the ice and the bed. Because the sorted beds are laterally continuous, they document small-scale sheet flow. Sheet flow requires water storage, at least over the area where the sheet flowed. This water was shallow, no more than 20 cm deep, as indicated by the scouring on the underside of boulders that were suspended from ice into the escaping flow. Cycles of meltwater storage and drainage resulted in this rhythmic alternation of till and sorted beds, possibly representing annual sedimentation (see chapter 4).

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[1] Extensive descriptions, and interpretations, of the beds in this facies are provided in chapter 4.

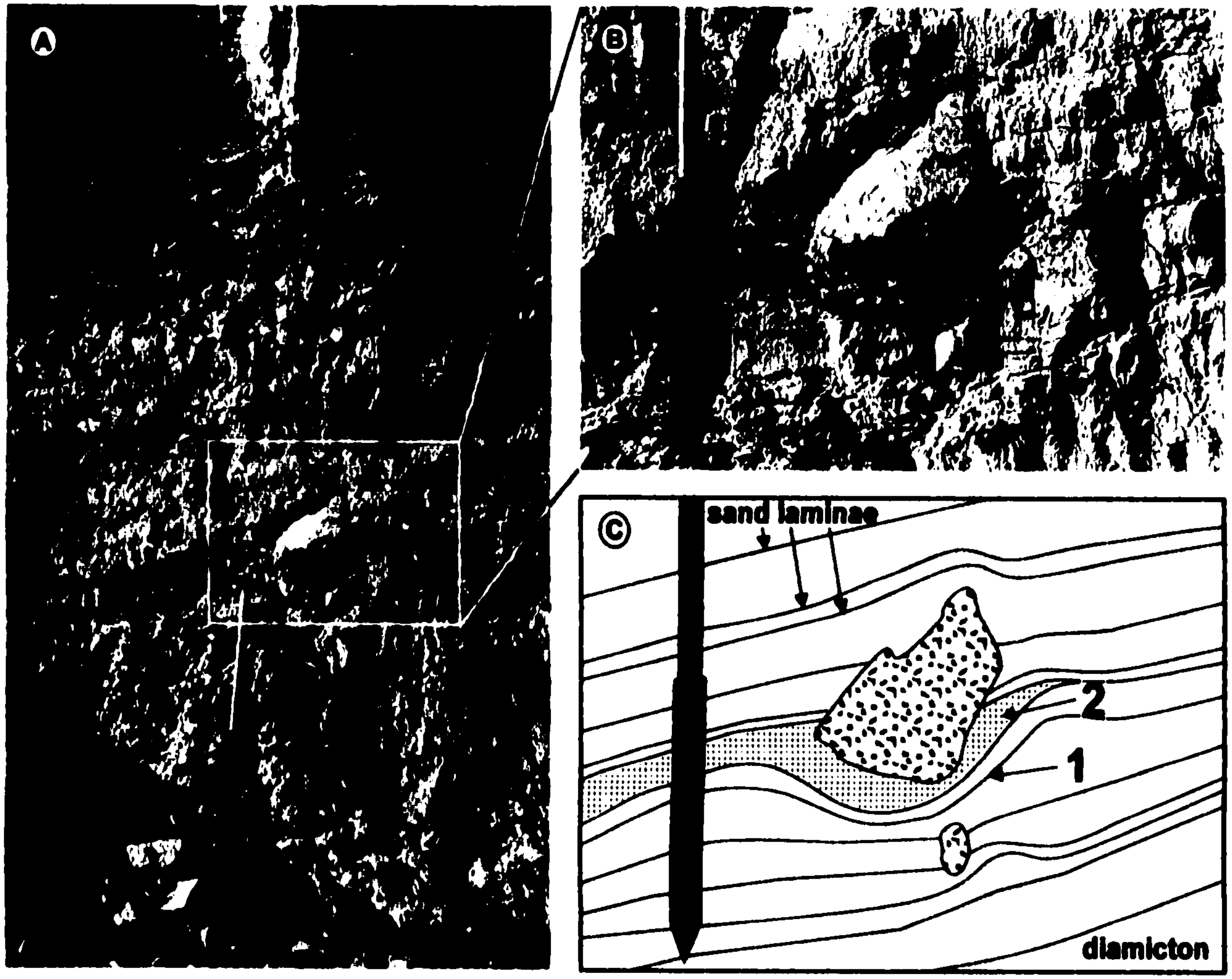

Figure 3.16: Facies O - silty diamicton with laterally continuous sorted beds. A. Alternating diamicton (thick beds) and sand (thin partings). The boulder in the centre of the photograph is shown in detail on B. B. Boulders often have sand-filled scours below them that cut into underlying diamicton units. Two phases of scouring took place under this boulder. The first scour (1) is lined by a thin unit of sand and then infilled with diamicton. The second scour (2), cuts into that diamicton indicated by the thinning of the diamicton below the boulder. This scour is filled with sorted sand.

Facies P - massive silt

Description

Where present, massive silt deposits ***always*** occur at the top of an exposure (Fig. 3.17). Beds range from a few centimetres to 2 metres thick and are generally loosely consolidated. Grain size is predominantly silt, although minor quantities of sand and clay are also present. There is no obvious stratification in the beds but often there are horizontal bands of reddish grey staining.

Interpretation

Beds belonging to Facies P are interpreted as aeolian loess. Their loose and massive nature, and their presence at the top of sedimentary sequences only, identify them as loess (Vreeken, 1993). The reddish grey staining is likely the result of palaeosol development.

EXPOSURES IN THE PREGLACIAL VALLEYS

Tee Pee preglacial valley at Carmangay

The Carmangay exposure is large at approximately 500 m long and up to 70 m high (Fig. 3.18). It is immediately northwest of the town of Carmangay, along an extensive cutbank of the Little Bow River. The exposure is immediately downflow of the confluence of the Tee Pee and Stavely preglacial valleys (Fig. 3.1). The quality of the exposure is exceptional in the upper 25 m (Fig. 3.18) but slumps cover much of the lower reaches. In spite of the excellent quality of the exposure, and the excellent access, the site has not been previously studied in detail. Stalker (1961) mentioned that there were three tills in the exposure, though he did not provide criteria for the identification of these, nor did he indicate the age, or the regional significance, of the tills.

Four sedimentary logs are presented for the Carmangay exposure (Fig. 3.19). All of the sedimentary facies described in this paper are present, except for Facies A and B. The exposure is divided into four major assemblages (Figure 3.19).

The lowermost assemblage is comprised of beds belonging to Facies C, D, E, and M. That is, the lowermost reaches of the exposure are dominated by blue/grey diamicton, and thrust and disturbed blue/grey diamicton. Where the diamicton has intruded through overlying cross-laminated sand beds, it has incorporated sand as soft sediment clasts. This assemblage is interpreted as deposition of clay-rich lodgement till, which was subsequently glaciotectonically thrust in rafts into the overlying sediment. Loading resulted in the diapirism of the clay-rich till into the overlying

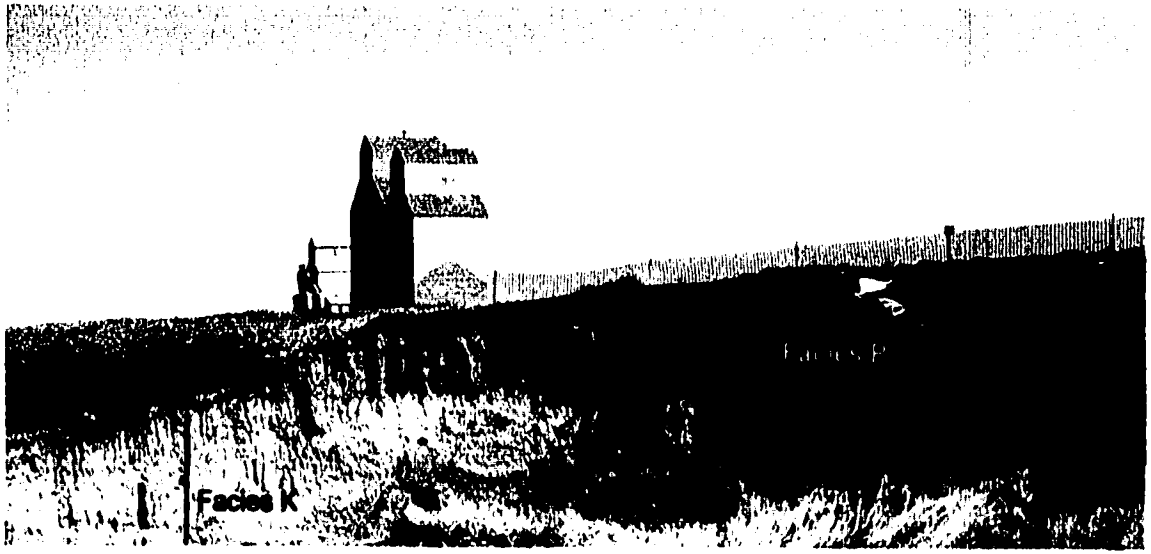

Figure 3.17: Facies P - massive silt. Massive silt beds only ever occur at the top of exposures. They can be up to 2 m thick, and often overlie beds of Facies K.

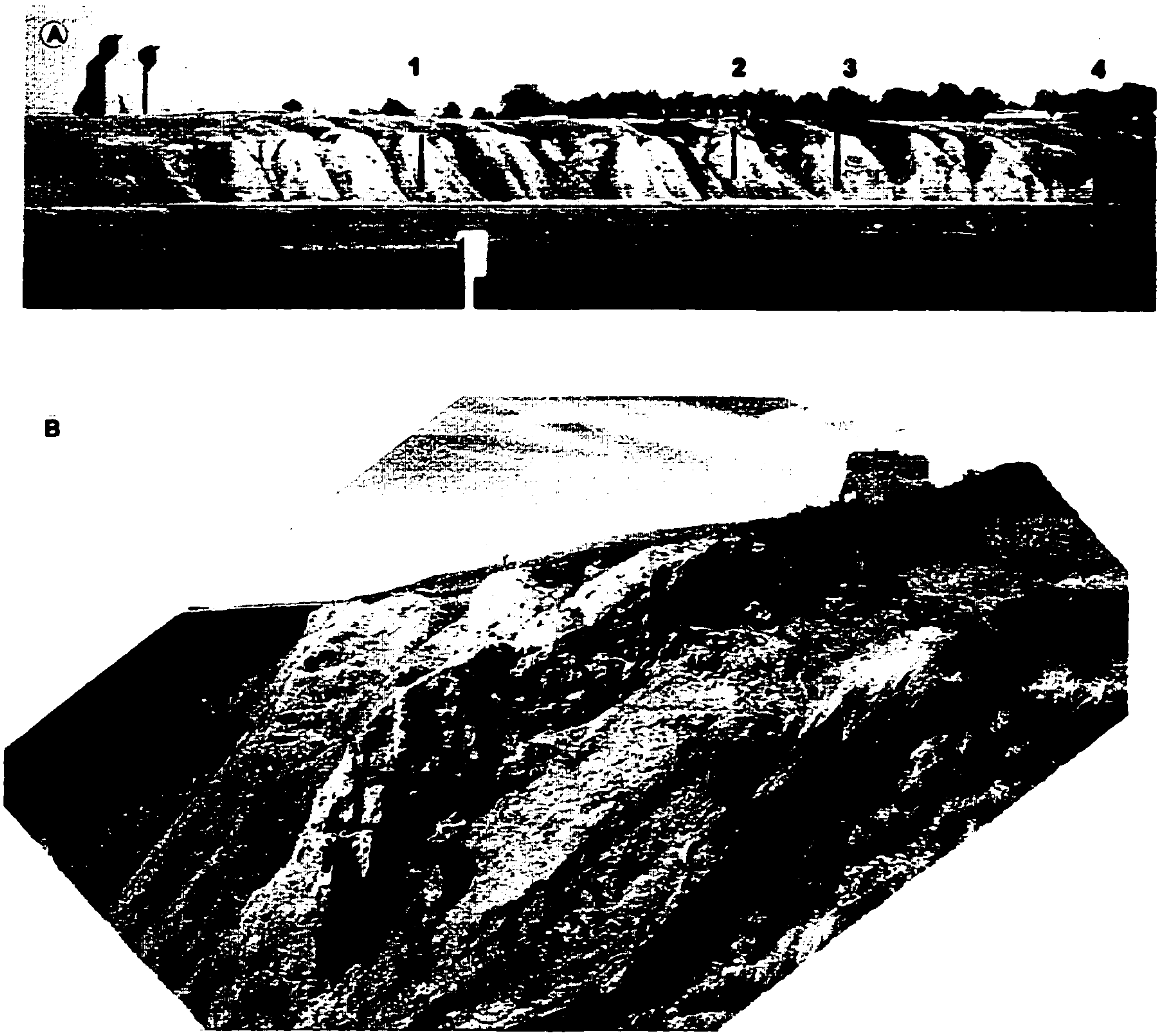

Figure 3.18: A. Location of transects at Carmangay. B. Transect #2.

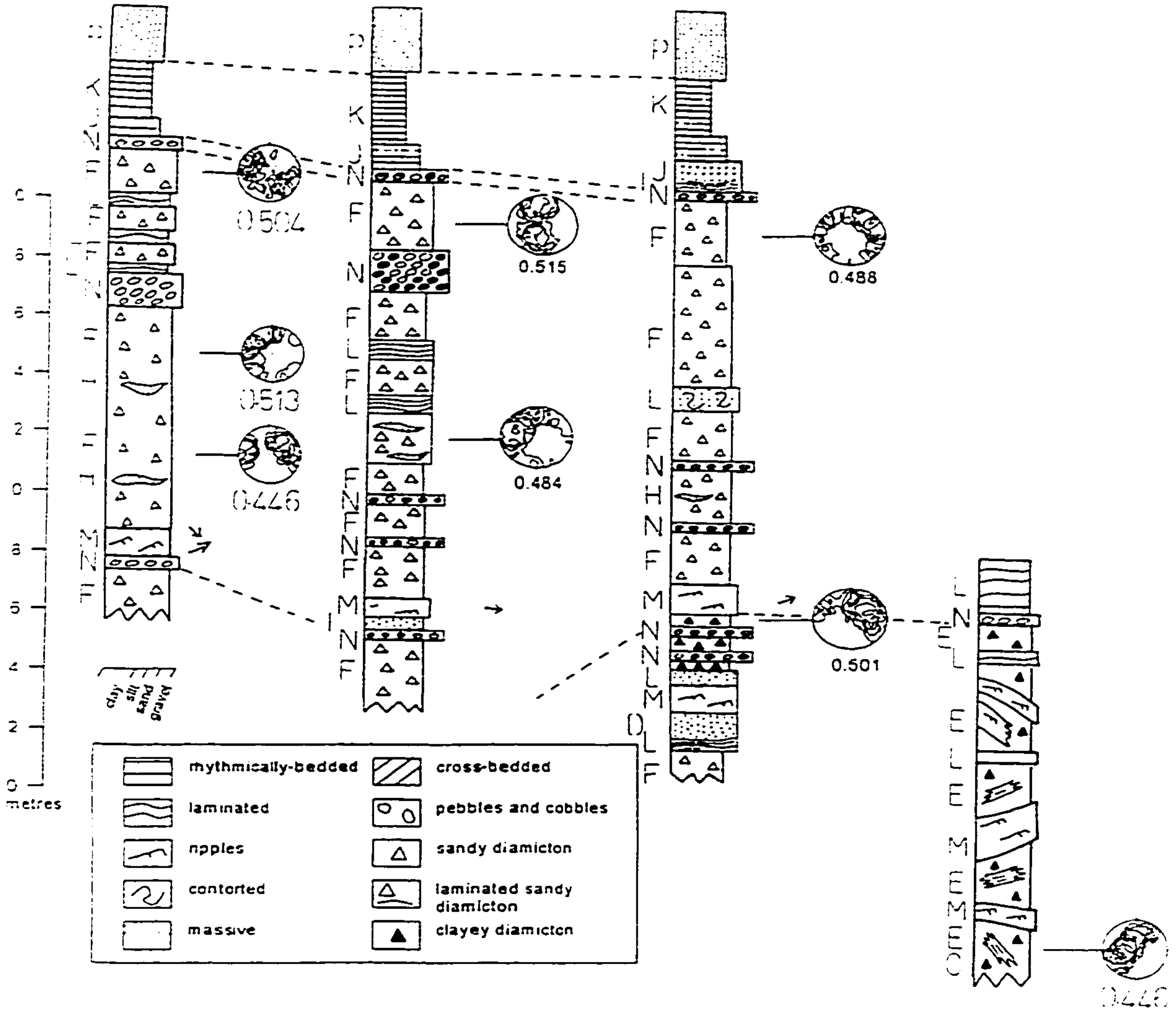

Figure 3.19: Sedimentary transects at Carmangay. Fabric plots with principal eigenvalues are shown for each unit where a sample was obtained.

sediments, disaggregating them and transporting soft sediment clasts upward in the diapir. The loading may have been caused by the advancing ice, however, there are no shear planes through the diapirs and the diapirs have not been overturned in a direction of shear. Also, because thick sand beds were deposited prior to diapirism, the ice must have been decoupled from its bed and diapirism might be directly linked to sediment loading.

The lower blue/grey diamicton beds are truncated by beds belonging to Facies F or L (see Figure 3.6). This unconformity marks a change in sedimentation, and the lower contact of the second assemblage at the site. This assemblage is comprised of beds from Facies F, G, H, I, J, K, L, M, and N. In simpler terms, it comprises massive silty diamictons with sorted interbeds, and some rhythmites. Sorted, laminated and rippled beds require glaciofluvial transport and deposition and hence these beds are indicative of an aqueous environment. Rhythmites of Facies J and I (coarse turbidites) also require the presence of water (e.g., Middleton, 1970). Diamictons are interpreted as debris flows which were also deposited subaqueously, as they are interbedded with the sorted sediment. Fabrics from the massive diamictons have relatively low eigenvalues with variable orientations, orientation strength (S_1), and variable, but generally high, plunge angles (Fig. 3.19). These values are typical of debris flows (e.g., Evenson et al., 1977; Lawson, 1979; Rappol, 1985; Hicock et al., 1996).

The second assemblage is abruptly truncated by an unconformity carrying a boulder (Fig. 3.19). This unconformity/lag is overlain by beds of facies I, J, and K, i.e. rhythmites. There are no more than forty rhythmites at the site. They generally grade from Facies J into Facies K and they also decrease in thickness from ~ 10 cm at the bottom of the assemblage to < 1 cm thick at the top. These beds are typical of rhythmites found at the top of preglacial valley fills over much of central and southern Alberta (e.g., Proudfoot, 1985; Evans and Campbell, 1995), and they are traditionally interpreted as representing proglacial lakes trapped at the front of the ice sheet during ice retreat. The beds at this exposure represent Glacial Lake Carmangay (Stalker, 1957). Coarser diamicton/silt rhythmites at the base of the assemblage represent proximal glaciolacustrine sedimentation, and thinner rhythmites at the top represent distal sedimentation, likely the result of a retreating ice margin. If the rhythmites represent annual sedimentation (varves), then Glacial Lake Carmangay was short-lived at only approximately forty years. If the rhythmites are seasonal or diurnal, then Glacial Lake Carmangay may have existed for as little as a few weeks and certainly no more than a few years.

Overlying the lake beds are beds of Facies P. Facies P is interpreted as an aeolian cap, which is observed regionally across southern Alberta (Catto, 1983). In the study area aeolian silts occasionally are deposited as transverse dunes (Shetsen, 1987).

Tee Pee preglacial valley at Travers Reservoir

Exposures at Travers Reservoir are in fifteen hummocks interpreted by many researchers as the ice-marginal Buffalo Lake Moraine (e.g., Warren, 1937; Stalker, 1977). However, the hummocks are more likely to be the product of erosion into pre-existing sediment and bedrock below the Laurentide Ice Sheet (Munro and Shaw, 1997; appendix A, also see following chapters). Exposures at Travers Reservoir are of excellent quality and they range from 1 - 25 m high. In general, sedimentation at Travers Reservoir was more chaotic than at Carmangay: units are slumped (Fig. 3.20)[1] and sheared at many locations. In general, the sediments at Travers Reservoir can be divided into two main assemblages.

The first assemblage comprises beds of Facies C, D, and E. This is identical to assemblage 1 at Carmangay. In general, though, the beds only occur in the basal 4 m of any of the exposures (Fig. 3.21). Sheared beds (Facies D) are more common than diapirism (Facies E) at this site, and hence glaciotectonic processes were active. The lowermost beds in exposure are deformed with thrust planes, reverse and normal faults, large-scale recumbent folds, large-scale slumps, and rafts of the underlying Facies 1 often lie along shear planes. The absolute direction of shear could not be determined, because the shear planes were only observed in two dimensions.

The second assemblage is composed of beds from Facies F, G, K, I, J, K, L, M, and N. The complex interbedded nature of these beds represents a complex subaqueous environment (Rust and Romanelli, 1975; Evenson et al., 1977), where coarse sorted beds probably represent ice-proximal glaciofluvial inflows, and cross and parallel laminated beds represent the distal parts of such flows. Ice was proximal during deposition of the whole sequence, as documented by slumping, folding, shearing , and the large volume of sedimentation.

McGregor preglacial valley at McGregor Lake

Like the exposures at Travers Reservoir, those at McGregor Lake also occur within the "Buffalo Lake Moraine". Exposures are numerous (totalling 70 or more), and exposure quality is generally excellent (Fig. 3.22). The sedimentary sequences have not been previously studied in detail. Sediment in the exposures are divided into two main assemblages (Fig. 3.23).

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[1] N.B. more exposures through hummocks are presented in chapter 6

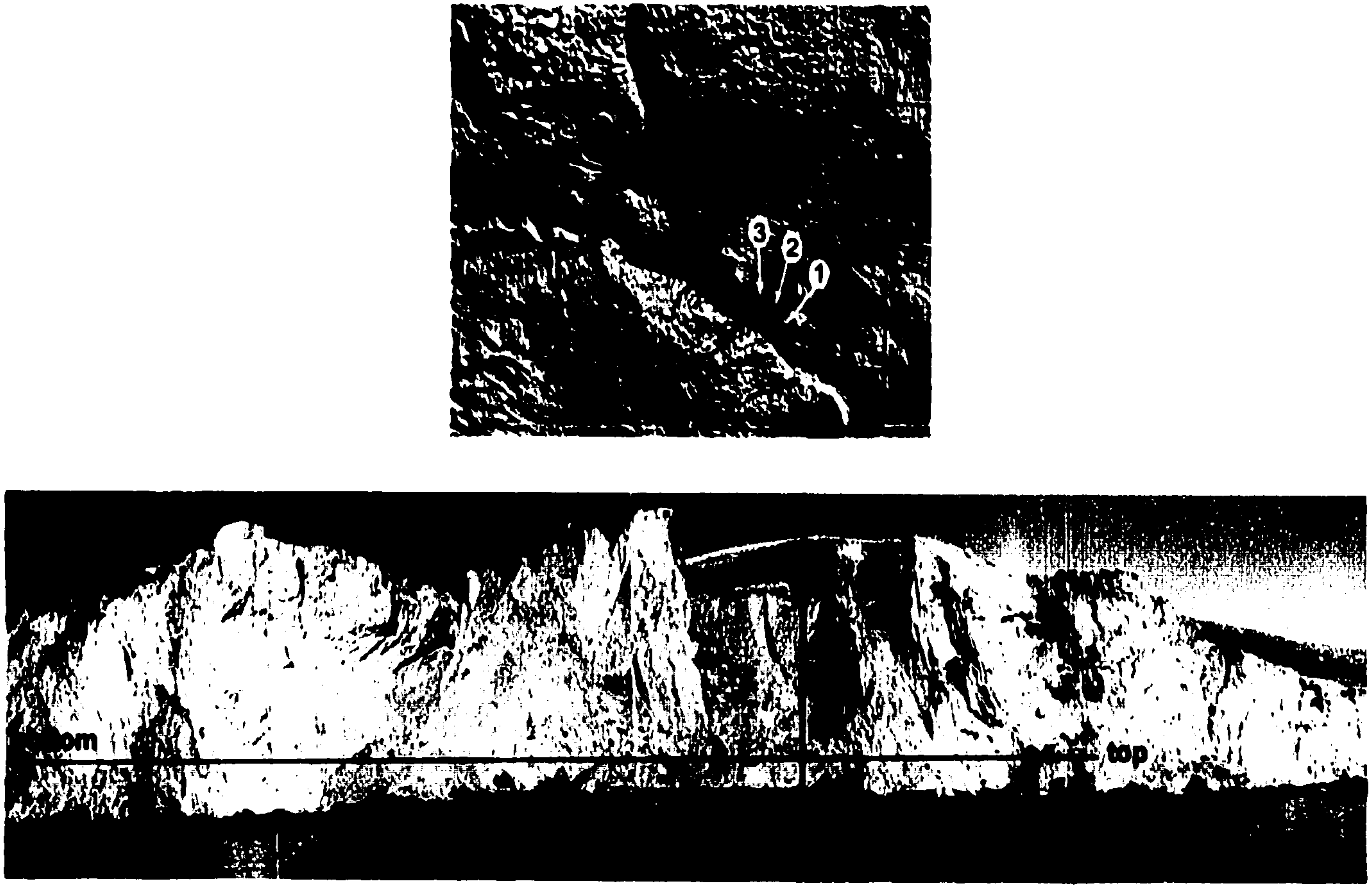

Figure 3.20: A. Locations of sedimentary transects presented from Travers Reservoir. B. Transect #2. As this exposure contains sediment that has been upturned, the transect was obtained along its length, rather than its height.

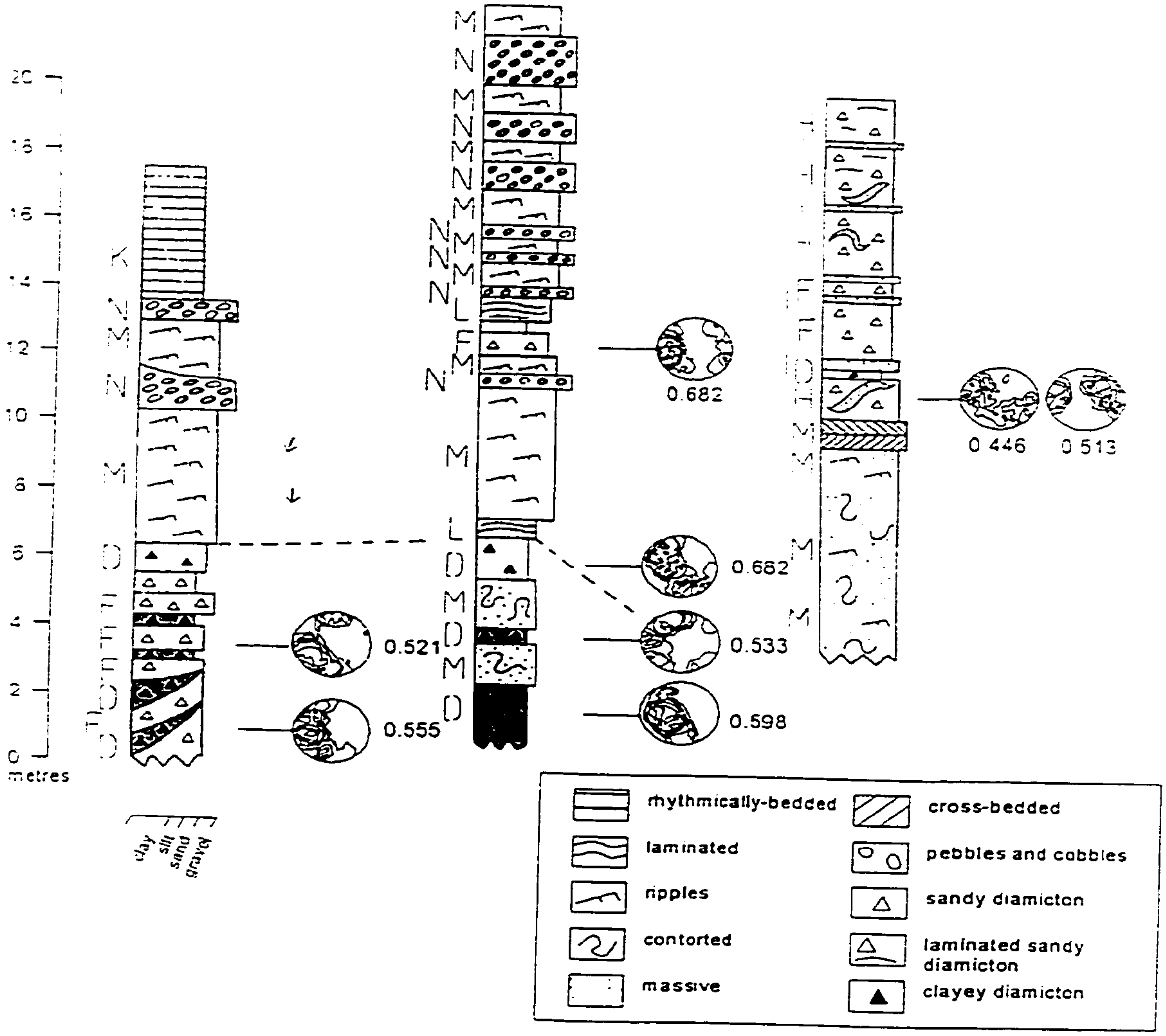

Figure 3.21: Sedimentary transects at Travers reservoir. Fabric plots with principal eigenvalues are shown for each unit where a sample was obtained.

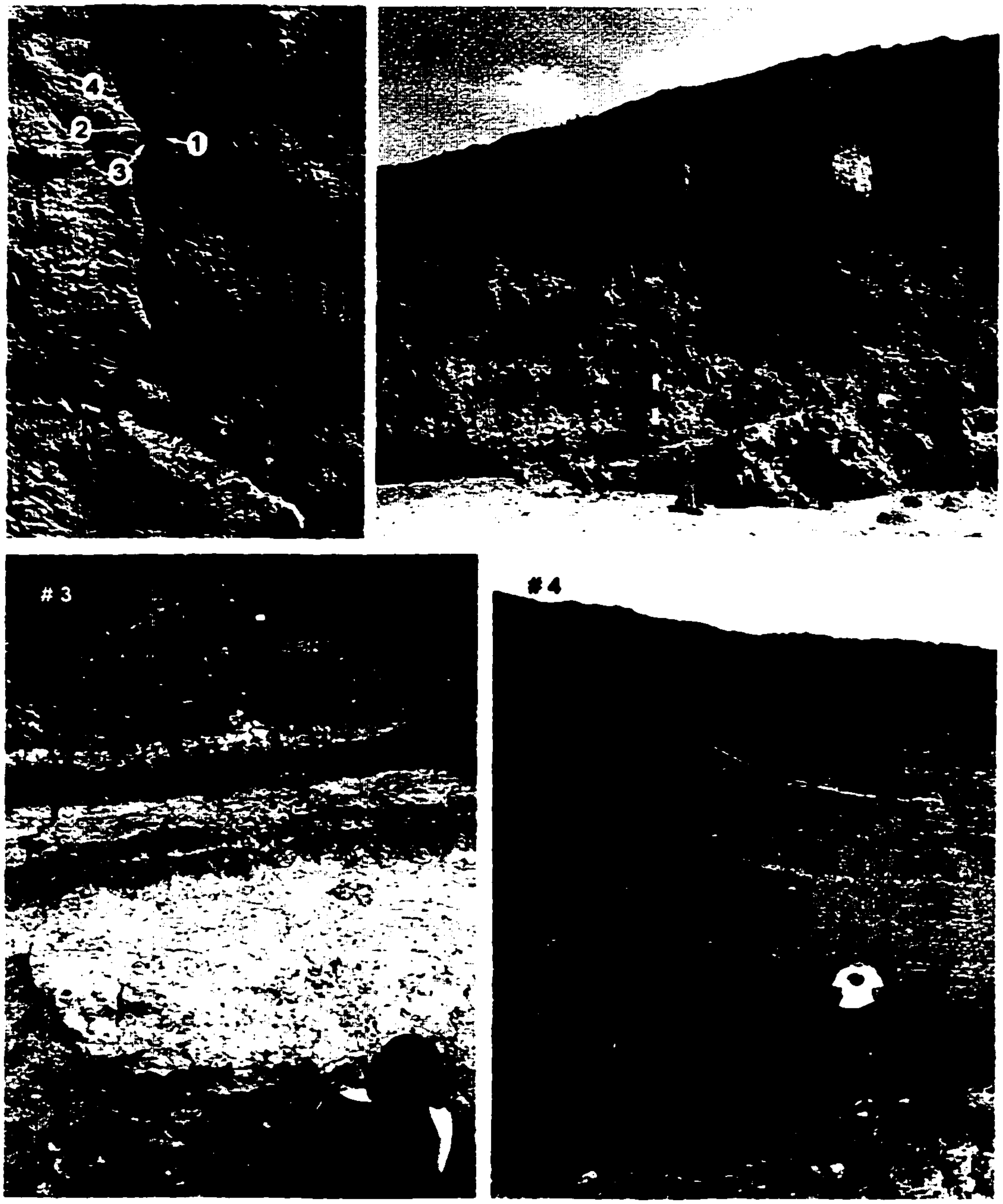

Figure 3.22: Location of sedimentary transects at Travers reservoir and, also, photographs of three of the exposures through which transects were constructed.

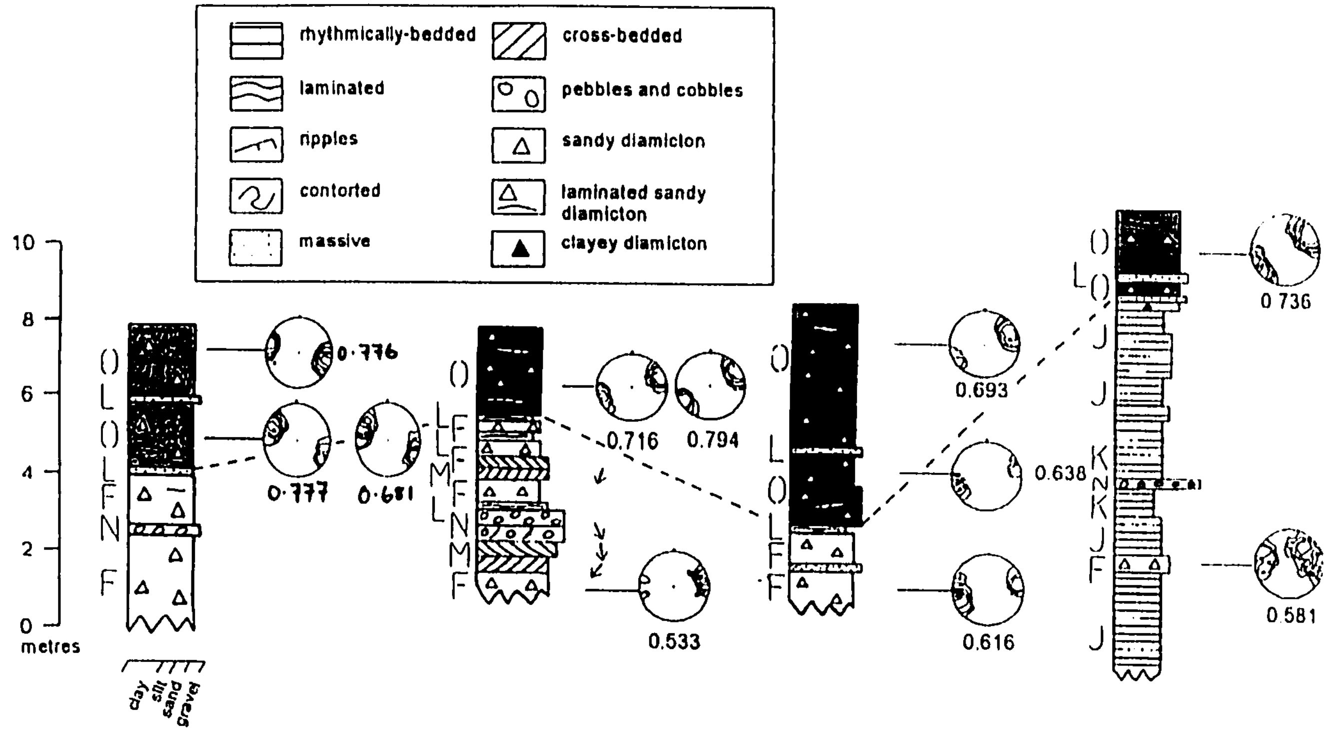

Figure 3.23: Sedimentary transects at McGregor Reservoir. Fabric plots with principal eigenvalues are shown for each unit where a sample was obtained.

The oldest assemblage is composed of beds belonging to Facies F, G, K, I, J, K, L, M, and N. Hence these beds are interbedded and probably represent the same complex subaqueous environment as that inferred for Travers Reservoir. However, beds are generally less disturbed, and the volume of well-sorted material is significantly lower than at Travers Reservoir. Two inferences can be made from these observations: 1. All sediment in the McGregor exposures was deposited in a more distal glaciolacustrine environment than the beds at Travers Reservoir (i.e., further from the meltwater inputs); 2. The role of shearing by ice was less important at this site, and also slumping was less frequent.

The lower lake assemblage, grades into beds belonging to Facies O, subglacial melt-out till. The melt-out till was observed extensively in exposure at McGregor Lake, and structures and fabric strongly support a melt-out origin for these beds (see chapter 4). These beds demonstrate that stagnation at McGregor Lake.

Although, exposure at McGregor Lake is relatively extensive, the stratigraphy is reasonably simple: lake beds grade into subglacial till. This grading suggests that the lake beds may also represent subglacial sedimentation. This is discussed again.

RECONSTRUCTION OF GLACIGENIC EVENTS

From examination of beds at Carmangay, Travers reservoir and McGregor Reservoir, it becomes apparent that sedimentation at the three sites is similar. Hence, a regional reconstruction of the immediate preglacial, glacial, and immediate postglacial events is possible. This reconstruction is discussed below and summarized in Figure 3.24.

Prior to the onset of continental glaciation in south-central Alberta, there was a period of intense fluvial incision and deposition. This is clear from the preglacial valleys (Fig. 3.1) and Facies A, preglacial valley gravel fill. Sometime after the deposition of these beds they were likely disturbed by cryogenic activity (Facies B) when ice wedges and sorted polygons (involutions) formed in the gravel. The recognition of these casts and involutions is important as it indicates that the mean annual air temperature during their formation was significantly lower than present (~ 2°C), at between -6°C (Péwé, 1966) and -1°C (Mackay, 1989). It is possible that these periglacial features formed as the Laurentide Ice Sheet was growing and advancing across the plains. The proglacial zone was likely dominated by permafrost. Alternatively the involutions may represent soft-sediment deformation structures resulting from loading of saturated sediment by the overlying ice.

Importantly, the preglacial beds in south-central Alberta provide age estimates for the

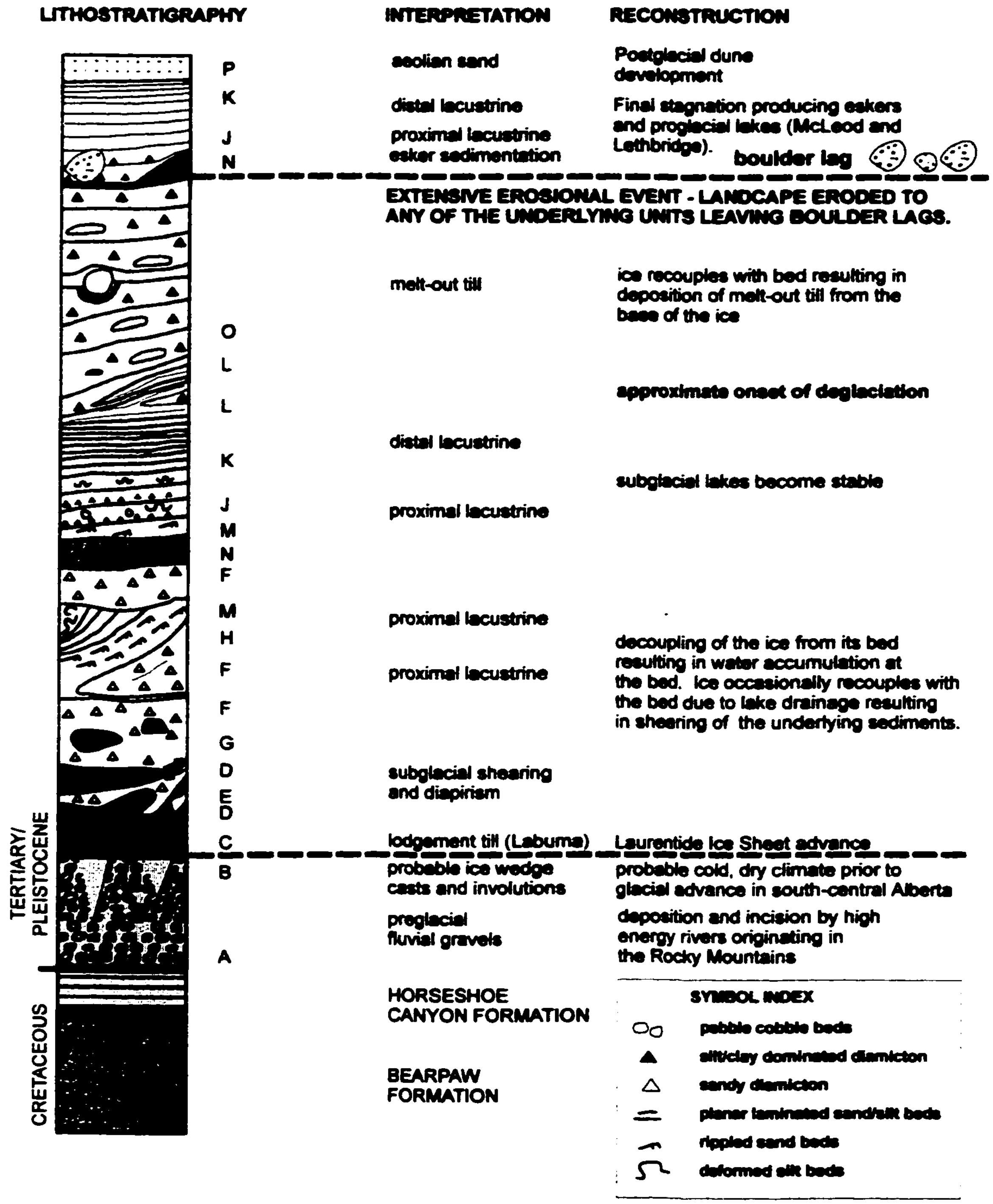

Figure 3.24: Simplified composite diagram of the stratigraphy of the preglacial valley fills of south-central Alberta. Also shown is the interpretation of the sediments in those fills and a simplified reconstruction of the events that led to those fills.

invasion of the Laurentide Ice Sheet. Beds belonging to Facies C are the first beds that contain clasts from the Canadian Shield and hence these beds represent initial Laurentide glaciation in south-central Alberta. Age estimates on these beds, "the Labuma Till", range from Nebraskan to Late Wisconsinan (e.g., Harris and Waters, 1977). However, it can be determined that the Laurentide Ice Sheet never advanced over this region until some time after 22,000 BP. This is documented by multiple radiocarbon dates on Pleistocene fauna from preglacial sediments upglacier from the present site (Young et al., 1994). These findings are also supported by Liverman et al. (1989) and Jackson et al (1996). This then demonstrates that all glacigenic deposits in the study area are Late Wisconsinan and therefore belong to one glacial advance.

As the Laurentide Ice Sheet advanced over the region it folded and thrust underlying bedrock as well as the newly-deposited lodgement till. Recumbent folds are observed in exposure (Fig. 3.5), and thrust ridges are also observed at the landscape surface. Both document that ice invaded the region from the northeast.

For some reason, after ice initially invaded the region, large quantities of meltwater were delivered to the bed, resulting in subglacial lakes in all preglacial valley settings. These lakes had to be subglacial, as their elevation relative to meltwater channels and other local topography, would have resulted in southward and westward drainage if they were not contained subglacially (Munro-Stasiuk, in press; chapter 5). Sedimentation rates in the lakes were high at all locations documented by the volume of sediment in the system. However, sediment input varied both spatially and temporally. High-magnitude events are recorded by turbidites and debris flows with rip-up clasts, and thick sets of ripple cross-lamination. Intervening periods of low sedimentation rates are documented by silt and clay rhythmites, representing deposition from suspension. Ice was either proximal to, or in direct contact with, sediments during deposition of most of the sequence as slumping and shearing are common in most of the beds. Ice/bed interaction was negligible during the latter phases of deposition as the younger lake sediments are stratified and undisturbed.

Lake beds grade into subglacial till beds at McGregor Reservoir only. Hence, the lake at McGregor Reservoir must have drained, bringing ice into contact with its bed and depositing melt-out till. No till is present high in the sequences at Travers Reservoir or Carmangay, hence, lakes in the Tee Pee preglacial system were likely maintained. Melt-out till deposition represents the onset of ice stagnation. Stagnation may started before deposition of the melt-out till, but evidence for such cannot be obtained from the sedimentary record.

All beds at each site are cut by an unconformity overlain by a boulder lag. This is represented in the modern landscape by the hummock surfaces (the tops of the exposures) at Travers and McGregor Reservoirs, and also by an unconformity approximately 4 m from the surface at the Carmangay exposure. This unconformity represents regional scale erosion and is attributed to meltwater erosion (Munro and Shaw, 1977; Appendix A). The unconformity is discussed extensively in chapters 6 and 7.

In exposure, the only sediments overlying the unconformity are at Carmangay. Rhythmically-bedded silt and clay represent proglacial lakes trapped at the front of the ice sheet during ice retreat. At this site the beds represent Glacial Lake Carmangay (Stalker, 1957). Fining upwards of the rhythmites are likely the result of a retreating ice margin or decreased input of sediment. As few rhythmites are observed, the lake was short-lived.

Finally, the exposure at Carmangay is capped by aeolian loess, demonstrating relatively dry and windy conditions immediately postdating glacial lake drainage.

DISCUSSION AND CONCLUSIONS

It has been demonstrated that the preglacial valleys of south-central Alberta contain a complex sedimentary fill. Part of that fill is preglacial gravel, but glacigenic beds are by far the most prominent. Of the sixteen facies recognized and described, twelve of them were the result of subglacial deposition and processes. Although the beds are of varying origins it is proposed that the glacigenic facies classification can be simplified and divided into three major groups: lodgment till deposited during ice advance (Facies C, D and E); subglacial lake sediments (Facies F - N), and subglacial melt-out till (O). In the subsequent chapters of this thesis, these beds are simply referred to as glacigenic Facies 1, 2, and 3 respectively.

Most of the beds observed in the preglacial valleys of south-central Alberta are glaciolacustrine in origin. These comprise up to 75% of the valley fills. The preglacial valleys therefore acted as natural storage areas for meltwater below the Laurentide Ice Sheet. The subglacial lakes that accumulated there filled and drained on several occasions. This is documented by glaciotectonic shearing in the glaciolacustrine beds. It is also possible that the preglacial valleys acted as natural interconnected cavities at below the Laurentide Ice Sheet. This is discussed further in chapter 5.

Preglacial valleys were naturally protected from extensive erosion of beds by glacial ice or by meltwater flows. Hence those valleys now contain the best preserved record of glaciation in central and southern Alberta. Studies between preglacial valleys would aid in reconstructing glaciation and subglacial conditions across Alberta, and further such studies are recommended.

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CHAPTER 4: RHYTHMIC TILL SEDIMENTATION: EVIDENCE FOR REPEATED HYDRAULIC LIFTING OF A STAGNANT ICE MASS[1]

INTRODUCTION

Till characteristics provide insight into the flow dynamics and sedimentation processes of ancient glaciers. Correct interpretations of glacial diamictons help to reconstruct basal conditions during advance and dissipation of the last great ice sheets. These reconstructions are of fundamental importance to numerical models for the Laurentide Ice Sheet. Such models propose fast flow in Alberta (Fisher et al.,1985; Clark, 1994; Marshall et al.,1996) on the basis of the presence of "deformable beds", in this case Cretaceous shales and their complementary fine-grained tills. "Deformed" beds have been recognized in other locations, and their presence is believed to result from rapid ice flow or even surging (Clarke, 1987; Hicock and Dreimanis, 1992).

The youngest glacigenic facies observed in south-central Alberta (Fig. 4.1A) does not display any characteristics predicted by the deformable-bed hypothesis. This paper presents evidence for till sedimentation, partially deposited into water that was stored beneath the stagnating Laurentide Ice Sheet. The sudden and repeated release of that water resulted in current deposition of thin beds of sand or silt. The resultant facies is a previously unreported rhythmic complex of alternating subglacial till and sorted beds. To the best of my knowledge, such a combination of processes has not been invoked to explain till sedimentation during the last glaciation, although storage and release of water at high pressures, and of similar magnitudes, has been inferred (e.g., Iken et al., 1983) or documented (e.g., Skidmore, 1995) at modern glaciers. It is also proposed that this till was deposited after ice had surged or streamed, and the ice sheet profile was low, resulting in little or no ice movement.

STUDY AREA

Sediments discussed in this paper are part of a complex glacigenic fill of the McGregor preglacial valley (Fig. 4.1B) in south-central Alberta, Canada. Exposures along McGregor Reservoir are excellent as a dam was built in the 1960s, flooding the valley, and resulting in extensive shoreline erosion. There are now more than 70 exposures in hummocky terrain at McGregor Reservoir.

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[1] In press, Journal of Sedimentary Research (A)

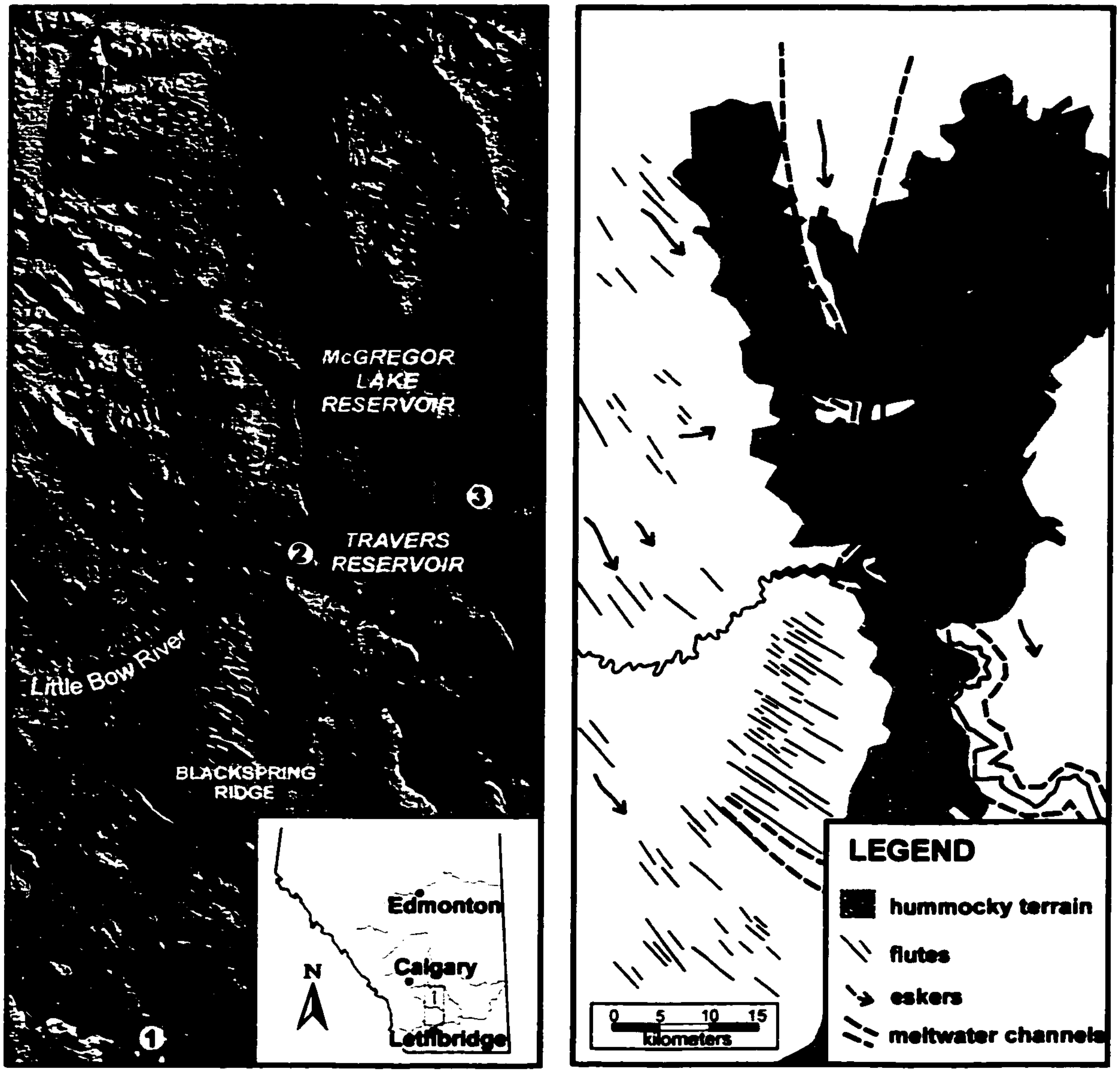

Figure 4.1: A. Digital Elevation Model (DEM) showing the physiography of the study area. Numbers refer to sites in the text: 1. Oldman River; 2. Thrust ridges at Travers Reservoir; 3. Thrust ridges. Inset is a map of Alberta showing the location of the study area. B. Generalized geomorphology in the study area. Preglacial valleys are mapped from Farvolden (1963), Campbell (1964), and Geiger (1967). Note: the areas covered by these figures are slightly different.

All exposures are within the north to south- trending hummocky zone named the "Buffalo Lake Moraine" (Stalker, 1977). Stalker (1977) suggested that this " hummocky moraine" represents the westernmost extent of the Late Wisconsinan Laurentide ice sheet, but Shetsen (1984) indicated that the hummocks were likely the result of convergence between a southward-flowing ice lobe and the main Laurentide ice front during ice disintegration. She renamed it "the McGregor Moraine". The recent work of Munro and Shaw (1997) demonstrates that the hummocks are the product of subglacial erosion of preexisting sediment, probably by meltwater. Sedimentary strata within hummocks are abruptly truncated by an erosion surface that represents the hummocky topography, and sedimentary units are readily traced laterally from one hummock to the next. The stratigraphically youngest pre-erosion units in the hummocks are the main subject of this paper. There is clear evidence of primary subglacial sedimentation and multiple small-scale drainage events. Because this is the youngest pre-erosion unit in the area, it documents subglacial conditions prior to the event responsible for hummock erosion. As the hummocks are erosional, sediment interpretations in this paper do not point to a model of hummocky terrain formation.

TOPOGRAPHIC AND STRATIGRAPHIC SETTING OF THE TILL (Facies 3)

The preglacial McGregor Valley is incised ~ 200 m (Campbell, 1964), into upper Cretaceous Horseshoe Canyon sandstones and shales, and Bearpaw Shale (Jackson, 1981). This ancient valley is now partly occupied by McGregor Reservoir (Fig. 4.1B) and, as in many other preglacial valleys in Alberta (e.g., Evans and Campbell, 1995), thick deposits of well-rounded fluvial gravels (quartzites and some carbonates) directly overlie bedrock (Campbell, 1964). The absence of Canadian Shield clasts indicates that the gravels predate Laurentide glaciation in the region (Stalker, 1968a). Sediments belonging to three main glacigenic facies (Facies 1 to 3) directly overlie the gravels. In some places sedimentary strata belonging to these facies are entirely *in situ*, but in others they are intensely sheared, faulted, and folded, recording a complex glaciotectonic history during and after deposition of the whole sedimentary sequence. Below are brief descriptions and interpretations of the two oldest glacigenic facies (Facies 1 and 2). The interpretations of these are important for understanding the environmental implications of Facies 3, the subject of this paper.

Facies 1- massive grey diamicton

Description

Facies 1 contains beds of massive grey diamicton that disconformably overlie preglacial gravels (Fig. 4.2A). In some places, it forms a single unit (Fig. 4.2A), but commonly, it interfingers with thrust and folded bedrock (Fig. 4.2B) or diapirically intrudes into, or is sheared into, overlying sediments (Fig. 4.3A). Facies 1 was only observed as rafts (Fig. 4.3A) within overlying sediments at McGregor reservoir where most of the grey diamicton appears to be buried. At Travers Reservoir to the south, however, diamicton and thrust bedrock form multiple ridges oriented NW to SE (#2, Fig. 4.1A). Other obvious ridges at site # 3 (Fig. 4.1A) may represent the same phase of thrusting, but their internal structures were not observed. The diamicton is bluish-grey (Munsell: 2.5Y 7/2 - 2.5Y 4/1 (dry) light grey to dark grey), very fine-grained, compact, and in places, fissile. It contains striated, faceted, and bullet-shaped clasts, and lithologies of both Shield and Cordilleran origin. Clast fabrics from the diamicton are variable in strength ($0.446 < S_1 < 0.683$), and primary orientations are inconsistent (Fig. 4.4).

Interpretation

Striated and faceted clasts indicate that abrasion played a major role during transport of debris in this unit (Haldorsen, 1983). Abrasion, together with fissile planes, compact, clayey matrices, bullet-shaped clasts, and thrusting suggest that the diamicton is lodgement till (cf., Dreimanis, 1982; Haldorsen, 1983; Clark and Hansel, 1989). Clast fabrics do not preserve the direction of ice movement (Fig. 4.4B), but this is expected given the tectonization and diapirism that accompanied or postdated deposition. Transverse ridges of thrust bedrock oriented NNW to SSE, which in exposure show fold noses pointing towards the WSW (Fig. 4.2B), indicate that ice was advancing towards the WSW. Clasts from the Canadian Shield indicate that this deposit is the first Laurentide glacigenic material in south-central Alberta.

A similar massive grey diamicton is observed across much of southern Alberta (e.g., Horberg, 1952; Stalker, 1960, 1962, 1968b, 1983; Harris and Waters, 1977). It is commonly named the "Labuma Till", and is easily recognized because of its bluish-grey color inherited from the Bearpaw Shale in the region. There is much argument over the age of the till, and estimates range from Nebraskan to Late Wisconsinan. However, there is no evidence in the region for a long period of time between deposition of this till and the overlying units: there are no weathering zones or areas

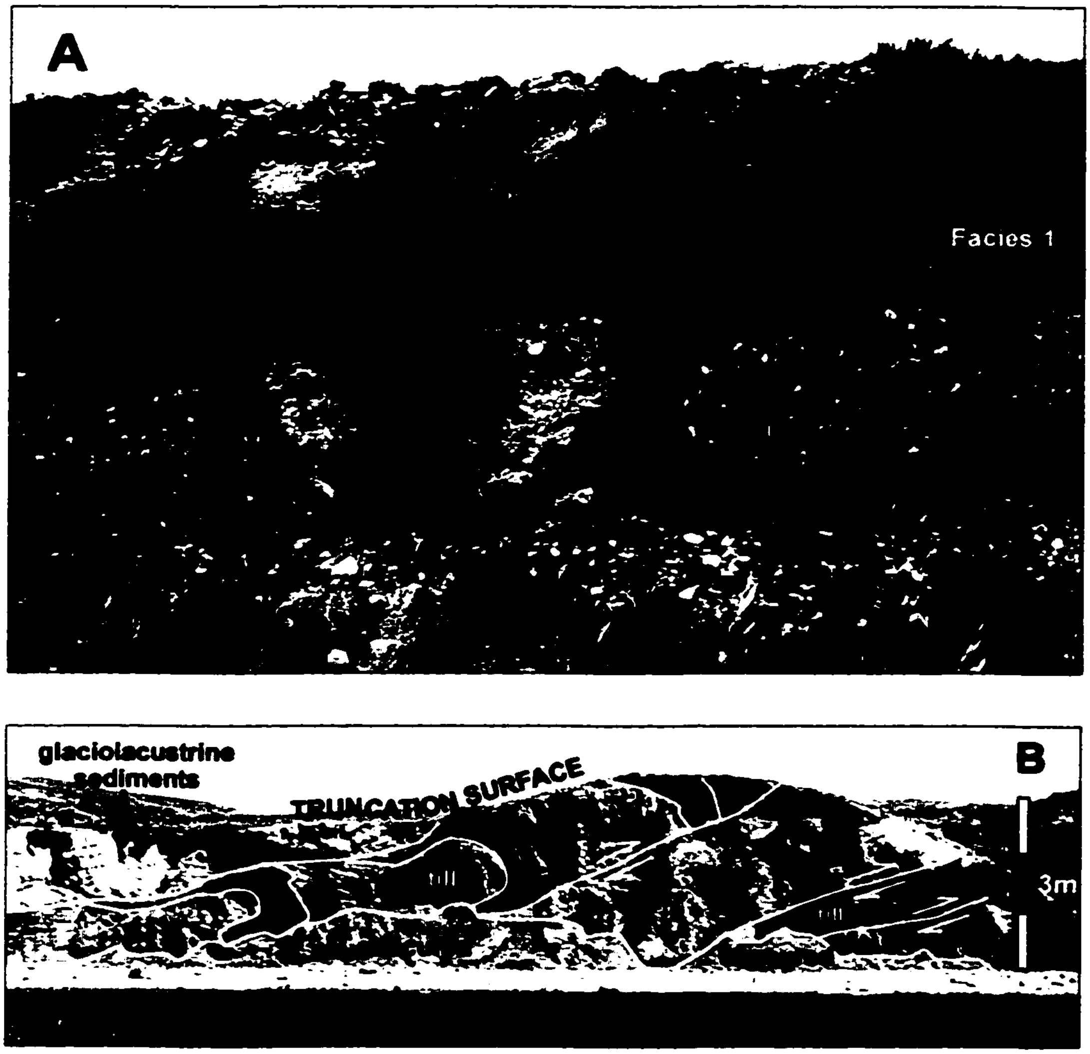

Figure 4.2: Typical exposures showing Facies 1. A. Till often erosionally overlies frost-heaved preglacial gravels (#1 in Figure2.1A). Exposure faces south. B. (#2 in Fig.21A). All unmarked units on this diagram are bedrock. The sediments and bedrock were tectonized by ice moving from the northeast. All units are truncated (including the younger glaciolacustrine sediments) by a later erosional event. Exposure faces west (from Munro and Shaw, 1997).

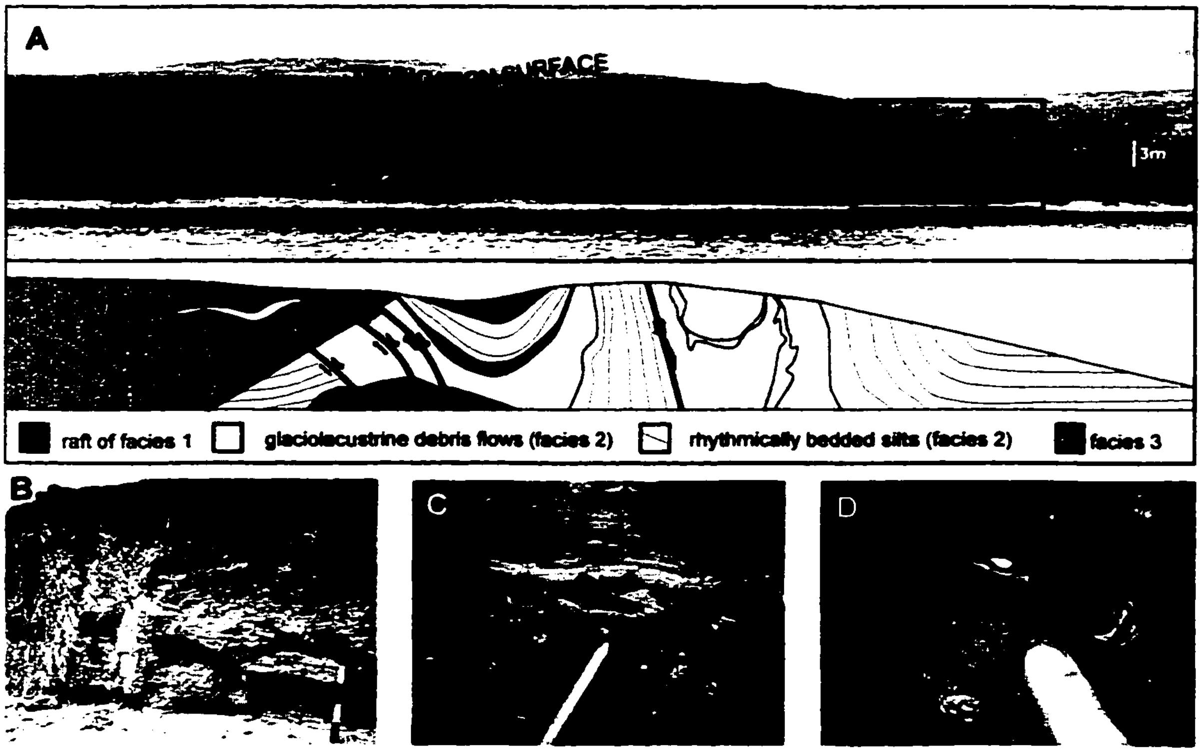

Figure 4.3: A. Exposure at McGregor Reservoir showing sediments of all three main facies. Note the truncation of all sediment types. Exposure faces east (modified from Munro and Shaw, 1997). B. Typically, within Facies 2 debris flows and other gravity-deposited sediments grade both vertically and laterally into fine-grained rhythmically-bedded silts and clays (immediately above the metre stick) (modified from Munro and Shaw, 1997). C. Where coarser-grained sediments overlie finer silts and clays, density instabilities occur because of loading, resulting in diapirism of the fine-grained sediments into the coarser grained sediments. Diapirism was penecontemporaneous with deposition of the coarser-grained sediment as the diapirs are turned in the direction of loading (southward). D. Thicker debris flows typically contain rip-up clasts of underlying finely laminated silts and clays.

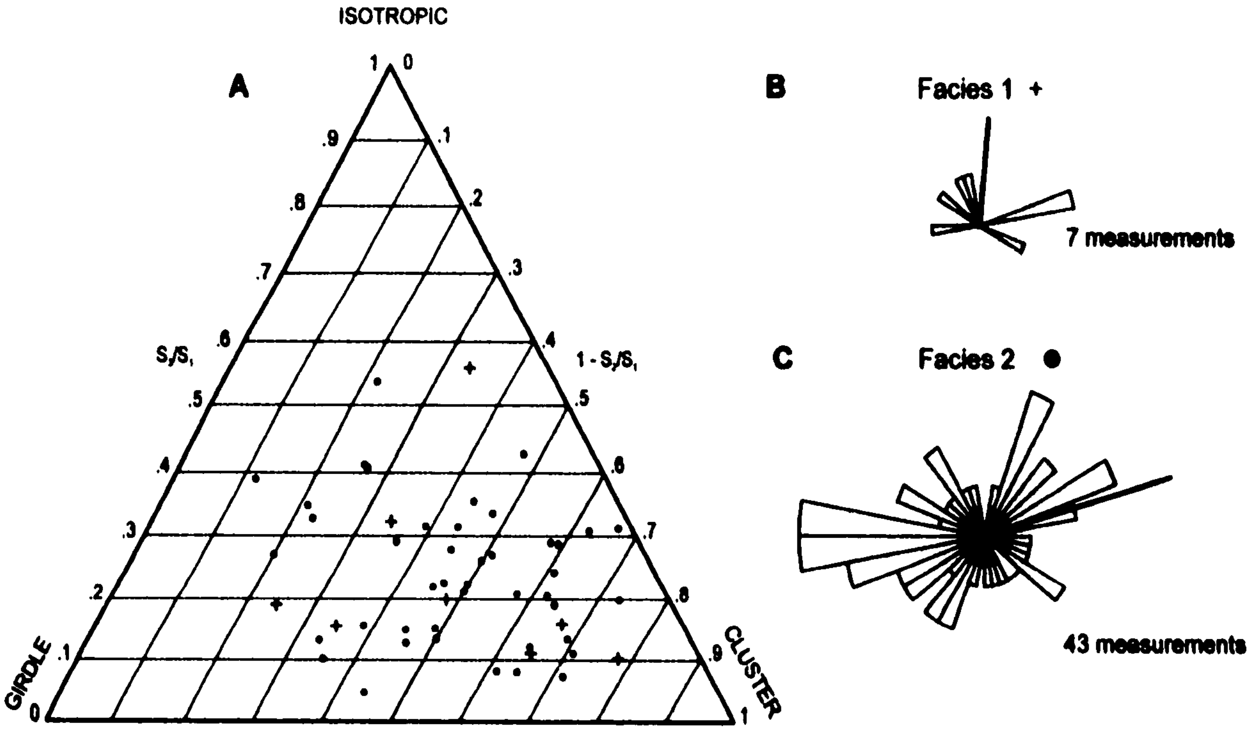

Figure 4.4: Clast fabric results from Facies 1 and 2. A. All results are plotted on a Benn diagram, allowing easy comparison with Figure 7E. B. Unidirectional rose diagram displaying average plunge orientations from Facies 1. C. Unidirectional rose diagram displaying average plunge orientations from Facies 2.

of soil development. Also, recent work north and west of the study area demonstrates that the Late Wisconsinan Laurentide glaciation was the most extensive, and only glaciation in this part of North America (Liverman et al., 1989; Young et al., 1994; Jackson et al., 1997). It is assumed here, on the basis of stratigraphy, spatial relationships, and evidence for a single glaciation in this part of Alberta, that this unit is Late Wisconsinan in age, and thus all overlying sediments are also Late Wisconsinan.

Facies 2 - complex interbedded sorted and non-sorted sediment

Description

Facies 2 is a thick, complex sequence of sediments that may be *in situ*, or pervasively deformed (Fig. 4.3A). This facies is areally extensive: it is observed along the entire length of the Little Bow River, along parts of the Oldman River, at Travers Reservoir, and at McGregor Reservoir. Facies 2 includes compact silty diamicton, massive diamicton with rip-up clasts, sorted pebble and cobble beds, cross-laminated sand beds, and rhythmically-bedded silts and clays. Most common are moderately compact, massive silty diamicton beds up to 4 m thick, which are stacked to create the major thickness of sediment. These beds thin laterally and vertically to sandy diamictons with rip-up clasts of clay and other sediment (Figs. 4.3C, D). In most cases, the lower contact of each diamicton bed is erosional. Clast orientations obtained from these beds vary significantly in strength, plunge direction, and plunge angle (Fig. 4.4).

The lowermost beds in this facies are deformed with thrust planes, reverse and normal faults, large-scale recumbent folds, large-scale slumps, and rafts of the underlying Facies 1 often lie along shear planes (e.g., Fig. 4.3A). At most locations the uppermost beds are entirely undeformed. The absolute direction of shear cannot be determined, because the shear planes are only observed in two dimensions. In general it is southward.

Interpretation

Diamictons within Facies 2 are interpreted as multiple, stacked, cohesive debris flows, slurry flows, and turbidites. Units with erosional contacts and rip-up clasts are likely a combination of turbidity current sedimentation (some sorting), and slightly more cohesive slurry flow sedimentation (no sorting). Flows were relatively fast and capable of eroding the substrate. Distal thinning of units, with overlying thin silt or clay layers, supports a turbidite interpretation. At some locations density instabilities resulted in flame structures (Fig. 4. 3C). Silts overlying the mass-flow deposits were deposited from suspension when flow ceased (cf., Middleton, 1970).

Larger and thicker flows are stacked without intervening fine sediment, indicating only short intervals between flows. Stratified sand within this facies is from glaciofluvial deposits or turbidites, or a combination of these. High flow velocities are recorded, in places, by pebble and cobble beds.

The abrupt transitions between sediment types are typical of a complex subaqueous environment (Rust and Romanelli, 1975; Evenson et al., 1977). Ice was proximal during deposition of the whole sequence, as documented by slumping, folding, shearing ,and a large volume of sediment in the system. Gravels probably represent ice-proximal glaciofluvial inflows. Rippled and laminated beds may represent the distal parts of such flows, or they may simply represent periods of low flow.

Facies 2 may be glaciolacustrine, deposited in a proglacial lake episodically overridden by the Laurentide ice, or in a subglacial lake that drained episodically. Munro-Stasiuk (in press) demonstrates that the regional topography is not conducive to a proglacial lake. The restricted areal extent of this facies requires that water was impounded subglacially. Ice recoupling with the bed and extensive sediment shearing point to drainage events. Ice/bed interaction was negligible during the latter phases of deposition because sediments are stratified and undisturbed.

FACIES 3 - DIAMICTON WITH SAND BEDS AND PARTINGS

Description

Facies 3 contains the youngest sediments in the McGregor Reservoir exposures and is observed along approximately 4 km of both the east and west shores of the reservoir. Unlike older facies, which are regionally widespread, Facies 3 is restricted to the McGregor Valley, where at most locations it conformably overlies, and interfingers with glaciolacustrine silts of Facies 2 (Fig. 4.5).

There are two main sediment types in Facies 3: (i) beds of laterally extensive, massive, fine-grained diamicton; and (ii) thin, continuous beds of sand and/or silt. These are conformably and alternately interbedded (Figs. 4.6A and B). Both sediment types extend over tens to hundreds of meters, with little variability in bed thickness. At some locations channel-like scours, between 3 and 30 m across, cut through several diamicton and sand/silt beds (Fig. 4.6C). Channel fills are commonly sand or gravel at the base, which mantle the channel, then mainly diamicton beds with sand/silt interbeds, characteristic of Facies 3. All beds in Facies 3 are generally *in situ*, although

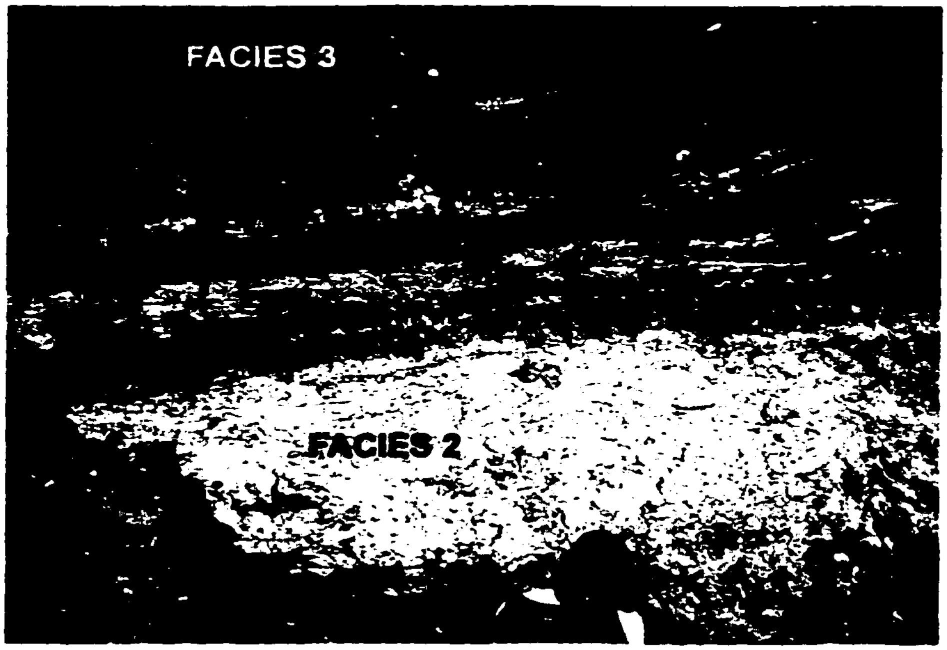

Figure 4.5: Typically the contact between sediments of Facies 2 and sediments of Facies 3 is conformable. This is represented by the alternating deposition, and interfingering of, glaciolacustrine silts (light coloured material), and the darker silty/clay diamicton of Facies 3.

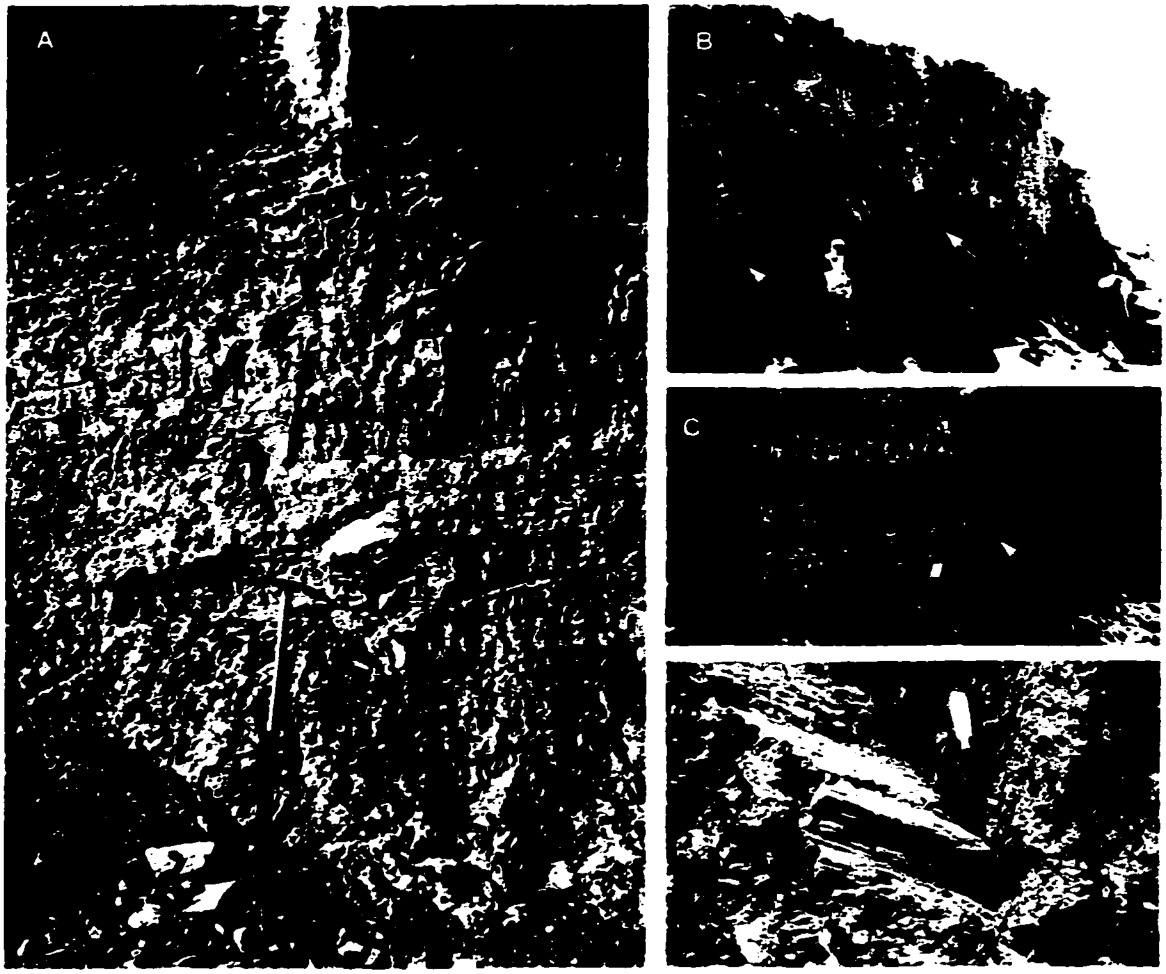

Figure 4.6: A. Facies 3 is typified by alternating beds of diamicton (the thicker units on the photograph) and thin sand strata. The boulder in the centre of this photograph is the same boulder shown in Figure 4.9. Exposure faces east. B. This exposure demonstrates the continuous nature of both the sand and diamicton beds in Facies 3. The two arrows are about 10 m apart, but they point to the same sand bed. Exposure faces east. C. At some locations, channels cut through beds of Facies 3 (indicated by arrow). This channel is small, approximately 3 m wide and 1 m deep. As with all the other channels observed, each is infilled with diamictons and silt or sand strata, typical of the main body of the unit. Exposure faces west. D. At one exposure a rock was dragged through sediment to produce these erosional flute marks (arrow) oriented northwest to southeast. Exposure faces west.

large-scale folds disrupt the sequence in the northernmost exposures.

The diamicton and the sand/silt strata are evidently products of different processes and are first described and interpreted separately. A good understanding of the depositional processes for each of these provides a more powerful reconstruction of subglacial events.

Diamicton beds

Diamicton beds are discussed in terms of (i) sedimentary structures and properties, and (ii) clast fabric analysis.

(i) Sedimentary structures and properties

The diamicton beds are of remarkably similar thicknesses (5-20 cm) both laterally along the exposures, and vertically (Figs. 4.6A, B). They are distinguished by colour: shades of greyish brown [Munsell: 2.5Y 3/2 (moist) - 2.5Y 5/2 (moist)], and are, therefore, easily differentiated from the underlying lighter glaciolacustrine sediments (Fig. 4.5). The diamicton is moderately compact and composed of up to 30% clay and 40% silt. Larger clasts, granules and pebbles, with some cobbles and boulders, vary in shape (spheres, rollers, and blades) and roundness (angular to very well rounded). Quartzites transported from the Rocky Mountains by high-energy rivers dominate the very rounded category; many of the largest clasts are subangular, Canadian Shield erratics. Most large clasts display striae. At some locations, small diapirs (~ 1 cm) intrude vertically into overlying sand beds: they show no signs of overturning by lateral shear. Color, texture, and clast content throughout diamicton beds do not change substantially. Interestingly, at one location, from where a boulder has fallen from the exposure, the indented face exhibits parallel grooves that resemble erosional flute marks (Fig. 4.6D). The indentation is the same shape as the fallen boulder.

(ii) Clast fabric analysis

Thirty-eight clast fabric samples, most consisting of 25 measurements, were obtained from the diamicton beds in Facies 3 (Fig. 4.7; Table 1). Axis orientation and plunge were measured on rod or blade-shaped clasts, between 2 and 10 cm long, and with a b/a ratio 0.67. All samples are adjusted for bed dip. Plunge orientations are plotted on a unidirectional rose diagram, with most samples showing a preferred plunge towards ENE (Fig. 4.7B).

Standard normalized eigenvector (eigenvalue) methods which estimate both clast orientation

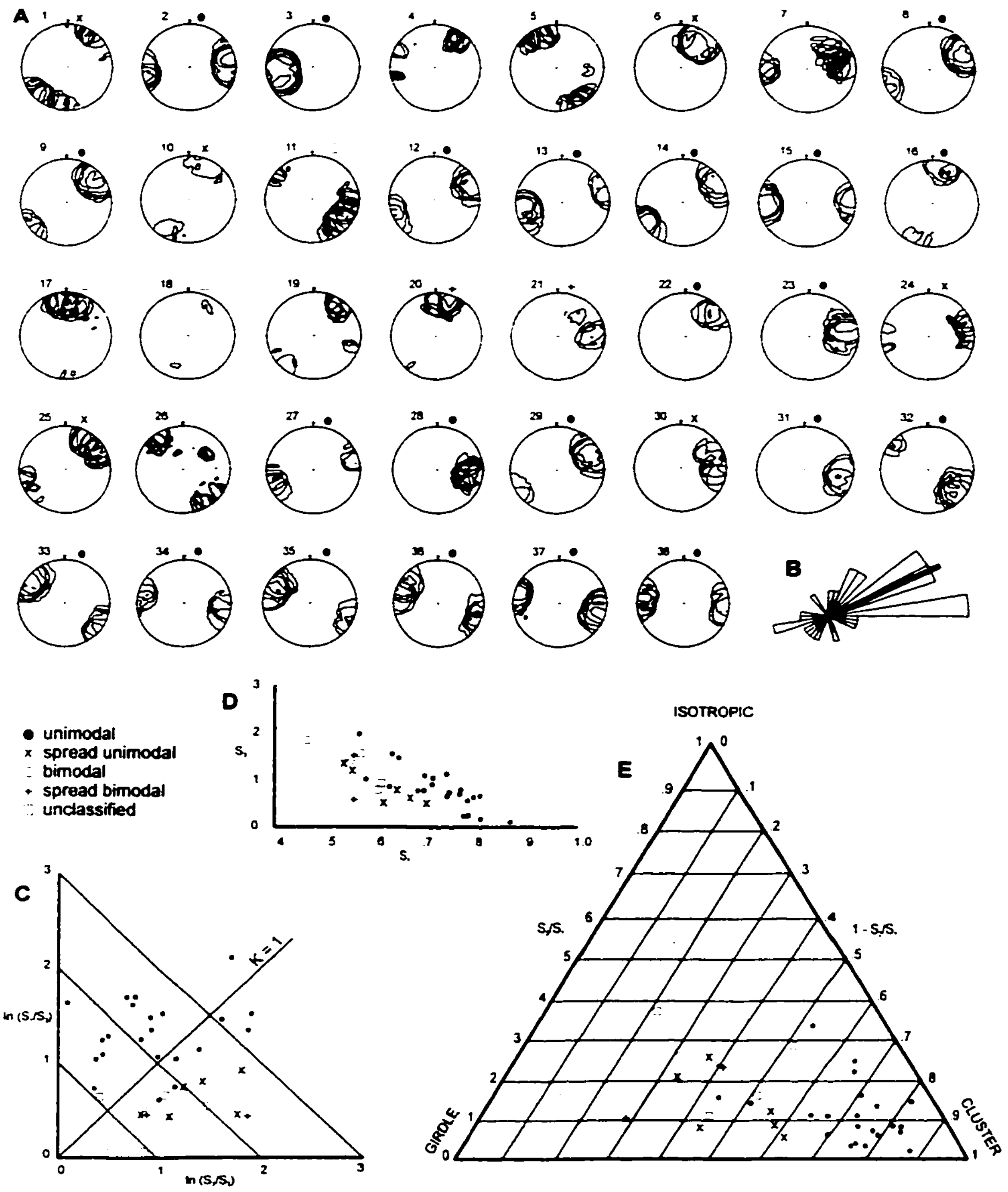

Figure 4.7: A. Stereonet plots of clast fabric results from Facies 3. Mean orientations, plunges, S_1, S_2, S_3, and K-values are listed in Table 4.1. On each plot, Hicock et al.'s (1996) classification is noted. B. Unidirectional rose diagram with all 38 mean orientations plotted. Dips are mainly towards ENE. C. 2-axis ratio plot showing the relationship between cluster and girdle distributions as defined by Woodcock (1997). D. May diagram showing the relationship between the principal eigenvalue and S_3. E. Benn diagram showing the tendency of the samples towards clusters, girdles, and isotropy. Note: all values are plotted using Hicock et al.'s (1996) classification.

Sample	O	P	S1	S2	S3	K
1 x	209.6	5.4	0.607	0.342	0.051	0.299
2 ●	81.4	7.9	0.784	0.185	0.031	0.803
3 ●	261.5	28.5	0.801	0.174	0.025	0.778
4 ○	68.4	7.3	0.489	0.424	0.087	0.090
5 ○	324.4	0.9	0.541	0.326	0.133	0.562
6 x	31.2	33.2	0.693	0.266	0.041	0.512
7 □	68.2	15.2	0.562	0.272	0.166	1.479
8 ●	51.5	15.2	0.803	0.135	0.062	2.268
9 ●	161.1	17.4	0.868	0.113	0.019	1.153
10 x	21.6	8.1	0.528	0.334	0.138	0.523
11 □	119.2	16.8	0.600	0.332	0.068	0.375
12 ●	69.9	9.0	0.716	0.199	0.085	1.510
13 ●	253.7	10.1	0.730	0.220	0.050	0.805
14 ●	58.8	3.6	0.794	0.142	0.064	2.142
15 ●	275.8	6.4	0.766	0.174	0.060	1.316
16 ●	19.1	7.5	0.635	0.220	0.145	2.563
17 □	7.5	19.9	0.603	0.299	0.098	0.630
18 □	222.8	0.3	0.448	0.382	0.170	0.198
19 ○	52.4	8.5	0.512	0.357	0.131	0.362
20 +	23.2	12.6	0.546	0.324	0.130	0.572
21 +	83.4	26.2	0.552	0.392	0.056	0.176
22 ●	36.0	18.7	0.575	0.326	0.099	0.472
23 ●	86.0	26.7	0.685	0.200	0.115	2.241
24 x	92.9	5.8	0.533	0.354	0.113	0.355
25 x	59.0	11.2	0.638	0.284	0.078	0.627
26 ○	326.5	7.1	0.422	0.354	0.225	0.394
27 ●	258.0	4.0	0.616	0.297	0.087	0.589
28 ●	89.4	22.1	0.550	0.261	0.189	2.329
29 ●	64.7	10.7	0.749	0.188	0.063	1.274
30 x	84.9	21.8	0.661	0.276	0.063	0.590
31 ●	103.2	15.9	0.697	0.225	0.078	1.072
32 ●	128.2	18.9	0.716	0.279	0.105	2.625
33 ●	301.8	8.8	0.780	0.164	0.056	1.442
34 ●	97.6	1.3	0.620	0.221	0.159	3.159
35 ●	295.8	13.2	0.748	0.138	0.114	8.500
36 ●	291.9	7.8	0.776	0.152	0.072	2.185
37 ●	97.4	5.6	0.777	0.195	0.028	0.720
38 ●	274.0	1.9	0.681	0.248	0.071	0.816

Table 4.1: Statistical results from clast fabric analysis. Numbers refer to Figure 4.7A, and symbols are the same as those used in Figure 4.7. O is the mean orientation, P is the mean plunge angle, S_1, S_2, and S_3, are the eigenvalues, and K is the degree of clustering. Hicock et al.'s (1996) classification is noted next to each sample number.

and plunge, were used to determine the degree of clast alignment in each sample (cf., Mark, 1973; Woodcock, 1977). Principal eigenvalues (S_1) > 0.65 indicate a tendency towards clustering of the sample around one axis in three dimensions. Where $S_1 = 1$ the sample is perfectly oriented and has a unimodal distribution ($S_2 + S_3 = 0$). Where $S_1 = S_2 = S_3 = 0.333$, the sample is perfectly isotropic (evenly distributed). The relationship between these eigenvalues reflects the shape of the fabric data on an equal-area net, which can be displayed graphically (Figs. 4.7C, D, E) or determined subjectively by simply observing the shape of sample distributions as they appear on the equal area net (Hicock et al., 1996). Using Hicock et al.'s (1996) classification, 22 samples are classified as unimodal clusters (Figure 7, Table 1), and a further 6 as spread unimodal. Twenty of these show clustering between ~ 20° and 80°, and they are considered to be well-oriented and indicative of the direction of shear. Eight cluster distinctly around ~305° (# 31-3), and although these are perpendicular to most other measurements, their eigenvalues are high, their plunge orientations are consistent, and they are regionally consistent. They are, therefore, also considered to be representative of local shear. Fabrics with bimodal distributions are intriguing because their axes of principal clustering take place around the same azimuths as the unimodal distributions: ~ NE - SW (#4, 19, 20), and ~ NW - SE (#5, 26). Four samples remain unclassified.

These subjective classifications can be tested graphically. On Woodcock's (1977) two-axis ratio plot (Fig. 7C), the line $K = 1$ separates girdle distributions from cluster distributions. Interestingly, all samples (except one) already determined as unimodal plots using Hicock et al.'s (1996) classification, lie above or just below the line $K = 1$. Values that plot near the origin of the graph represent both uniform and random patterns, and preferred orientation increases further from the origin. This explains why one measurement (sample #7 - modality unclassified) plots above the line $K = 1$, and yet the sample is not well-oriented, reflected by a low S_1 (0.562), and a relatively high S_3 (0.166).

The May diagram (Fig. 4.7D) demonstrates the relationship between the principal eigenvalue (S_1) and S_3. Many of the samples plot high on the x-axis (high S_1) and low on the y-axis (low S_3), indicating that they are well-oriented. Similarly, the Benn diagram (after Benn, 1994) demonstrates well that most of the samples plot towards the cluster point on the ternary plot. Twenty-six of the samples plot distinctly on the cluster area on the diagram ($1 - S_2/S_1 > 0.5$). These include all except one of the predetermined unimodal plots, three of the spread unimodal plots, and two unclassified plots. Hence, subjective and objective methods compare well.

All estimated shear directions from clast fabric analysis are plotted on Figure 4.8. Because the partly subjective and objective methods used above compare well with each other, all directions are plotted using Hicock et al.'s (1996) classification. Unimodal and spread unimodal are the most reliable indicators of shear. Directions are regionally consistent, and it is concluded that the primary shear responsible for orienting the samples was from ENE. This is also demonstrated on Figure 4.7B.

Sand and silt interbeds

Sorted interbeds are composed of sand in the northernmost exposures, and silt in the southernmost exposures at McGregor Reservoir. Sand interbeds are usually only a few grains thick (Fig. 4.9), but in some places they are up to 3 cm thick. The thicker strata are horizontally bedded, well-sorted, normally graded, and undisturbed. These thicker beds, in places, have thin, conformable, diamicton beds interleaved with sand strata (Fig. 4. 10A). These thin diamicton beds are similar in composition and colour to the main diamicton beds in Facies 3, but are discontinuous, and pinch and swell along their length. At some locations, where large boulders are present, adjacent sand strata swell into convex-downward lenses of sand that infill scours eroded through one or more of the underlying diamicton beds (Fig. 4.9). Sand in the depressions is crudely bedded, and moderately well sorted. Diamicton strata adjacent to large boulders simply stop at the boulders, while strata immediately overlying the boulders drape them (Fig. 4.9).

In the southernmost exposures, sorted beds are dominated by silt, and range from a few millimeters to approximately 15 cm thick. Faint stratification can be observed, although grain size is relatively consistent. Lying along the contacts between the silt and the diamicton beds, and occasionally along a plane in the diamicton strata, are subangular clasts of soft, finely laminated clay (Figs. 4.10B, C). These range from a few millimeters to 3 cm in diameter, and bedding is always undisturbed. At most locations they are present as a single-clast-thick unit (Fig. 4.10B), but elsewhere they form a brecciated unit several clasts thick, supported by a silty matrix (Fig. 4.10C).

Interpretation

To understand the depositional environment for Facies 3, I first discuss the possible processes of formation for the diamicton beds, and then the sand/silt beds. Because these two sediment types are intimately related and extensive, the processes responsible for their deposition

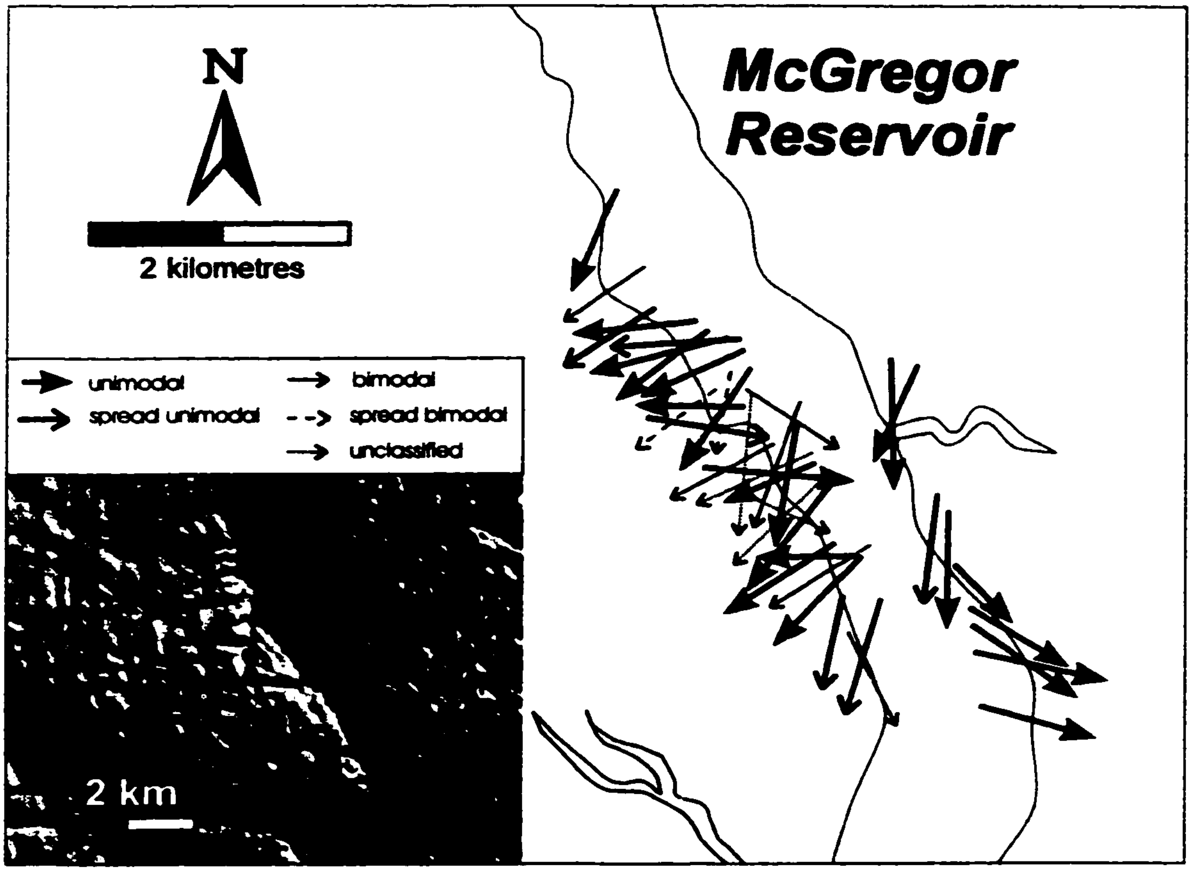

Figure 4.8: Regional distribution of inferred ice flow directions within the main area of exposures at McGregor Reservoir. The thickest arrows (unimodal and spread unimodal) are statistically the most reliable indicators. Inset is a DEM showing the hummocky topography in the region. The five anomalous directions in the southeast exposures are #34-38 in Figure 4.7 and Table 4.1.

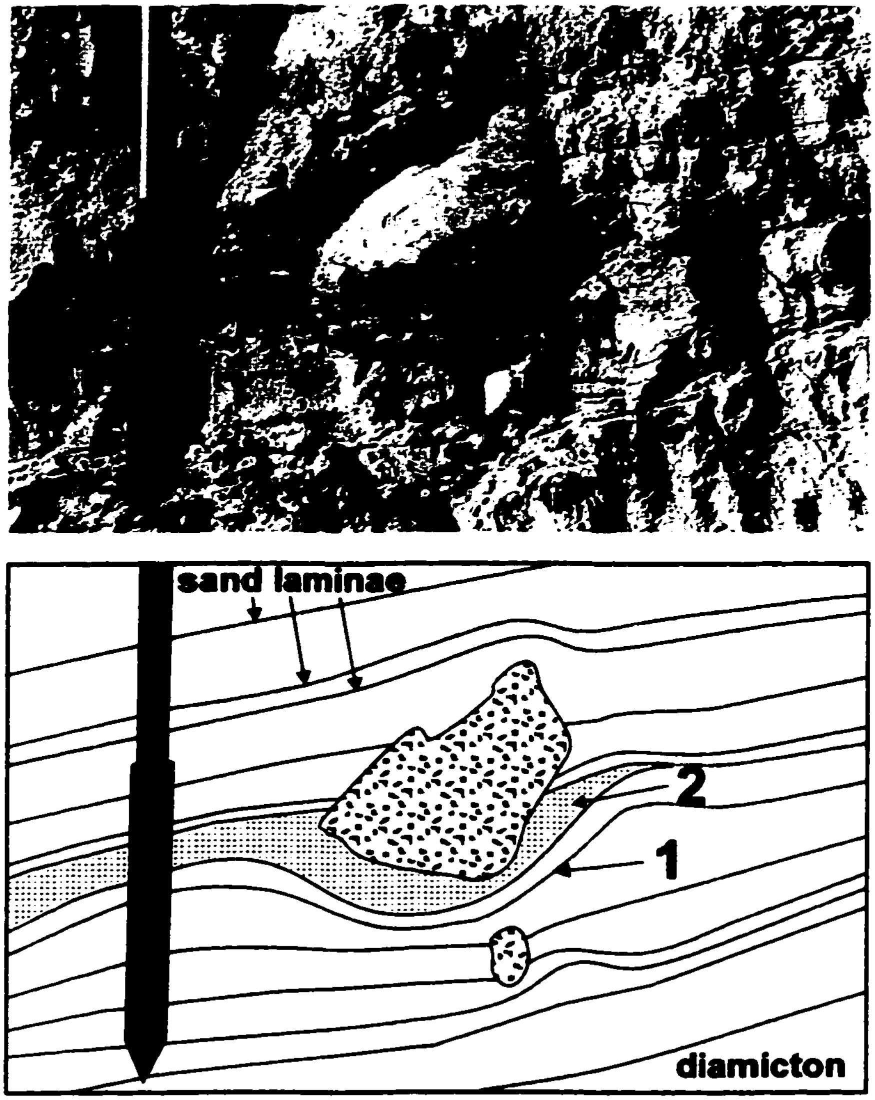

Figure 4.9: Large boulders in Facies 3 often have sand-filled scours below them that cut into underlying diamicton units. Two phases of scouring took place under this boulder. The first scour (1) is lined by a thin unit of sand and then infilled with diamicton. The diamicton is not of melt-out origin, because the boulder is immediately above it, and hence there was no sediment to melt out of the ice. It likely represents minor slurry flow into the depression after scouring occurred. The second scour (2), cuts into the slurry flow diamicton, indicated by the thinning of the diamicton below the boulder. This scour is filled with sorted sand.

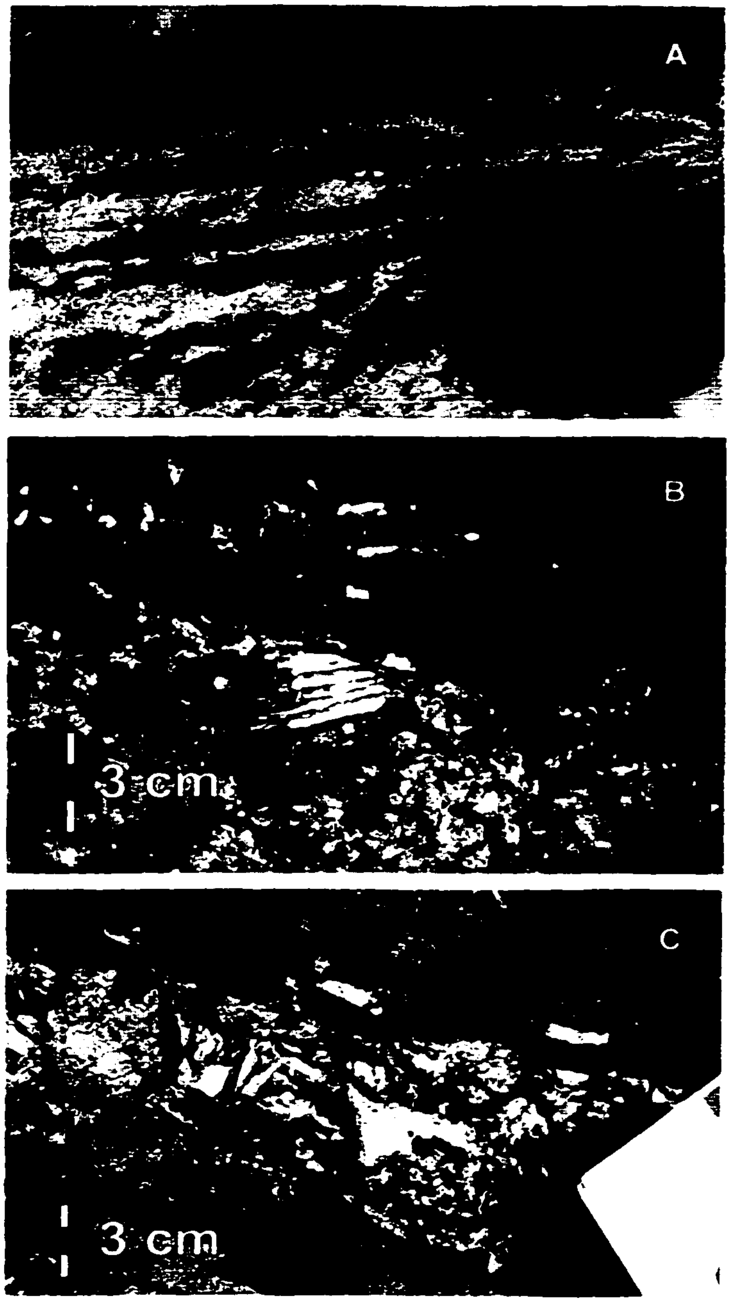

Figure 4.10: A. Some sand beds are relatively thick (> 1 cm). The interbedded diamictons (darker beds) are irregular in thickness and even taper and disappear in places. B. Silt beds in the diamicton occasionally have rip-up clasts of laminated silts and clays. These clasts are angular, indicating short transport distances. C. At some locations beds of rip-up clasts can be several clasts thick. These still maintain internal structures.

must operate at different times at the same location within a broad sedimentary environment. This inference leads to detailed reconstruction of sedimentary processes and the environment of deposition.

Diamicton beds

Two lines of evidence are used to interpret the diamicton beds: (i) sedimentary structures and properties, and (ii) clast fabric analysis.

(i) *Sedimentary structures and properties*

Although massive diamictons form in a variety of environments, the characteristics of these beds document subglacial sedimentation. First, striated clasts indicate that glacial processes were important in the transportation of the rocks within these beds (Haldorsen, 1983). The variability of shape, roundness, and the degree of striation and faceting is primarily a function of source, lithology, and original mode of transport and deposition. For example, Canadian Shield clasts have a greater tendency to be subangular to subrounded and have faceted faces due to primary transport by glacial ice. Quartzites were rounded during fluvial transport of preglacial gravels and were subsequently incorporated into glacial ice and redeposited. Many of these clasts are now striated, yet they maintain their primary fluvial characteristics. The hardness of quartzite, and the relatively short ice transportation distances, prevented significant modification of the original shapes of these fluvial clasts.

Sorted interbeds indicate that deposition by flowing water intervened between periods of diamicton deposition. Importantly, where large boulders intersect sand laminae, sorted sediment infills erosional scours cut into underlying beds (Fig. 4.9). These scours, and sand fills, located beneath boulders are best explained as resulting from water erosion followed by deposition. Because the scours are beneath the boulders, and sand intervenes between the boulder and scoured bed, the boulders must have been supported from above into flowing water (Shaw, 1982). A reasonable means of doing this in the subglacial environment is to suspend the boulders from the ice bed. A boulder projecting in this way acts as an obstruction to flow, causing local flow acceleration, turbulence, and scour. During waning flow, graded sand was deposited in the scour depressions. Thus, water flowed at the base of the ice sheet and eroded into the underlying sediments where boulders projected downwards into the flow. Diamicton beds were deposited by melt-out at the base of the ice as beds drape over the melted-out boulders (cf., Shaw, 1982).

(ii) *Clast fabric analysis*

Clast fabric analysis is helpful in sedimentary interpretations and is best used in conjunction with other observations and analysis (e.g., Hicock et al. 1996). Of the 38 fabrics recorded from the diamicton strata, most have well developed orientation patterns (Table 1, Fig. 4.7).. With few exceptions, these fabric patterns are regionally consistent (Fig. 4.8), although there are some local patterns, such as at the southeast of McGregor Reservoir, that appear to be independent of regional trends. This local pattern at McGregor Reservoir is represented by # 33-38 in Table 1.

Deposits with well-oriented fabrics include lodgement till (e.g., Benn, 1995), melt-out till (e.g., Lawson, 1979; Shaw, 1979), some deformation tills (e.g., Benn and Evans, 1996), some rain-out diamictons (e.g., Domack and Lawson, 1985; Visser, 1989), and some debris flows (e.g., Visser, 1989). Debris-flow sedimentation is discounted for these diamicton beds because multiple fabrics from debris flows are expected to be more variable in strength and orientation than is observed in this facies (cf., Lawson, 1979). Both lodgement and subglacial deformation are discounted as origins of Facies 3 because continuous sorted strata could not survive these processes, and the expected properties for lodgement and deformation, such as fissility, rotation of clasts, and sediment deformation, are not present. Also, multiple fabrics from deformation tills are generally characterized by spread bimodal and multimodal fabric patterns (Hicock et al., 1996), and hence low principal eigenvalues. Large variations in plunge angle are also usually recorded (Benn and Evans, 1996).

Multiple fabrics with high principal eigenvalues, strongly unimodal distributions, and consistent plunge orientations are usually attributed to direct subglacial melt-out (e.g., Lawson 1979; Shaw 1979), where clasts melted out from glacial ice preserve the flow pattern inherited from the ice. Passive melt-out results in little modification of the fabric, although through consolidation plunge angles decrease, and in some cases even reverse (Lawson, 1979). Plunge reversal explains why some unimodal plots have clasts plunging towards the ENE but many also plunging to the WSW.

If clasts throughout the diamicton beds inherited their orientation from ice, then that ice was previously flowing across the area from the ENE. These clasts and associated debris were melted out from the base of stagnant glacial ice. The alternative, that the ice was active, is contradicted by the presence of small diapirs that occasionally intrude into the overlying silts and sands, which would be overturned by any degree of subglacial basal shear. Also, the unconsolidated laminated clay clasts that lie between some diamicton beds, but in direct contact with them, would have been destroyed.

It is not certain why fabrics # 33-38 have different orientations, but those orientations are locally consistent, their eigenvalues are high, and, therefore, they are taken to represent ice flow direction. There may have been local changes in ice flow direction prior to stagnation related to local topographic control, or to melting patterns at the ice bed (cf., Brennand et al., 1996). Alternatively, if Facies 2 sediments are representative of a subglacial lake (Munro-Stasiuk, in press), ice flow patterns may relate to the position of that lake at the base of the ice where ice flow was fast over the lake area, and then divergent at the downflow end and in the lee of the subglacial lake (Shoemaker, in press).

On the basis of sedimentary structures, and spatially consistent well-oriented fabrics, the till beds were most likely formed by melt-out at the base of the ice sheet when it was close to its bed.

Sand and Silt Strata

It has already been established above that sorted beds were deposited by flowing water, and interbedding of these with diamictons indicates an alternation of glacial and glaciofluvial processes. Strata are unusually laterally extensive giving entire exposures of the beds in Facies 3 the appearance of banded diamicton (e.g., Figs. 4.6A, B). It is important, however, to note the difference between stratified and banded diamictons because they imply different environments of deposition. Banded diamictons consist of alternating strips of debris of differing compositions, but sorting is rarely observed. These have been attributed to a number of processes: melting, or sublimation, of ice preserving debris bands from glacial ice (Lawson, 1979; Shaw, 1979); pervasive deformation within the sediments at the base of ice causing attenuation of beds and streaking (Hart and Boulton, 1991; Hicock and Dreimanis, 1992; Benn and Evans, 1996); and flow of debris (Evensen et al., 1976; Proudfoot, 1985).

Sand and silt beds in Facies 3 are sorted, and therefore represent primary deposition rather than banding. Similar intradiamicton sorted sediment has been attributed to subglacial and englacial flowing water (Shaw, 1979), sedimentation in water-filled conduits or cavities below glacial ice (Gibbard, 1980; Dreimanis, 1982; Shaw, 1982, 1987), glaciolacustrine sedimentation between debris flows (Proudfoot 1985; Levson and Rutter, 1988), and deposition of laminated sands and muds from inflow plumes between winter periods of intense iceberg rafting (Cowan et al., 1997). Scouring under boulders indicates that the boulders must have been suspended from glacial ice, hence water must have flowed between the ice and the substrate. However, the lateral continuity over hundreds of meters is unlike the discrete lenses produced in englacial or subglacial channels (e.g., Eyles et al., 1982; Haldorsen and Shaw, 1982; Shaw, 1982), and suggests that the water flowed as a broad sheet. Such sheetflow requires that the average water pressure equaled the overburden pressure. Subglacially stored water with pressures slightly above overburden pressure can spread out laterally below the ice lifting the ice off its bed (Nye, 1976; Weertman, 1986). Sudden connection of stored water would result in sheet flow in the reservoir and beyond if the flow resistance at the outlet was high. The sheet in this case was shallow (< 20 cm), as indicated by the scours below boulders, which required rapid and shallow flow for their formation. Hence, the stored water layer was, also, likely very shallow. Because sheets are inherently unstable (Walder, 1982), channelization would have occurred rapidly, although turbulent flow can delay the collapse of sheetflow (Shoemaker, 1995). Channels are observed at a number of locations (e.g., Fig. 4.6C) which may represent this sheet collapse, but each represents only one scour phase: lags of coarse sediment and channel filling with till and sorted interbeds indicate that the channels were short-lived.

Thin diamicton beds that pinch and swell along their length, and are interbedded with the sand beds, likely represent deposition from highly liquid slurry flows. The preservation of all strata strongly supports deposition of the entire diamicton/sand complex under stagnant ice in the absence of ice-induced shear stress at the bed (e.g., Shaw,1979).

SEDIMENTATION MODEL

The diamicton beds at McGregor Reservoir are interpreted as melt-out till deposited directly from the base of the Laurentide Ice Sheet. Sorted laminae of sand or silt between diamicton beds record water flow at the base of the ice. Storage and release of meltwater are crucial to the explanation of laterally extensive sorted beds. This water likely also played a role in the deposition of the diamicton beds. Given the inference that a body of water existed under the ice, then rain-out would have occurred through a water column if material was being melted out of the base of the ice. However, since the englacial fabric orientations are preserved, this further indicates that the water was shallow. If clasts fall through only a few centimeters of water, they would maintain their fabrics although plunge angles of englacial clasts would change. If, however, they fall through a substantial column of water, clasts would be reoriented (Boulton et al., 1974; Dowdeswell and Sharp, 1986), many with high plunge angles typical of rain-out diamicton (Domack and Lawson, 1985; Visser, 1989). Rain-out through deeper water, perhaps exceeding ~ 20 cm (the thickness of the thickest diamicton bed), may explain weaker preferred clast fabric orientations at a few locations.

Multiple sorted strata record many drainage events. Each event resulted in minor erosion and winnowing of sediment from the surface of the last-deposited diamicton bed, and from the base of the ice. It also resulted in removal of fine sediment (silt and clay) in suspension. However, the sand partings are thin, probably because the surrounding diamicton beds contain little sand. Unusually thick sand beds (e.g., Fig. 4.10A) can be explained in either of two ways. (i) The sediment melted out of the ice at that location may have been sand-rich and hence more sand was available for transport. (ii) More plausibly, sheet flows may have cut into older, sand-rich sediments and deposited thicker sand beds downflow from the local sources. This latter explanation is preferred because it also explains rip-up clasts in some silty interbeds in the southernmost exposures at McGregor Reservoir (Figs. 4.10B, C). These unlithified, angular clasts indicate short transport distances. Rhythmically bedded silts and clays underlie Facies 3 only 10 - 30 m laterally from the location of the rip-up clasts. The preservation of these clasts is also in keeping with the idea that ice was stagnating during the deposition of these beds. In summary, Facies 3 is inferred to have formed in the following sequence (Fig. 4.11):

1. Water accumulated at the glacier bed during basal melting of the ice sheet. As a result, the ice was lifted off its bed and diamicton was deposited by direct melt-out and rain-out into the meltwater reservoir.

2. When the reservoir connected to another subglacial cavity at lower pressure, or to a channel, or to the ice front, it drained rapidly. During drainage, fine-grained sands, silts, and clays were transported by suspension and coarser sands as bed load. Frictional melting of the debris-rich basal ice added sediment to the flow as did erosion of the underlying diamicton, especially at constrictions in the sheet such as below boulders. Fining towards the south marks subglacial palaeoflows in that direction.

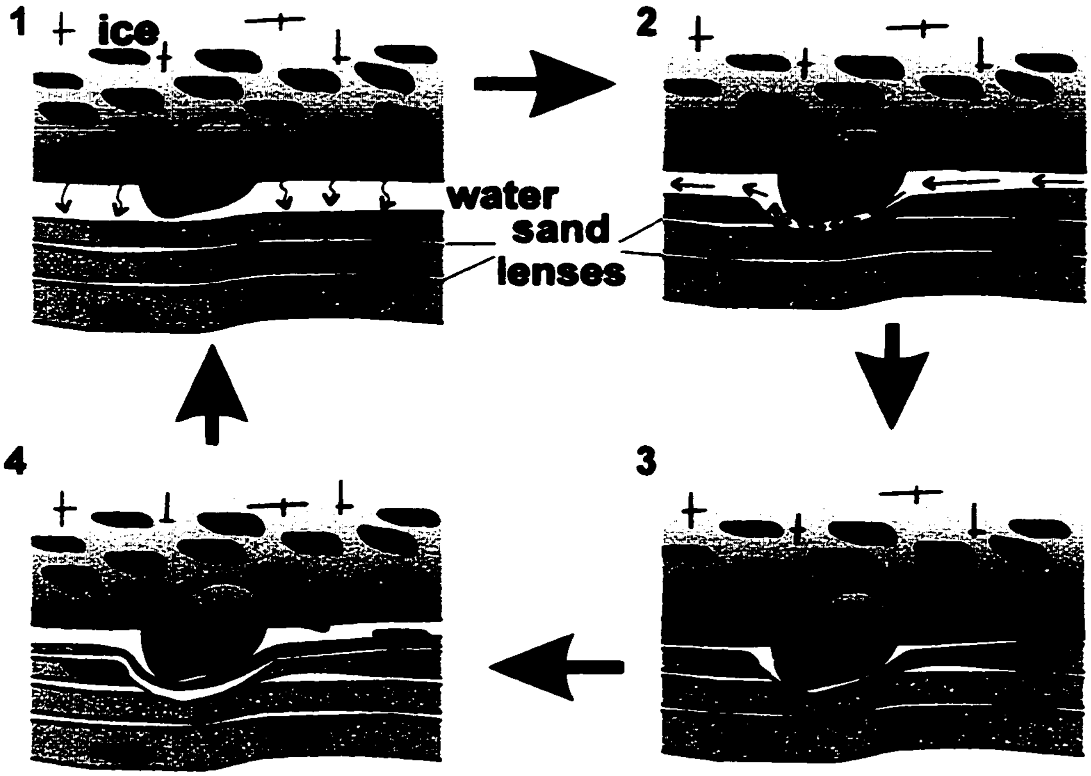

Figure 4.11: Proposed model of till sedimentation. See text for explanation.

3. After drainage, the ice and bed recoupled, and sedimentation was by direct melt-out on to the bed.

4. A subglacial reservoir was reestablished; the interval between drainage and reservoir reestablishment (the period of melt-out till deposition) is discussed in the next section.

RHYTHMICITY OF SEDIMENTATION

Each diamicton bed is taken to represent a period of steady melt-out and/or rain-out directly onto the bed and/or into a shallow subglacial water body. Each sand/silt bed then represents the sudden drainage of that reservoir. Repetition of these events marks rhythmic sedimentation, and each diamicton and sand/silt unit is a couplet. These couplets likely represent a drainage threshold imposed by ice thickness and bed elevation (Nye, 1976) and, hence, also record changes in water pressure. For McGregor Lake, the drainage connection was via a tunnel channel, carrying meltwater southward to a large lake at the site of Travers Reservoir (Facies 2 at Travers Reservoir). The north to south fining in the sorted beds of Facies 3 supports southward drainage.

Rhythmicity may also record annual cycles. Similar thicknesses of diamicton beds may support this. Iken et al., (1983) noted that the surface of Unteraagletscher is uplifted by as much as 60 cm, and this was attributed to storage at the bed at the beginning of each melt season. Skidmore (1995) observed outbursts from John Evans Glacier, Ellesmere Island, and attributed these to the annual release of stored subglacial water. Contemporary sediments deposited in subglacial reservoirs, however, have not been observed. If these couplets are varves, it is unlikely that the sand/silt layers represent the final sedimentation stage of a particular year. If, as suspected, drainage occurs near the beginning of the melt season, then the year is defined as the time between drainage events: from spring to spring. If these layers are annual, then between 5 and 20 cm of debris was melted out of the ice each year, which is significantly higher than reported average melt rates (Nobles and Weertman, 1971)

The sequence of events that would have led to water build-up and drainage is outlined below, and these are shown diagrammatically on Figure 4.12.

1. Water was fed into the McGregor Valley from various sources, including supraglacial meltwater delivered to the bed and transported subglacially via

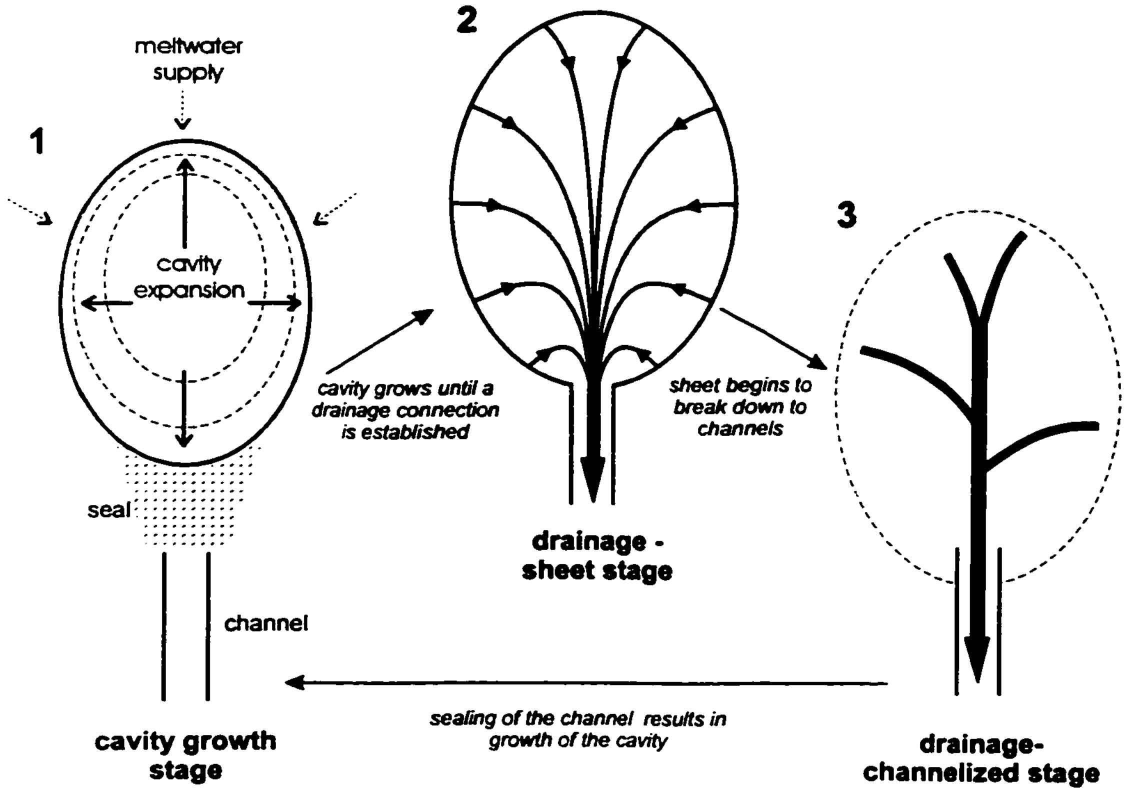

Figure 4.12. Proposed model of till accumulation and expulsion of subglacially stored water. Dashed arrows represent meltwater inputs. Dashed circles represent the growth or decay of the stored water. See text for explanation.

channels, and meltwater produced by frictional and geothermal heat. Because there was no outlet for the water, it was stored in the preglacial McGregor Valley and continued to accumulate with increasing water pressure, hydraulically lifting the ice and extending the reservoir area (Weertman, 1986).

2. The cavity grew large enough to make a connection with a channel at the south end of the McGregor Valley, resulting in drainage. It should be noted that the depth of the channel in today's landscape (Fig. 4.1) erodes Facies 3 and is therefore younger. As the water was stored over a broad area, flow in the reservoir was as a sheet towards the outlet. Scouring, winnowing, and transport in suspension and by traction resulted from this. This sheet flow was followed by deposition of extensive sand and silt sheets with localized scours.

3. The sheet flow was unstable, and broke down into channels. Smaller, lateral channels (Fig. 4.6C) fed a large channel along the valley floor (cf., Shreve ,1972). Drainage eventually ceased when the outlet was sealed, leaving minor disconnected cavities in place of the large reservoir.

DISCUSSION AND CONCLUSIONS

Consistently well-orientated fabrics, striated clasts, preservation of sand strata, and draping of sand and diamicton strata over clasts indicate that the diamicton beds in Facies 3 at McGregor Reservoir are primary, subglacial melt-out till (cf., Lawson, 1979; Shaw, 1982). Laterally extensive, sorted strata document small-scale sheet flow at the base of the ice. Sheet flow requires water storage, at least over the area where the sheet flowed. This water was shallow, no more than 20 cm deep, as indicated by the scouring on the underside of boulders that were suspended from ice into the escaping flow and the preservation of clast fabrics. Because ice was melting, the diamicton beds are at least partly the result of rain-out through a water column. Cycles of meltwater storage and drainage resulted in this rhythmic alternation of till and sorted beds, possibly representing annual sedimentation.

The reservoir covered a maximum area of ~ 4 km by 1 km, documented by the areal extent of the sorted beds. At 20 cm water depth, the total storage would have been ~ 8×10^5 m ^{3}. This estimated depth is probably a maximum and, therefore, the total storage estimate is also a maximum. During specific storage events, total volume may have been significantly less than this estimate if the storage area was smaller. Channels may have ranged from approximately 3 m by 1 m (size of smallest channels observed cutting the till beds), to up to 1 km across (widest channel observed in the area leading away from McGregor Reservoir). Unfortunately the actual dimensions cannot be determined, because evidence of old channels has been removed by the deep meltwater channel that now joins McGregor Reservoir to Travers Reservoir (Fig. 4.1). At critical flow velocities for sand (~ 0.3 m/s) (Sundborg, 1956), and channel cross-sectional areas ranging from ~ 3 m^2 to 2 x $10^4 m^2$, drainage duration would have been between ~ 2 minutes to 21 days, depending on the size of the channel(s) that removed the water. These times assume that there were no constrictions to drainage.

Prior to till deposition at McGregor Reservoir, both the McGregor and Travers preglacial valleys contained relatively deep subglacial lakes (up to ~ 60 m) which are inferred to have controlled local ice and water flow patterns (Munro-Stasiuk, in press). Extensive shearing in the lowest units of Facies 2 indicates ice/bed recoupling during the initial existence of these large subglacial water bodies. The incidence of deformation decreases upwards throughout the beds of Facies 2, that eventually grade into, and interfinger with Facies 3 (Fig. 4.5), which represents stagnating ice. Hence, the sequence represents initial active ice, followed by stagnation. Whether this transition was gradual or abrupt cannot be determined. Ice dynamics inferred from these sediments are typical of those observed at modern glaciers where water is present below the ice (Iken et al., 1983; Arnold and Sharp, 1992). As well, the presence of subglacial reservoirs results in local flattening of the ice sheet. Low ice-sheet surface gradients were suggested for the prairie regions on the basis of moraine gradients (Mathews, 1974) and extreme lobation of the ice front (Clayton et al., 1985). The presence of water either as a film above the clayey tills of the prairies, or within the tills, has been suggested for the rapid ice movement and hence low profiles in the region (Mathews, 1974; Boulton et al., 1985). Here, it is suggested that the presence of stored water in the preglacial valley system may have been as, or even, more important to ice streaming and flat ice profiles than the presence of deformable beds (cf., Shaw, 1994).

Resurgence of the ice after till deposition is also recorded by folding of all facies (although not at all locations). Also, flute marks created by the dragging of boulders through wet sediment (Fig. 4.6D) may record this resurgence. The distance traveled by basal ice cannot be determined, but it may be as little as tens or hundreds of metres given the low strain recorded by folds. After modern glacier surges, snow accumulation upstream results in steepening of the ice profile (Paterson, 1994). Modeling of ice sheets also demonstrates flattening of the ice-sheet profile near the ice margin, resulting in an oversteepened profile further upstream (Fisher et al., 1985; Arnold and Sharp, 1992). Such steepening may result in quiescence/surge sequences typical of modern surging glaciers (Kamb, 1987).

Although the rhythmic sedimentation model presented in this paper is new, similar sedimentary packages observed elsewhere (e.g., Proudfoot, 1985) may be ascribed to similar processes. Detailed sedimentary observations and interpretations should inform ice-sheet models. For instance, most models of the Laurentide Ice Sheet assume that bed deformation was responsible for flat profiles and ice streams (e.g., Fisher et al., 1985). I suggest that water reservoirs at the ice/bed interface may have been a factor in glacier flow and ice-sheet profiles. As well, sediment deformation with relatively low strain (folds are not highly attenuated) records ice recoupling with the bed following reservoir drainage and effective pressures > zero.

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CHAPTER 5: EVIDENCE FOR WATER STORAGE AND DRAINAGE BENEATH THE LAURENTIDE ICE SHEET, SOUTH-CENTRAL ALBERTA, CANADA[1]

INTRODUCTION

All exposures discussed in this paper occur within the preglacial valley system in south-central Alberta. These exposures are at Carmangay and Travers Reservoir (in the Tee Pee preglacial valley) and at McGregor Reservoir (in the McGregor preglacial valley) (Fig. 5.1). Extensive riverbank and reservoir shoreline erosion exposes up to 70 m of sediment. The Carmangay exposure lies within an area of fluted terrain, which is draped by Glacial Lake Carmangay sediments (Fig. 5.1). All other exposures lie within the McGregor Moraine (Shetsen, 1984; Buffalo Lake Moraine of Stalker, 1977), a major north-south trending zone of hummocks. This moraine was originally thought by Stalker (1977) to represent the Late Wisconsinan maximum in Alberta, but was later reinterpreted as interlobate (Shetsen, 1984). More recent research indicates that the hummocks are erosional rather than depositional (Munro and Shaw, 1997). Hence, the hummocky zone is not a moraine, and the sedimentary descriptions and interpretations presented here do not support a depositional model for hummocky terrain in south-central Alberta. The two youngest glacigenic facies in the preglacial valleys are interpreted as subglacial, aqueous deposits. This interpretation implies local storage of meltwater in subglacial reservoirs.

LITHOSTRATIGRAPHY IN THE PREGLACIAL VALLEYS

Deposits in the preglacial valleys of the study area are described in three major facies:

Facies 1 occurs throughout the study area, both in the preglacial valleys, and on the Prairie surface. It is composed of massive, fissile, clayey, bluish-grey diamicton which often interfingers with thrust, bedrock or is sheared, or diapirically intruded into the overlying younger facies (see Figures 3 and 4; Munro and Shaw, 1997 - appendix A). Erratic Canadian Shield clasts transported by continental Laurentide ice appear first in these beds, and record initial Laurentide glaciation in the region. Most clasts are striated, faceted, or bullet-shaped, indicating that they were transported by this ice sheet. Clasts are weakly oriented, probably as the result of the widespread disturbance.

Properties of Facies 1 indicate that it is likely lodgement till (cf., Dreimanis, 1982; Clark and Hansel, 1989). Although clast fabric relates to post-depositional disturbance, and gives no indication of ice direction, fold noses in thrust bedrock indicate that flow was towards the southwest.

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[1] In press, Annals of Glaciology, v. 28

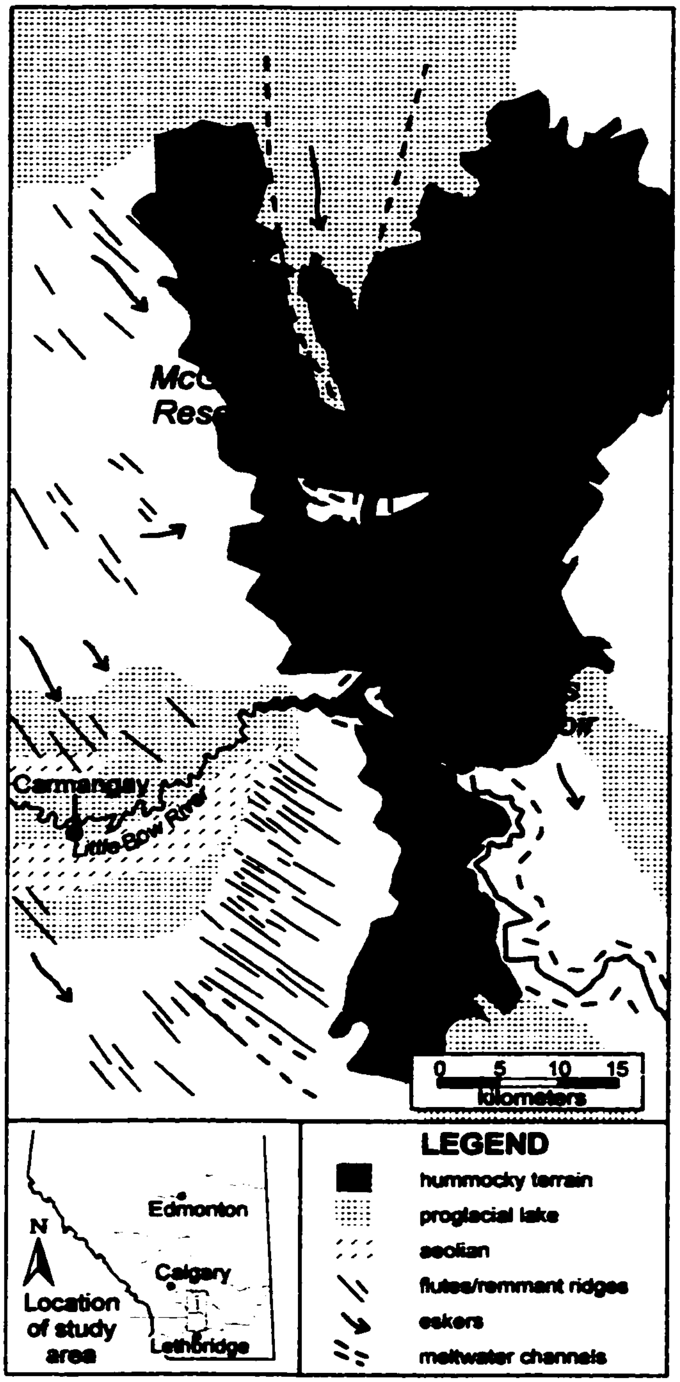

Figure 5.1: Generalized geomorphology of the study area. Also marked are the locations of places mentioned in the text.

A similar till extends over much of southern Alberta and is named the Labuma Till. Although there is much argument over its age (cf., Harris and Waters, 1977), it is inferred here on the basis of stratigraphy and spatial relationships to be Late Wisconsinan. This age is supported by evidence for a single continental glaciation in other parts of Alberta, both upglacier and downglacier from the study area (Liverman et al., 1991; Young et al., 1994; and Jackson et al., 1996).

Facies 2 (Figs. 5.2, and 5.3) is complex with multiple interbedded subfacies. Subfacies include, thick units (metres), of compact, silty diamicton, and massive diamicton with rip-up clasts (Fig. 5.3). Beds of this subfacies are thinner (10's of cms thick) in the top 10 m of Facies 2, where they commonly occur as part of rhythmically-bedded sequences (Fig. 5.3A). Sorted pebble and cobble beds, rippled sand, rhythmically-bedded silt and clay, and laminated silt, sand, and clay are also common (Figs. 5.3A and 5.4). While Facies 2 continues over the entire length of McGregor Reservoir, Travers Reservoir, and the Little Bow River exposures, subfacies are limited to no more than 200 m in length. Contacts between subfacies may be gradational, but most are abrupt. While the lowermost beds of Facies 2 are intensely sheared, faulted, and folded (Fig. 5.5), the upper beds are undisturbed. Laminated and rhythmically-bedded silt of Facies 2 grades upwards into, and interfingers with, Facies 3 (Figs. 5.4, and 6). Cross-cutting shear planes document multiple phases of thrusting southward and southwestward. Facies 2 is restricted to the preglacial valley system (Fig. 5.2). It is at least 70 m thick in places (e.g., Fig. 5.7), but this may be exceeded where the lower contacts are not always exposed.

Abrupt transitions between subfacies are typical of complex depositional subaqueous environments fed by seasonally varying glacial meltwater (Rust and Romanelli, 1975). Sediment input varied both spatially and temporally, and high-magnitude events are recorded by turbidites with thick sets of ripple cross-lamination, and debris flow deposits. Intervening periods of low sedimentation rates are documented by silt and clay rhythmites, representing deposition from suspension. Turbidites, debris flow deposits with rip-up clasts, and suspension deposition, are common to glacial lake environments. Ice was either proximal to, or in direct contact with sediments during deposition of the entire sequence, as documented by slumping, folding, shearing, and the large volume of sediment in the system.

Facies 3 is largely restricted to McGregor Reservoir (Fig. 5.2). It conformably overlies, and interfingers with, beds of Facies 2 (Figs. 5.4 and 6). Two main sediment types are present: laterally extensive, massive, fine-grained diamicton beds of about the same thickness (5-15 cm); and thin (several grains to a few mms thick), beds of sand that grade continuously southward, over a distance of about 1 km, to thicker silt beds (2-15cm) (Munro-Stasiuk, in press). The diamicton and sorted

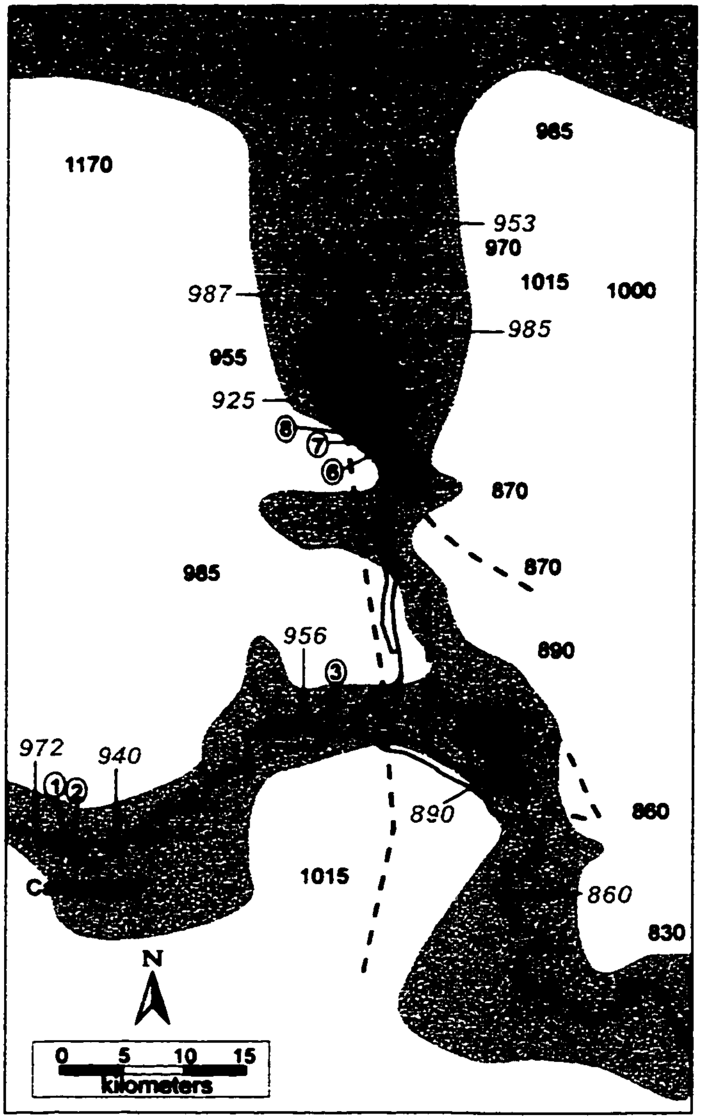

Figure 5.2: Spatial distribution of Facies 2 (light grey) and Facies 3 (dark grey). Locations of all transects in Fig. 5 are marked as #'s 1 - 8. Elevations (in meters) of Facies 2 are indicated in italics. Topographic elevations are also shown in black text. Preglacial valley thalwegs are marked by the dashed lines.

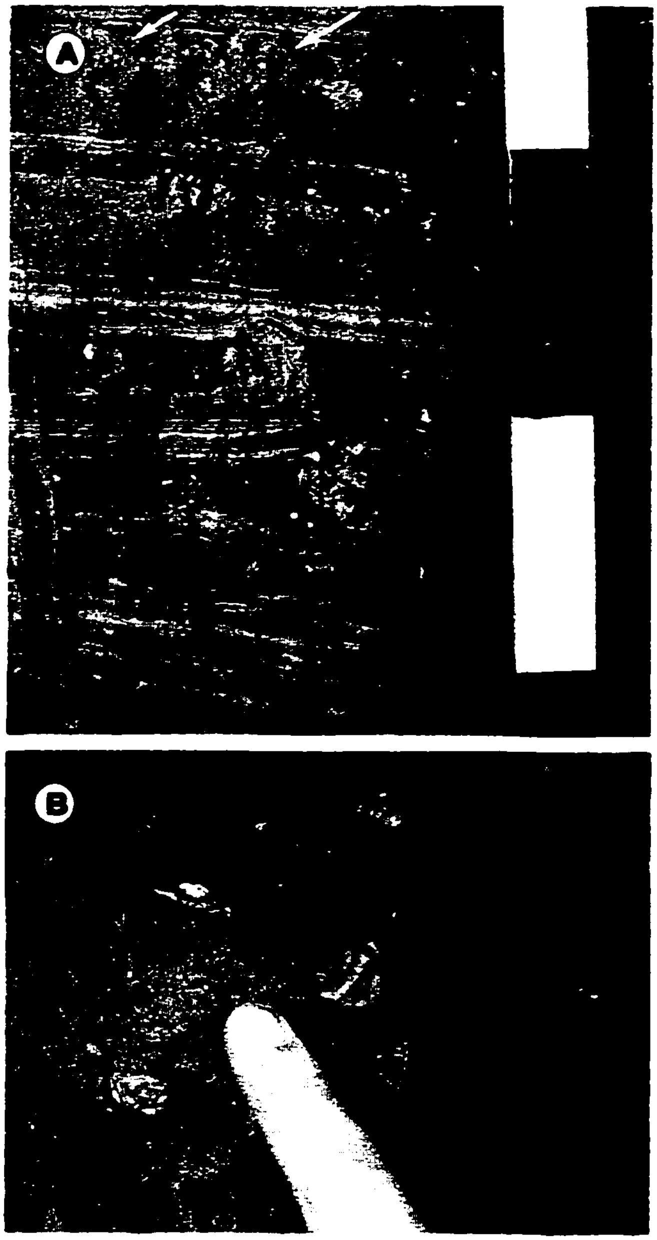

Figure 5.3: A. Sediment typical of gravity flows in Facies 2. Silty diamictons with rip-up clasts are draped by silt laminae and load underlying silt laminae (arrows). Large rip-up clasts have been rolled along for some distance and rounded. B. Typical rip-up clasts of rhythmically-bedded clays within massive silty diamictons.

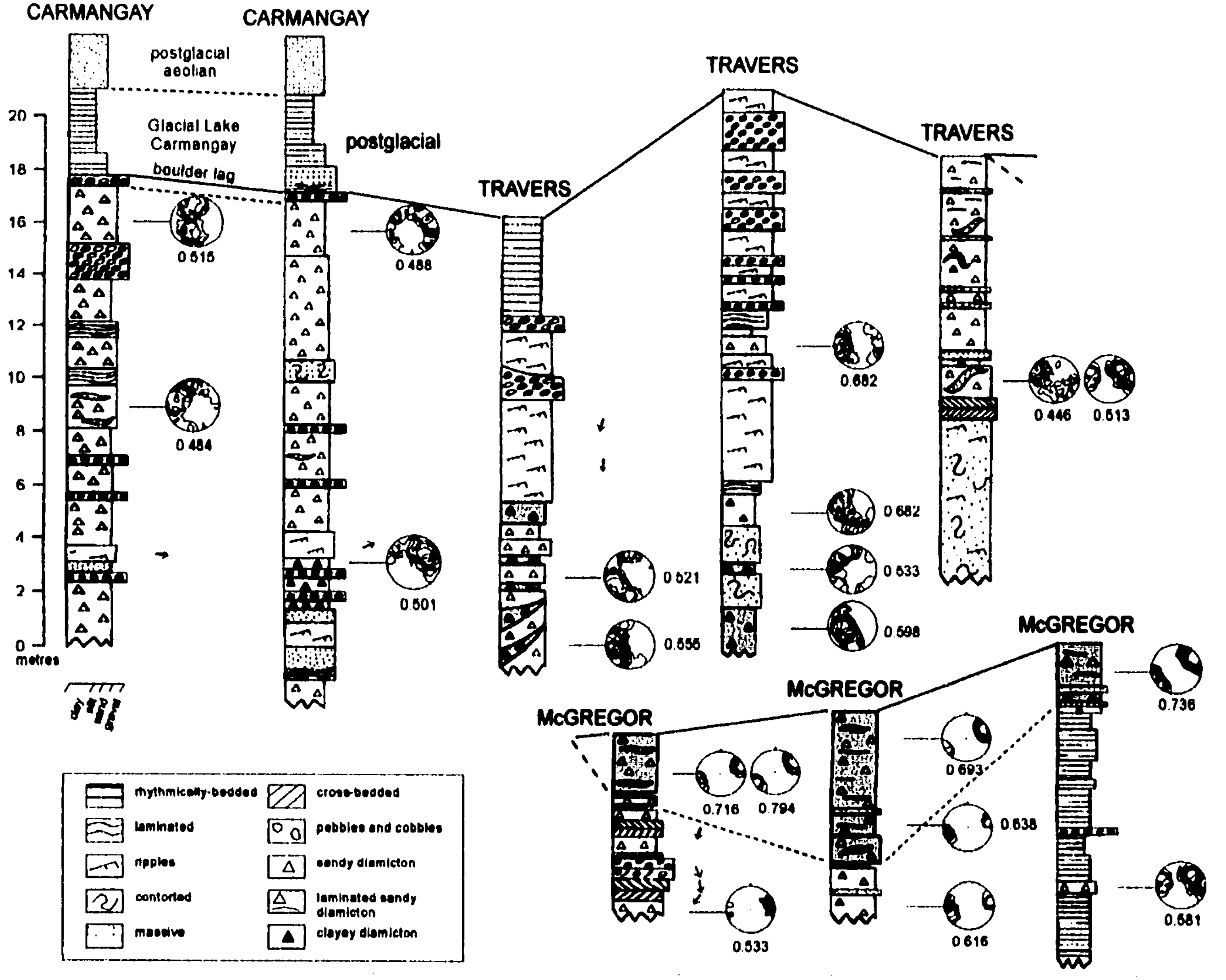

Figure 5.4: Sedimentary logs through exposures at Carmangay, Travers Reservoir, and McGregor Reservoir. Fabric plots with principal eigenvalues are shown for each unit where a sample was obtained. Palaeoflows from sorted sediments are also indicated as arrows.

Figure 5.5: Typical exposure from sheared zone at base of Facies 2. 1 is intact bedding of Facies 2, and 2 shows multiple rafts of Facies 1 which have been subsequently incorporated into Facies 2. The double-ended arrow points out a major plane of movement. A sense of direction could not be obtained from this.

Figure 5.6: Contact between Facies 2 (lower light sediment) and Facies 3 (upper dark sediment). Units from both facies are interbedded for approximately 1.5 m.

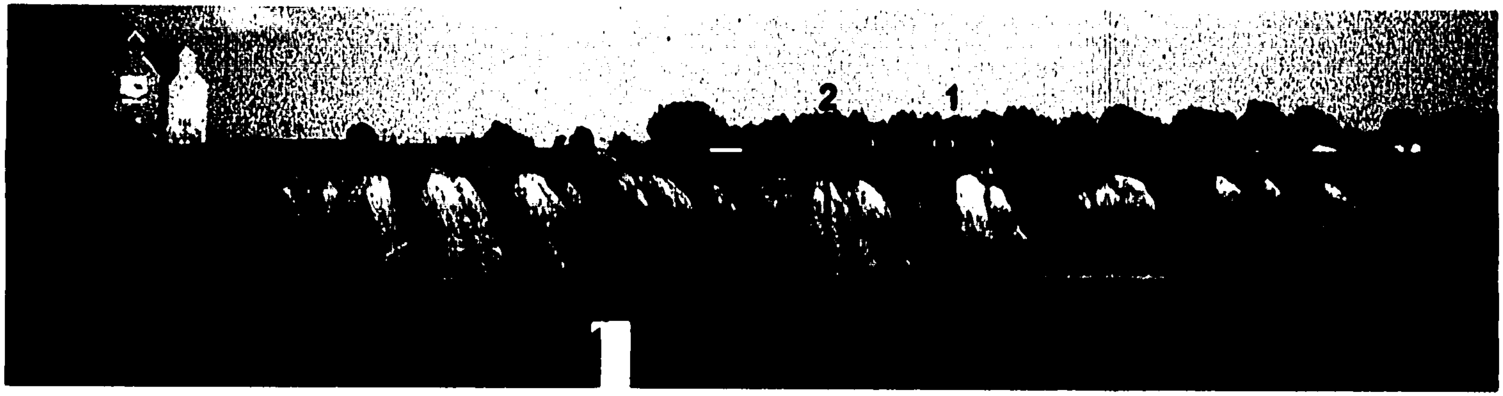

Figure 5.7: Over 70 m of sediment is present at Carmangay. The lower 60 m belongs to Facies 2, although large diapirs of "Labuma Till" are intruded into it. The light sediment at the top of the exposure consists of proglacial rhythmites, that unconformably overlie Facies 2. An aeolian cap overlies this. Locations of transects in Fig. 5.4 are also noted.

beds are conformable and alternate in rhythmic sequences (Fig. 5.6B). Boulders are infrequent, and rest on sand filling scours which cross-cut underlying beds (Munro and Shaw, 1997). Analysis of 38 clast fabric samples from the diamicton beds, show principal eigenvalues generally >0.65 (Fig. 5.4) (Munro and Shaw, 1997; Munro-Stasiuk, in press), and significant clustering of long axes towards ENE (Fig. 5.8).

A subglacial melt-out origin is interpreted for Facies 3 for the following reasons. Strongly oriented clasts indicate a regional ice flow from the ENE (Munro and Shaw, 1997; Munro-Stasiuk, in press). Although such trends may result from lodgement (e.g., Benn, 1995), subglacial or englacial melt-out (e.g., Lawson, 1979; Shaw, 1979), or deformation (e.g., Benn and Evans, 1996), preservation of delicate sand and silt beds supports deposition by passive melt-out (cf., Shaw, 1979). As well, clast dips lie at low angles, often with bimodal directions, as expected for melt-out tills (Lawson, 1979). Furthermore, scours below boulders indicate flowing water beneath the ice sheet and suspension of the boulders by overlying ice in the flow (Shaw, 1982).

FACIES 2: PROGLACIAL OR SUBGLACIAL?

Facies 2 represents an ice-proximal or ice-contact glaciolacustrine environment. A water body accounting for the sediment distribution and elevation, could not have existed proglacially because several topographically lower areas extending from the McGregor and Travers Valleys in all directions (Fig. 5.2) are not underlain by lacustrine deposits. Small lakes could have existed proglacially, such as at Carmangay, provided an ice dam blocked eastward drainage through the large meltwater channel presently occupying the Tee Pee preglacial valley. It is, however, more difficult to block drainage in the McGregor Valley. To maintain a proglacial lake there, an ice dam would have to exist to the north of McGregor Reservoir. Yet, lacustrine sediments in the McGregor Valley reach elevations of > 980 m asl (Fig. 5.2). A proglacial lake could not have existed at this elevation, given lower elevations in the Travers Reservoir region, and both to the east and the west immediately south of the main body of McGregor Reservoir (Fig. 5.2). Only a very large lake, covering most of southern Alberta could explain lacustrine sediments at 980 m asl. The area of this lake would have been ~ 10^4 km^2. This estimate is conservative: lake levels could have been tens of metres higher than the observed sediments. The absence of lacustrine sediments and extensive shorelines questions the existence of such a lake. Furthermore a proglacial lake at ~ 985 m asl would have drained by way of tunnel channels that cross the Milk River Ridge drainage divide approximately 150 km to the southeast, at an elevation of ~910 m (personal communication from C. Beaney, 1998).

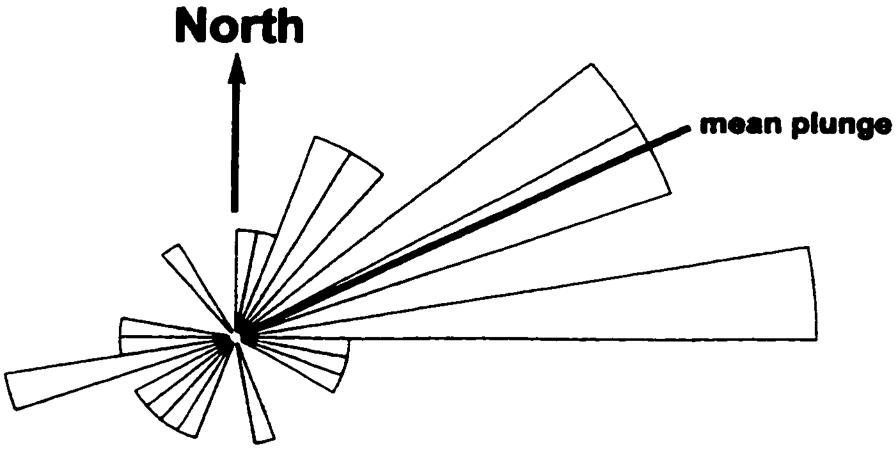

Figure 5.8: Plot of mean dip directions of the 38 clast fabrics obtained from Facies 3. The mean plunge is towards ENE.

More importantly, sedimentary evidence points to a subglacial origin of Facies 2. Silt beds in Facies 2 conformably grade into, and interfinger with, Facies 3 for approximately 1.5 m (Fig. 5.6). Consequently, there must be a genetic and environmental relationship between the two facies, and continuity in sedimentation. Because Facies 3 represents subglacial till, if the lake was proglacial, ice must have advanced and retreated several times over the lake sediments to produce the interbedded silts and till. Loading by advancing ice would result in some shearing and deformation, but the contact zone is undeformed.

An alternative explanation is provided that can account for both the spatial distribution and the elevation of the deposits in their present topographic location. Laminated silt (Fig. 5.6) is interpreted as the product of sedimentation into subglacially stored water. Facies 3 (Fig. 5.7) is interpreted as resulting from direct basal deposition when the water drained and ice recoupled with its bed. The reservoir alternately filled with water resulting in the deposition of laminated silt, and drained bringing the ice near, or onto, its bed, resulting in till deposition. Each time when the reservoir refilled, the water depth was either significantly lowered, or the duration of storage was shorter, documented by the thinning upwards of each set of silt laminae. This alternation of processes continued until the primary mode of deposition was by direct basal melt-out. The fill/drainage cyclicity continued at a smaller scale during the deposition of the till, as documented by the alternation of diamicton beds, and sorted strata (Munro-Stasiuk, in press).

NATURE OF THE SUBGLACIAL RESERVOIRS

After initial ice advance into south-central Alberta, water began to pond below the ice in the McGregor and Tee Pee preglacial valleys. The areal extent of ponding is recorded by the distribution of Facies 2 (Fig. 5.2). The depths of these reservoirs are unknown, but, based on sediment thickness, they are estimated to have been up to 40 m deep at McGregor Reservoir, and up to 80 m deep at Carmangay and Travers Reservoir. Phases of minimal water input, recorded by thin silt and clay rhythmites most likely represent diurnal, seasonal, or annual variations in supraglacial meltwater supply. At other times, large volumes of water flowed into the system, as indicated by thick debris flows, and thick sequences of turbidites. Multiple palaeoflow directions (Fig. 5.4) suggest water was delivered from several sources.

Drainage events completely emptied the reservoir(s) during the time of Facies 2 deposition. Such events are documented by shearing which indicates ice sheet bed recoupling. Rafts of Facies 1 incorporated into Facies 2, record periods of grounded ice and complex subglacial tectonics. At this time density instabilities, caused by elevated porewater pressures in the fine-grained till (Facies

1), resulted in diapirism of the till into the overlying lake beds.

Facies 2 distribution indicates that the McGregor and Travers areas lay beneath a single, large subglacial lake. Following drainage events, when the reservoirs were not at full capacity, ice was pinned on the higher ground now separating McGregor Reservoir from Travers Reservoir, dividing the large lake into two smaller ones.

Since there was no shearing or deformation of beds deposited in the last phases of Facies 2, there was little or no ice movement. This was also the case for Facies 3. As Facies 3 is only observed in two locations, it is suggested that most of the McGregor subglacial lake drained, but the larger lake at Travers Reservoir was sustained.

It is proposed that small-scale drainage events continued during the deposition of Facies 3 at McGregor Reservoir, resulting in deposition of thin sorted beds. Diamicton beds document sedimentation by direct melt-out, and rain-out, through a laterally extensive but shallow water body, never more than 20 cm deep (determined by the thickness of the diamicton strata). The water must have been stored as sudden release of the water is required to produce the discrete beds of sorted sediment between diamicton beds. The laterally extensive beds cannot represent channelized flow at the base of the ice, which would have produced discrete lenses of sorted material (Shaw, 1982). Neither do they represent melting out of debris-rich layers in the ice (Shaw, 1979), as the beds are sorted. Water was stored under high pressure, forcing it to spread out laterally at the base of the ice (cf., Nye, 1976; Weertman, 1986). Drainage occurred when a connection to another cavity or the ice front was made. Thus small reservoirs drained into the larger subglacial lake that occupied the Teepee preglacial valley. The north to south fining in the sorted beds of Facies 3 support this important conclusion.

DISCUSSION

Based on the known areal extent of Facies 2 (Fig. 5.2), the minimum area of the proposed subglacial lake at McGregor Reservoir is estimated at 378 km^2. The average observed thickness of Facies 2 at McGregor Reservoir is 20 m, and hence a conservative estimate of 20 - 40 m water depth is adopted. Thus the calculated minimum volume of the subglacial lake is 8 - 15 km^3. This is comparable to the maximum volumes of Grimsvötn, Iceland, at any time over the last 60 years (Gudmundsson et al., 1995). The minimum area of the subglacial Lake at Travers Reservoir is 232 km^2. Sediment thicknesses are greater here, with an average of 58 m at the western end of the system (estimated 58 - 78 m water depth), and 30 m at the eastern end of the system (estimated 30 - 50 m water depth). The minimum volume of the subglacial lake at Travers Reservoir was 10 - 16

km^3. Since the full spatial extent of Facies 2 is unknown, estimates of lake volume are probably conservative.

Few authors have inferred the presence of subglacial lakes under ancient ice sheets. Gjessing (1969) interpreted a sequence of incised terraced deposits in Norway as remnants of sedimentation in a subglacial chamber. Lacustrine deposition was in isolated depressions, with subglacial channels leading from them at relatively high elevations. As well, McCabe and O'Cofaigh (1994) interpreted a thick prograding sequence of glaciolacustrine sediments in Ireland as subglacial, based on conformable relationships with an overlying subglacial till. They also argued that the elevation of the deposits, relative to the drainage network, required that the lake be subglacial, as a proglacial lake would have drained. Also, contemporary subglacial lakes are known from under modern ice sheets in Iceland (e.g., Gudmundsson et al., 1995), and Antarctica (e.g., Oswald and Robin, 1973) although their presence is generally related to geothermal effects. Theoretically, subglacial lakes are predicted to form at topographic lows, and where the relationship $11a < y$ is not met, where a is the ice-surface gradient, and y is the bed slope (Shoemaker, 1991). As evidence in southern Alberta and south of the Alberta-Montana border points to very low (almost flat) ice sheet surfaces, this condition is easily met at the present study site.

Large volumes of meltwater stored below the Laurentide Ice Sheet in the region can also explain other observations. For instance, the ice would have lifted off a significant portion of the bed, substantially reducing basal shear stress, and elevating the shear stress where the ice was pinned. This probably resulted in local ice flow acceleration, and thrusting over the grounded areas. The presence of water either as a film above the clayey tills of the prairies, or within the tills, has been suggested for the rapid ice movement (e.g., Boulton et al., 1985). Here, however, it is suggested that the presence of stored water in the preglacial valley network may have been as important to ice flow acceleration as the presence of deformable beds. Importantly, ice flow was rapid at the time of the subglacial lakes. This conclusion is supported by multiple shearing events when the lakes drained.

CONCLUSIONS

Sediment distribution, topography, and conformable relationships between glaciolacustrine sediments and subglacial till, suggest that relatively large subglacial reservoirs were maintained below the Laurentide Ice Sheet within the preglacial valley network of southern Alberta. Extensive shearing, in punctuated events between periods of lake sedimentation, indicates that these unstable lakes filled and drained often. Also, while one lake (Travers) continued to fill and drain, another

(McGregor) drained significantly and never re-established itself, although small-scale fill/drainage cycles continued throughout subsequent till deposition. It is therefore suggested that in the present study area the preglacial valley network formed a large, interconnected cavity system beneath the Laurentide Ice Sheet.

Although this study only addresses two main preglacial valleys in south-central Alberta, the preglacial drainage network is regionally extensive (Geiger, 1967). If many valleys stored water below the Laurentide Ice Sheet, then these would have had significant influence on the dynamics of the Laurentide Ice Sheet. Hence, sedimentary studies are recommended to estimate the regional significance of subglacial reservoirs.

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CHAPTER 6: HUMMOCKY TERRAIN IN SOUTH-CENTRAL ALBERTA, CANADA: AN EROSIONAL ORIGIN

INTRODUCTION

Hummocky terrain is composed of tracts of hillocks and depressions of variable size and shape found in areas that have been glaciated. It is especially extensive in the northern Great Plains and in large belts of the Canadian Prairies (e.g., Shetsen, 1987, 1990; Klassen, 1989), and the mid-west U.S.A. (e.g., Clayton and Moran, 1974; Johnson et al., 1995). The terrain is commonly believed to represent the final stages of ice stagnation, when debris on the surface of the ice was slowly lowered as ice ablated in marginal areas of glaciers or ice sheets (e.g., Gravenor, 1955; Gravenor and Kupsch, 1959; Andersson, 1998). Therefore, hummocky terrain is often interpreted to illustrate recessional patterns of the Laurentide ice sheet in North America (e.g., Clayton and Moran, 1982; Dyke and Prest, 1987; Klassen, 1989; Stalker and Vincent, 1993). Some geomorphologists have noted, however, that not all hummocks are composed of sediments released at the ice surface, but are instead composed of primary subglacial debris (e.g., Hoppe, 1952; Stalker, 1960a; Menzies, 1982). and in some cases even bedrock (e.g., Kulig, 1985; Tsui and Cruden, 1986). This calls into question the common view of hummocky terrain formation as outlined above, and also suggests that many hummocky belts may not be ice-marginal features. Thus, hypotheses other than letdown are postulated to explain the variety of sediment types in the hummocks and the hummock form. These include: ice pressing (Hoppe, 1952; Stalker, 1960a; Eyles et al., 1999); thrusting at or near the ice margin (Hambrey et al., 1997: Bennett et al., 1998); subglacial meltwater erosion (Rains et al., 1993; Munro and Shaw, 1997); subsurface diapirism due to over-pressurized meltwater (Boulton and Caban, 1995); preferential lodgment till deposition (Menzies, 1982); active ice moulding (Aario, 1977; Lundqvist, 1981); loading by stagnant ice (Minell, 1977); and periglacial action (Henderson, 1952; Bik, 1969; Seppala, 1972) (see Chapter 2). As there is a general lack of consensus in the literature regarding hummock origin I choose not to use the common term "hummocky moraine" which implies direct deposition from glacial ice. Instead, I use the non-genetic term "hummocky terrain" as it simply describes landscape topography.

Results presented in this paper expand upon those of Munro and Shaw (1997). They demonstrated that hummocks are the product of erosion in the subglacial environment and suggested that the erosion was by meltwater. The study site is in south-central Alberta, Canada (Fig. 6.1) and is important for determining hummocky terrain genesis as, to the best of my knowledge, no

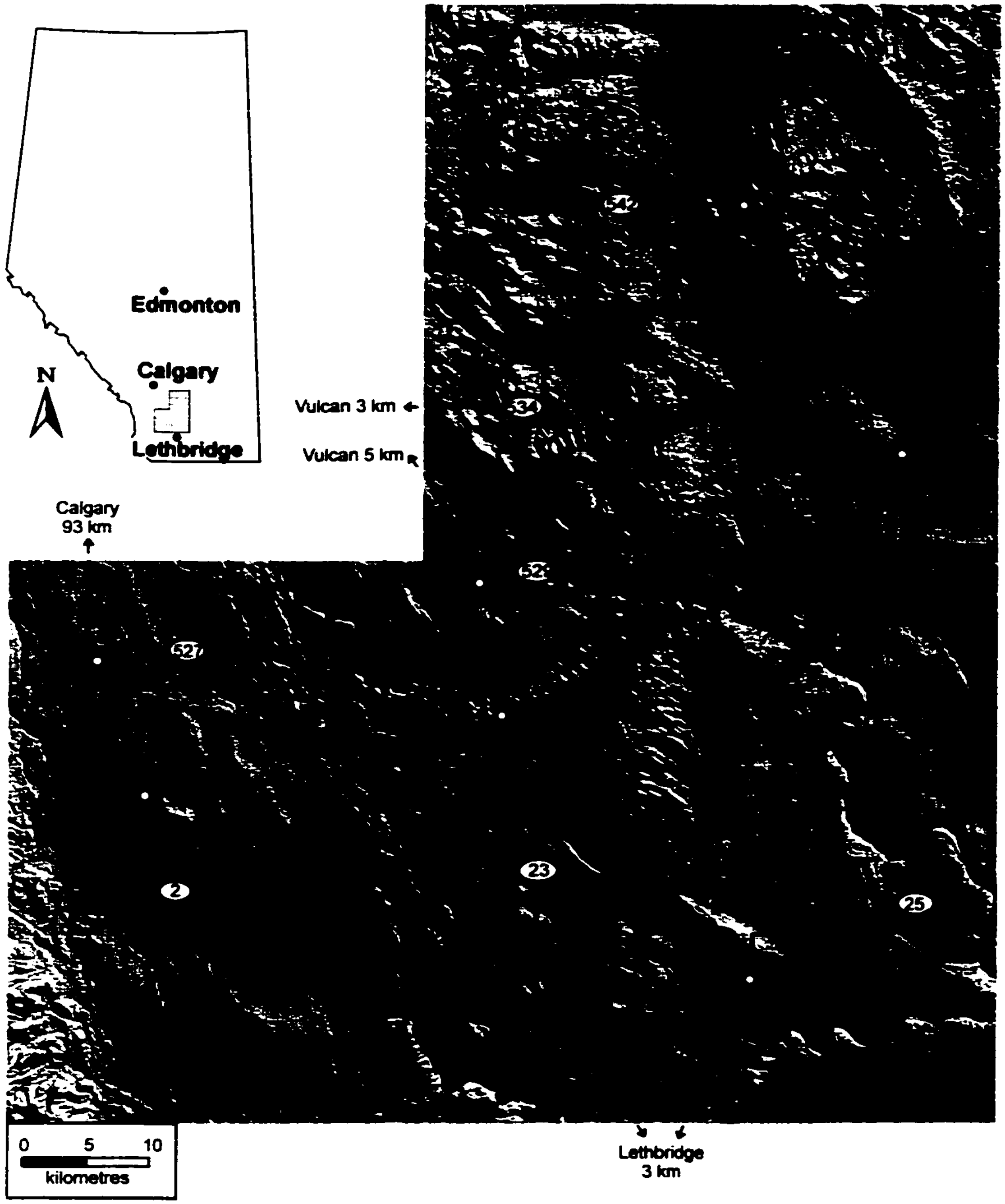


Figure 6.1: Digital elevation model (DEM) of the study area. Exposures discussed in this paper are at Travers Reservoir and McGregor Reservoir and are marked by the large black arrows. Fluting/remnant ridges oriented NW - SE are clearly observed on the DEM, as is a large esker complex to the west. Inset is a map of Alberta, showing the location of the study site.

exposures of comparable quality or quantity exist in glacigenic hummocks worldwide. The damming of McGregor Lake and the Little Bow River (now Travers Reservoir) in the 1960s resulted in extensive shoreline erosion, creating more than 100 hummock exposures in the Buffalo Lake Moraine (BLM). Exposures range from 2 to 25 m high. The main aim of this paper is to demonstrate and document the erosional nature of the Travers-McGregor hummocks.

SIGNIFICANCE OF THE HUMMOCKY BELTS IN ALBERTA

The BLM lies almost parallel to three other major hummocky belts in Alberta: the Duffield Moraine, the Viking Moraine, and the Couteau Moraine (Fig. 6.2). Early studies considered these hummocky belts to represent large terminal or recessional moraines marking marginal positions of the Laurentide Ice Sheet (e.g., Coleman, 1909; Johnson and Wickenden, 1931; Warren, 1937; Rutherford, 1941; Bretz, 1943). These researchers agreed on the significance of the hummocky belts but disagreed significantly on the age of the features. Warren (1937), for instance, suggested that the four belts represented four glaciations (Nebraskan, Kansan, Illinoian, and Wisconsinan) with successively younger glaciations being areally less extensive. Other researchers, such as Rutherford (1941), argued that some of the moraines were of similar age and, hence, they were considered as recessional features.

It was generally accepted that these zones represented recession until Stalker (1977) suggested that the Lethbridge Moraine (Fig. 6.2) represented the Late Wisconsinan maximum in Alberta because the landscape behind the proposed moraine appeared "young" in comparison to that in front of the moraine. Importantly, the BLM also came to represent the Late Wisconsinan maximum in this interpretation. Some researchers disagreed with Stalker (1977) and placed the Late Wisconsinan maximum much further south in Montana (e.g., Christiansen, 1979; Clayton and Moran, 1982; Dyke and Prest, 1987; Rains et al., 1990). Shetsen (1984) concluded that the BLM was an interlobate stagnation feature since there was little variability in geochemistry and lithology within the BLM or on either side of it. The age of the BLM and the other hummocky zones in Alberta now clearly lies within the Late Wisconsinan as it has been conclusively demonstrated that throughout most of central and southern Alberta there was only ever one continental glaciation, the Late Wisconsinan (Liverman et al., 1991; Young et al., 1994; Jackson et al., 1997). Therefore, if these features are moraines then they must be recessional. Paradoxically, all major hummocky zones in Alberta, and adjacent Saskatchewan and Montana, are now largely accepted and mapped as recessional positions of the Laurentide Ice Sheet (e.g., Clayton and Moran, 1982; Clayton et al.,

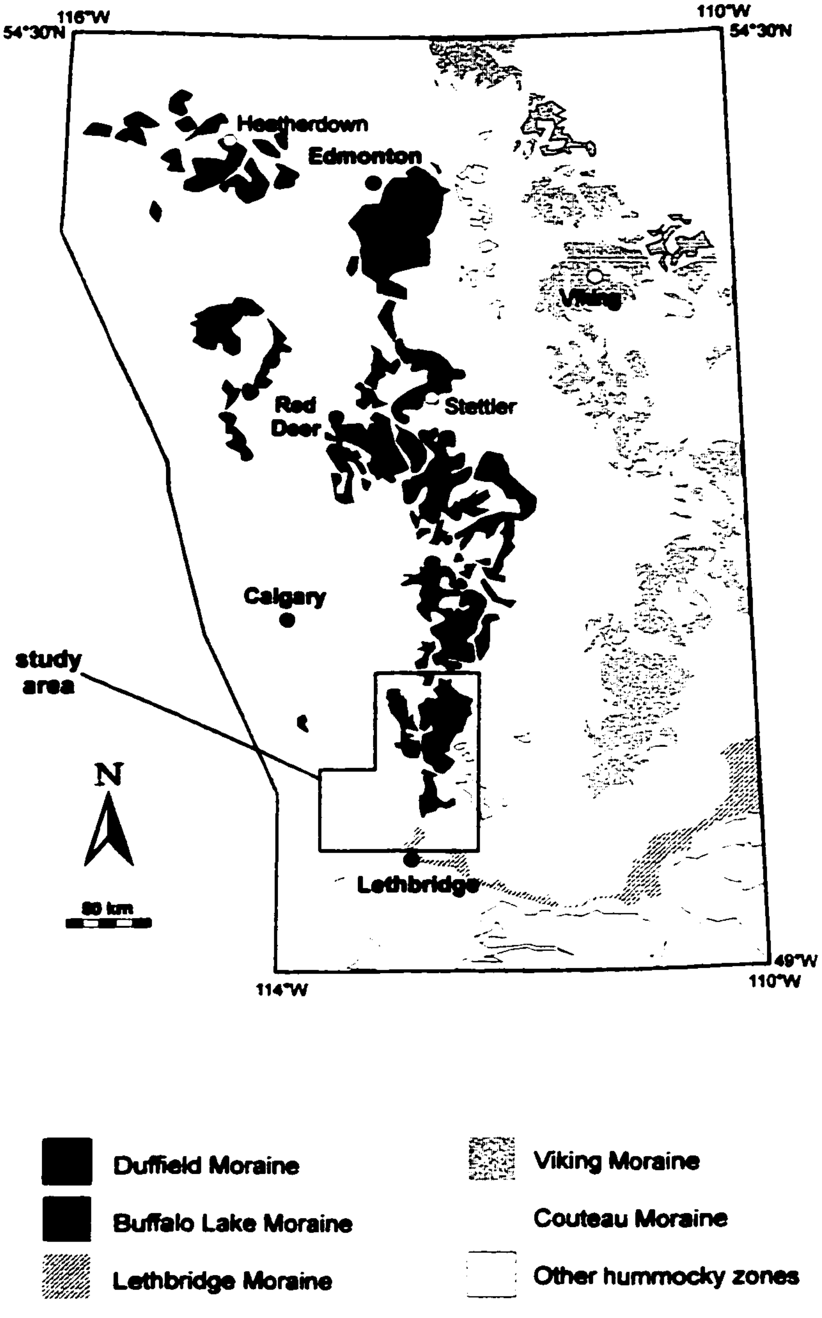


Figure 6.2: Distribution of hummocky terrain in central and southern Alberta. (modified from Shetsen, 1987, 1990; and Rains et al., 1993).

1985; Dyke and Prest, 1987; Klassen, 1989; Stalker and Vincent, 1993; Mandryk, 1996).

HUMMOCK MORPHOLOGY

Hummocks in the study area have a variety of forms typical of most other hummocky regions in the Great Plains. These forms include: A. symmetric circular mounds; B. asymmetric circular mounds; C. symmetric and asymmetric circular mounds with central depressions; D. transverse ridges; E. elongate streamlined hummocks; and F. moraine plateaux (Fig. 6.3). Each hummock type occurs in tracts and in each tract features are of similar shapes and dimensions. For example, in areas with transverse ridges, the ridges are of similar shape and size. This rule applies to all hummock types except for moraine plateaux which are generally isolated. The type forms are also transitional to each other (e.g., Fig. 6.4). Similar patterns and trends have been noted in hummock distributions by other researchers and are explained as subglacial bedforms (e.g., Lundqvist, 1981). Where known, the types of sediment within each hummock type are noted and are discussed in more detail in the next section.

Symmetric mounds

Symmetric mounds (Fig.6.3A) are the most common features observed in the study area. They are roughly circular in plan ("subequal mamillary hills" of Bretz, 1943, p. 36), are commonly 1 - 50m high, and 25 - 300 m wide and most often lie in non-sloping areas. In any one area heights of the hummocks are accordant. Hummock slopes lie in the range of 1 - 20°, and are generally convex towards the top of each hummock, and concave towards the bottom. Spacing between hummocks is both regular and irregular. In some areas the depressions appear more prominent in comparison to the surrounding mounds (Fig. 6.4). These combined features are commonly referred to as "knob and kettle topography", inferring that the holes resulted from melting of buried ice. Sediments within these mounds are sandy, silty, and clayey diamictons (debris flows and tills), laminated and rhythmically bedded sand, silt, and clay, and sorted gravel beds. These range from *in situ* to pervasively deformed.

Asymmetric mounds

Asymmetric mounds are similar in size and relief to symmetric mounds. Two properties differentiate the features. First, asymmetric mounds have one slope which is consistently steeper than the other (Fig. 6.3B). This steeper slope is generally < 20°, with the gentler slope typically

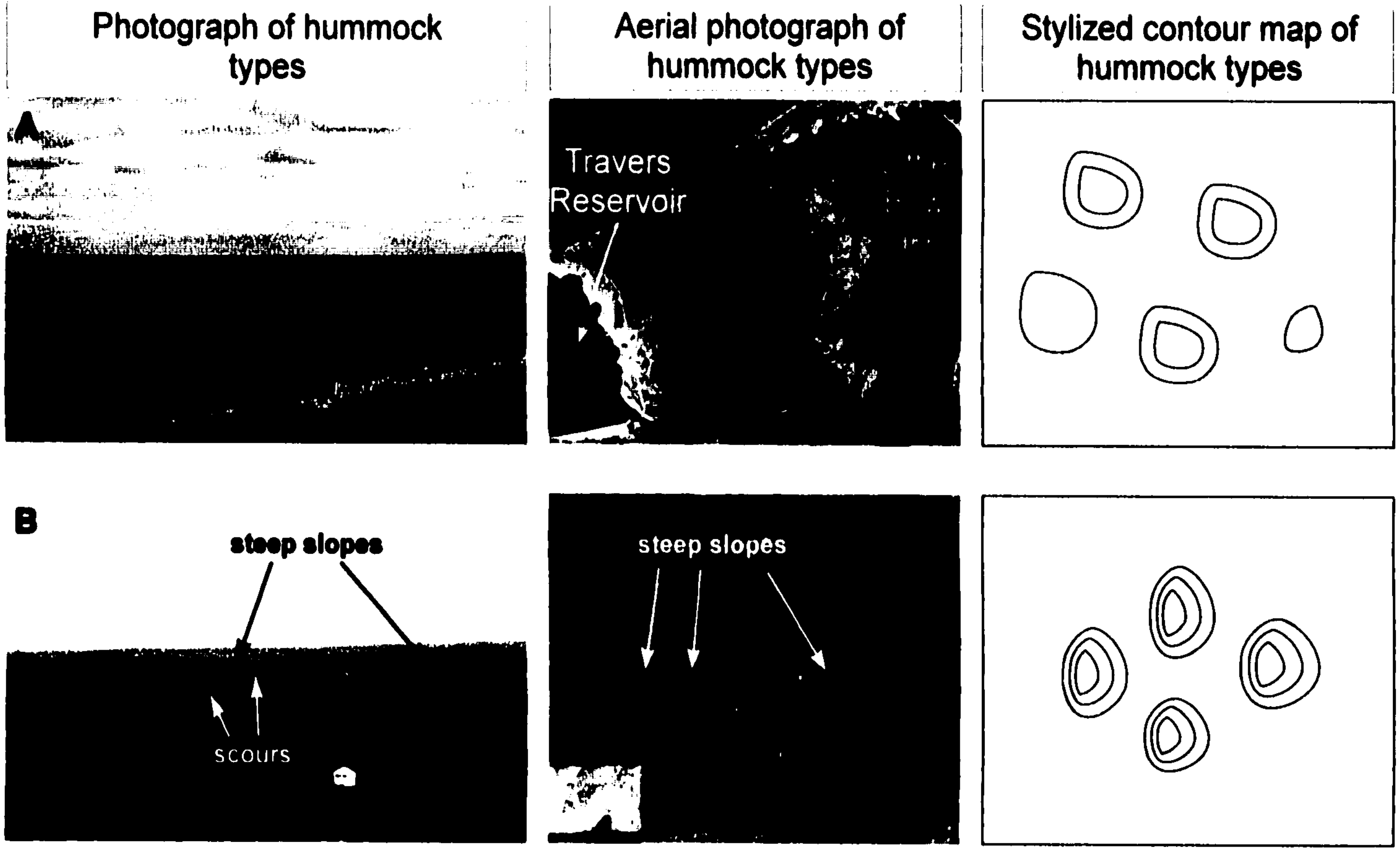
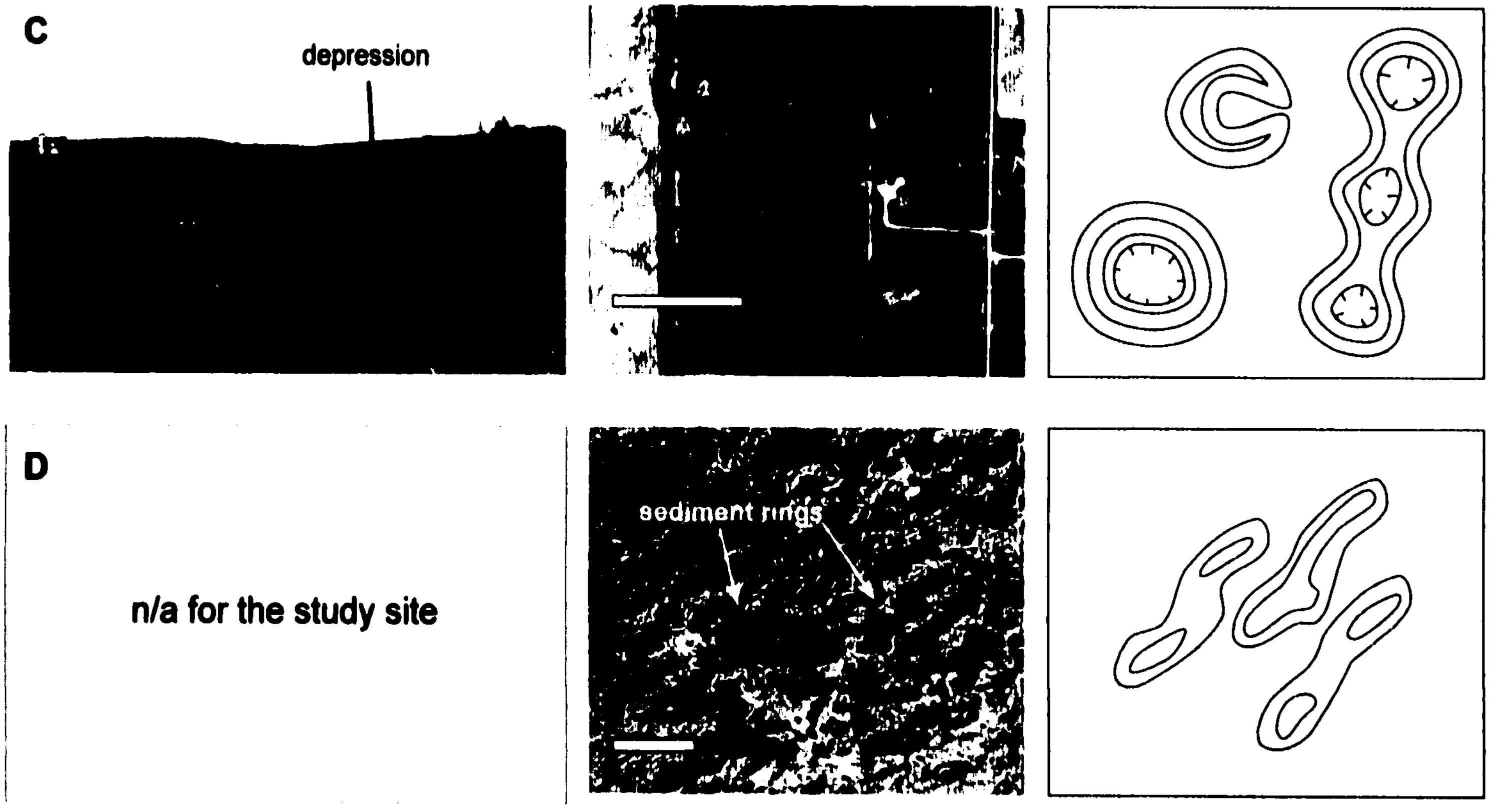


Figure 6.3: Ground photograph, aerial photograph, and stylized contour map of each of the different hummock types in the study area. A. Symmetric mounds; B. Asymmetric mounds; C. Symmetric and asymmetric mounds with central depressions; D. Transverse mounds; E. Elongate mounds; F. Moraine plateaus.



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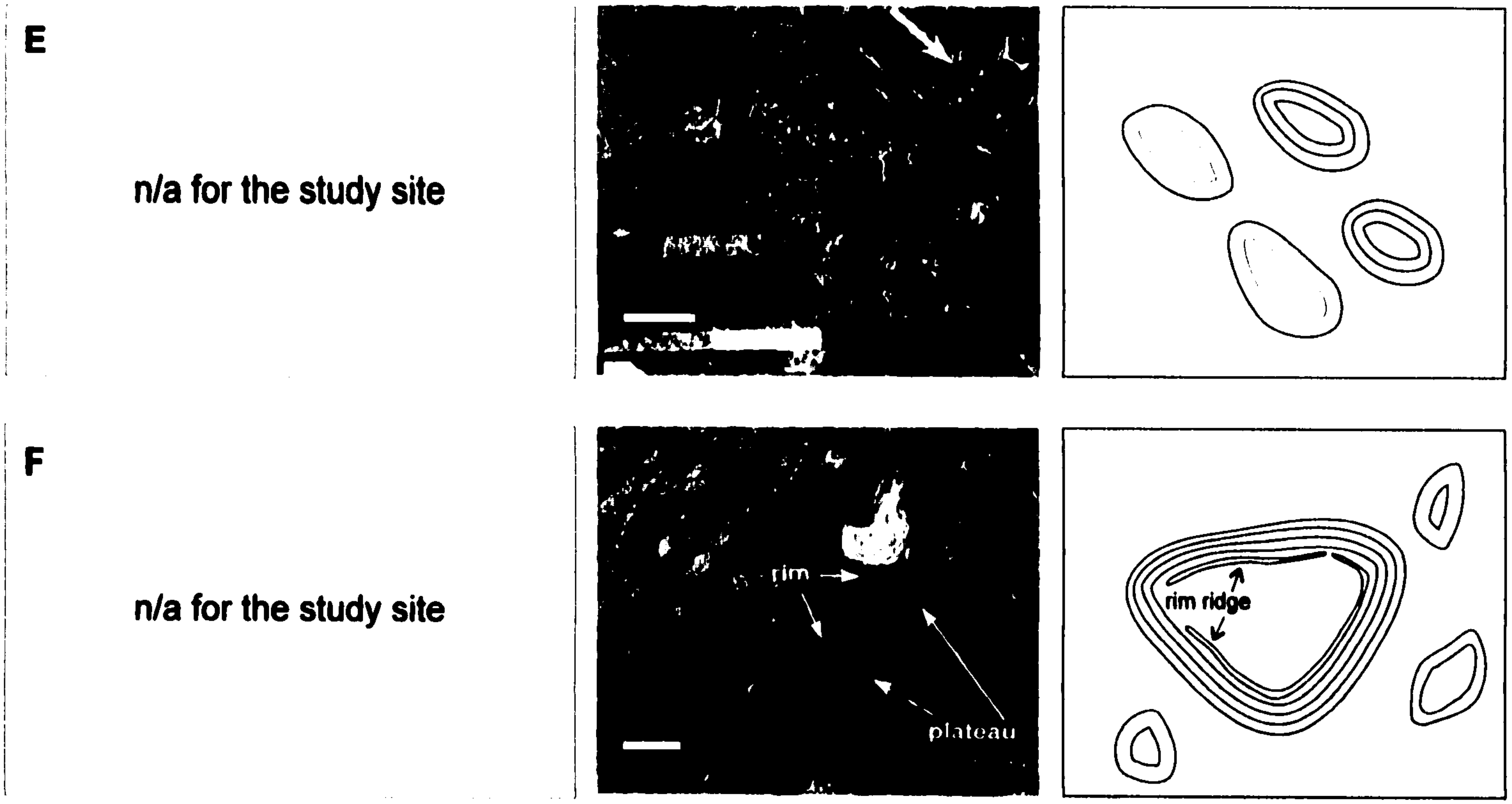

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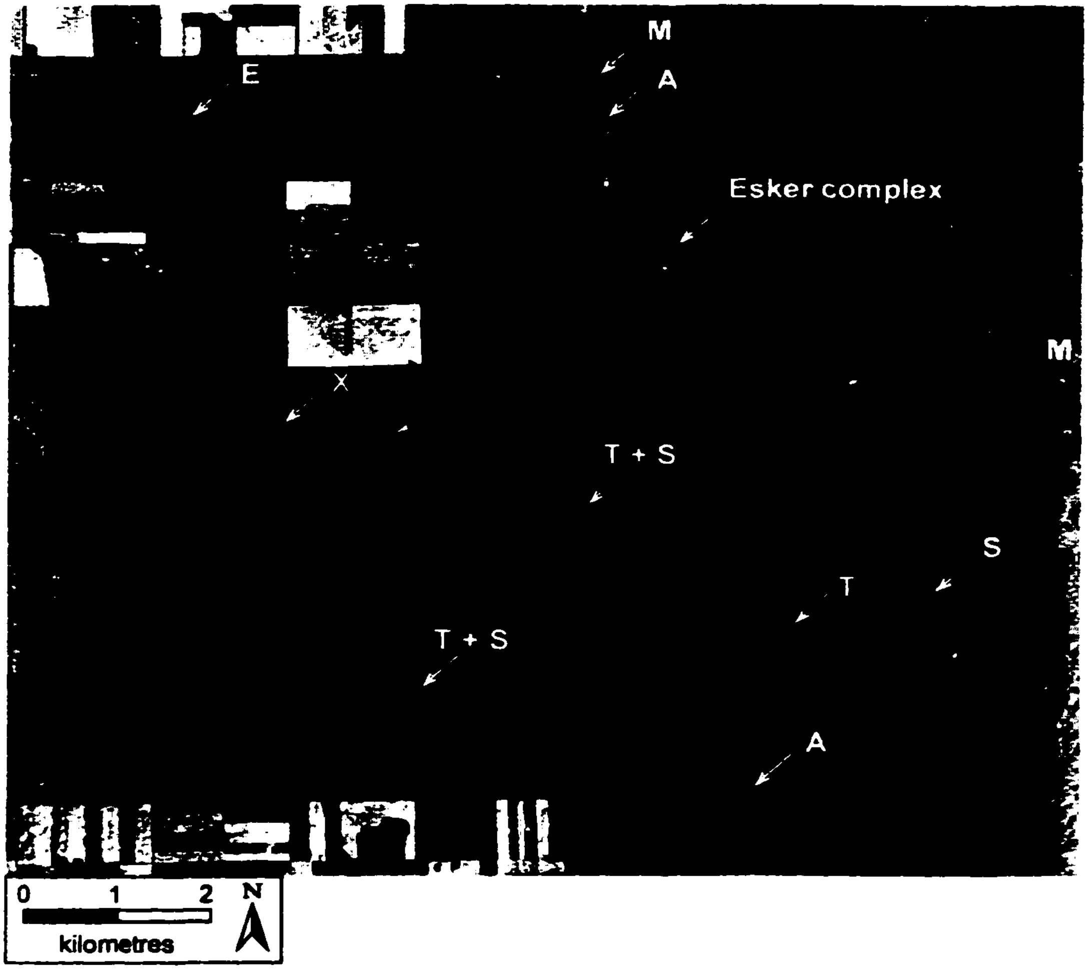

Figure 6.4: This photograph illustrates the transitional nature of the hummocks in the study area. The whole sequence which trends NW to SE is cross-cut by an esker complex trending NE - SW. The features marked by "X" are curious and were not seen at ground level. They may be small channels running parallel to the esker complex, or they may be features formed contemporaneously with the hummocks. Additional research needs to be undertaken on these intriguing forms. Marked features are: S - symmetric mounds; A - asymmetric mounds; E - elongate hummocks; T - transverse ridges; M - moraine plateaux.

between 5 and 10°. In any particular tract the steeper hummock slopes always face in the same direction. Second, at the base of the steepest side of some of these hummocks are concave-shaped depressions that are up to 2 m deep and 10 m across (Fig. 6.3B). These commonly extend around the hummock creating a horseshoe-shaped depression. In most areas, hummock surfaces are concordant. In areas with non-concordant hummocks, lower lying hummocks are typically smaller than surrounding hummocks although they have similar form. Sediment in asymmetric mounds is the same as in symmetric mounds.

Symmetric and asymmetric mounds with central depressions

These mound are of similar shape, dimension, and pattern as described for symmetric and asymmetric mounds. The significant difference is the presence of a depression in the centre of the hummock (Fig. 6.3C). Because of their distinctive donut shape these features have been referred to as prairie donuts (e.g., Gravenor, 1955), rim ridges (e.g., Stalker, 1960a; Lundqvist, 1981; Benn, 1992), and ring ridges (Aartolahti, 1974). The depressions are generally small, approximately 3 - 20 m across and up to 4m deep. Only exceptional depressions are larger than this.

Most features appear symmetric on air photos. However, when observed on the ground, most are virtually asymmetric with the depressions developed on the gentle-sloped side of the hummock. Such depressions are commonly so well-developed that the depression is open rather than closed; hummocks resemble large horseshoe-shaped mounds with two extending arms (Fig. 6.3C). The steeper side of the mound is always the enclosed end, the less steep side the open end. Donuts are commonly linked by their rims, forming hummock chains (Fig. 6.3C).

Sediment in donuts was not observed in detail. One road-cut exposed sorted sands in the rim on one side of the depression, and diamicton with variable clast fabric strengths and orientations was present in the opposite rim. It is therefore inferred that the sediment type is highly variable, as in symmetric and asymmetric mounds without central depressions.

Transverse ridges

Transverse ridges, which are relatively common in the study area, are most extensive to the northwest of McGregor Reservoir. Located on flat, relative to the flow direction , and gentle downhill slopes (< 5°), these ridges are in contrast to ridges elsewhere in Alberta where they have been reported on prominent uphill trending slopes (e.g., Stalker, 1973). Semi-parallel ridges are up to 1.5 km in length and 300 m wide and are consistently spaced at ~300 m (Fig. 6.3). They are typically about 5 m high and their tops are strongly accordant. Depressions between these ridges are similar in plan view to the ridges themselves. In some cases, rather than a single linear depression between the mounds, depressions are composed of a series of almost perfectly round, inset depressions that are commonly linked (Fig. 6.3D). Many of these depressions cut into bedrock and are commonly rimmed by steep-sided, sharp-tipped, sinuous ridges (Fig. 6.3D). The light appearance of these smaller ridges on aerial photographs, their apparent good drainage, and their morphology suggest that they are likely composed of relatively coarse sorted sediment. Sediment in the transverse ridges was not observed but bedrock is close to, and at the surface in the depressions between ridges.

Elongate, streamlined hummocks

Elongate, streamlined hummocks (Fig. 6.3E) are less common than other hummock types in the study area. They are transitional between fluted terrain and transverse ridges. In some classifications they may be considered as drumlins. Eyles et al., (1999) noted similar features and named them "humdrums" (a cross between hummocks and drumlins). They are transitional to transverse ridges, and to symmetric and asymmetric hummocks (Fig. 6.4). Since they do not cross-cut other hummocks, they are considered to be part of the continuum of hummock types. These features are generally < 300 m long , and < 100 m wide (Fig. 6.3E). This is in contrast to the adjacent flutes which are up to 7 km long, and 500 m wide. Sediment within these ridges was not observed but adjacent depressions are commonly cut into the underlying bedrock.

Moraine plateaux

Moraine plateaux are numerically the least common features in the study area, although they are widespread. Plateaux may be in groups in places, though they are usually present as single, somewhat flat-topped mounds ~50 m to 1 km across, interspersed irregularly with the regularly spaced features discussed above (Fig. 6.3F). They are consistently higher by 1-5 m than surrounding features and, where they occur in groups, they are of accordant elevation. Some mounds have rim ridges at their edges that are generally discontinuous. They are also consistently to the NW of the plateaux (Fig. 6.3F). Although sediments were not observed in these features, other researchers have noted them to contain diamicton and water-lain sediments (e.g., Stalker, 1960a). Moraine plateaux have typically been referred to as dead-ice plateaux (e.g., Stalker, 1960b), and ice-walled lake plains (e.g., Clayton, 1973), and are thought to be associated with stagnating ice. By contrast, Rains et al. (1993) suggested that plateaux are remnants of a surface that was extensively eroded during hummock formation.

TRENDS OBSERVED IN THE HUMMOCKS

Hummocky terrain is commonly considered to be chaotic with no discernable trends in size, shape, or distribution of features (e.g., Gravenor, 1955; Parizek, 1969). Nevertheless, many authors have noted both a degree of streamlining or moulding (e.g., Hoppe, 1952; Aario, 1977; Lundqvist, 1981), and some degree of pattern in the distribution of the features (e.g., Gravenor and Kupsch, 1959; Aario, 1977; Lundqvist, 1981; Lagerbäck, 1988; Rains et al., 1993; Burgess, 1994). Authors always attribute pattern to subglacial processes, and almost always state that the landforms resemble bedforms. Hence if these are bedforms then the flow direction of their formative agent should be preserved in the shape of the landforms.

To determine if hummocks preserve a sense of direction, trends were measured from aerial photographs, and then plotted on unidirectional roseplots (Fig. 6.5). For each hummock type the techniques for measuring trends are outlined. Orientations cannot be determined for individual symmetric hummocks, symmetric hummocks with depressions, or for moraine plateaux, all of which lack elongation.

Asymmetric hummocks have a distinctive shape: round with one steep slope, and one gentle slope. This along with the presence of horseshoe-shaped depressions around the steep sides of some ridges, suggests that they may be incipient drumlins. Eyles et al. (1999) hinted at this conclusion when they named similar features "humdrums". Thus, like drumlins the steeper side of the feature is inferred to be the stoss side, and is therefore pointing up-flow. Although only 34 measurements in total were obtained, there is a remarkably strong, preferred orientation in the sample: from 095° to 190°, with most measurements aligned between 110° and 140° (Fig. 6.5A). Therefore, the flow (ice and/or water) responsible for shaping these landforms moved towards the southeast.

Asymmetric hummocks with depressions (AHD) were more difficult to obtain measurements from. The criteria for choosing orientations are the same as for asymmetric hummocks. In identifying the alignments, it became obvious that the arms of the features were always pointing in the downflow direction. Although measurements were only obtained from one area (Fig. 6.5B), orientations of AHD are similar to those for the asymmetric hummocks in the same region. That is, flow was southeastward.

Measurements were easily obtained from the many transverse hummock ridges in the field area. Orientations were recorded across the ridge crests as in ripples and dunes. Transverse ridges

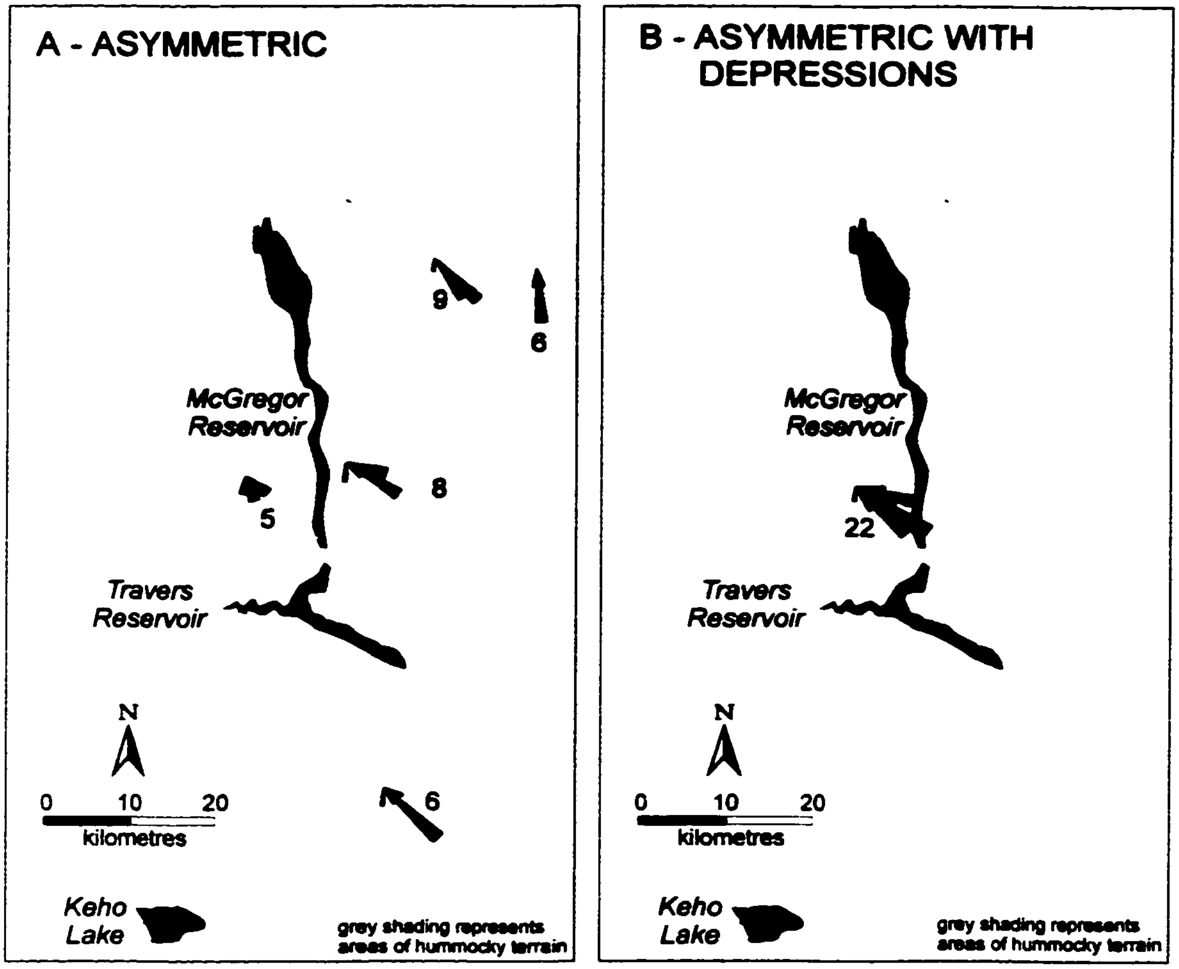

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Figure 6.5: Orientations shown as unidirectional roseplots measured from A - asymmetric hummocks; B - asymmetric hummocks with depressions; C - transverse ridges; D - elongate hummocks. The number of measurements is indicated beside each roseplot.

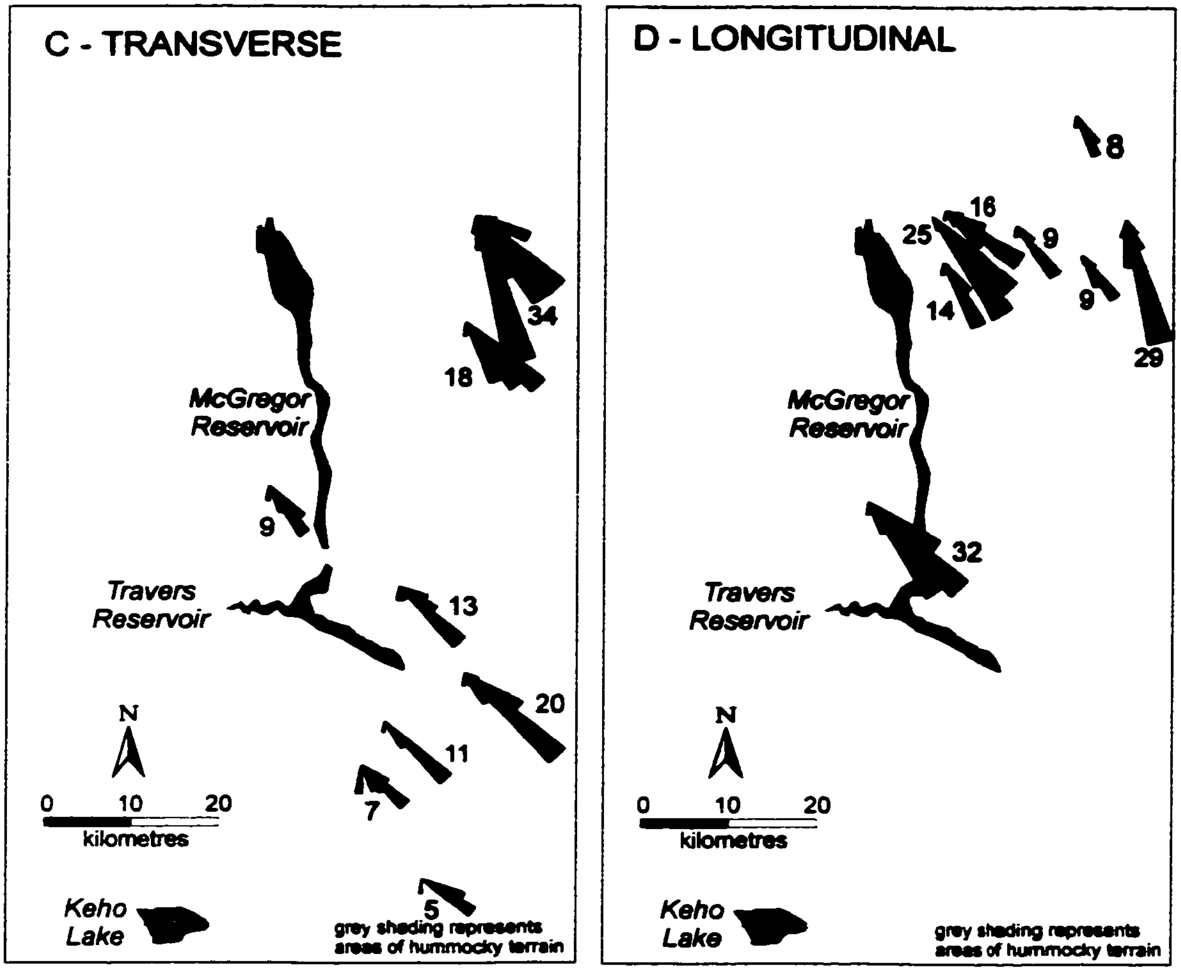

Figure 6.5: continued

have the widest variance in orientation: from 85° to 200° (Fig. 6.5C), but recorded flow is approximately southeastward.

It was also relatively easy to obtain measurements from longitudinal ridges. Orientations were determined from the long axes of the ridges. Distinct blunt flow noses, like drumlins, are observed to the northwest of many of the mounds and, hence, flow originated from that direction. Overall the orientations vary from 95° to 185° (Fig. 6.5D), but within a given sample area, the range in orientation is < 45°. Thus, flow trends are similar to those derived from other hummock types.

When all trends are observed together, there is a remarkable degree of alignment. In general, all hummocks, regardless of spatial position or type, record formative flows towards the southeast. Features measured furthest to the northeast are an exception; their alignment indicates southward flow. In general, the trends in the hummocks are parallel to flutes/remnant ridges and drumlins observed across the region (Fig. 6.1). This strongly suggests that there is a genetic link in between drumlins, flutes/ridges and hummocks. Continuous transitions from fluted terrain to hummocky terrain (Fig. 6.6) also suggest that the processes responsible for both landform types may be similar. Munro and Shaw (1996) demonstrated that the flutes in the region are erosional as they are cut into gravels that predate Laurentide glaciation, and also into local bedrock.

SEDIMENT IN THE HUMMOCKS

Sediment in the hummocks is not discussed in detail in this paper since the hummocks are erosional remnants. Consequently, the composition of the hummocks does not shed light on their formation. Yet, the interpretation of these sediments is important for understanding the glacial history of the region. For the purposes of this paper, the architecture of the sedimentary units, the structural features, and their relationship with hummock surfaces are crucial to determining hummock genesis. While sediment genesis is dealt with extensively in Chapters 3 and 4 of this thesis, a brief description and interpretation of the major sedimentary units is given here to provide a stratigraphic framework within which the depositional and erosional events are placed.

The oldest glacigenic sediment in the hummocks is a basal unit of lodgement till (Fig. 6.7). It is commonly associated with, and interfingers with, glaciotectonically thrust bedrock recording ice moving from the northeast (Munro and Shaw, 1997). This till is recognized across much of southern Alberta, and its distinctive blue-grey colour and fine matrix easily identifies it as the regional Labuma Till (cf., Stalker, 1960b). This is the oldest unit containing clasts derived from the Canadian Shield and, thus, it represents the initial Laurentide ice advance into the area. Although

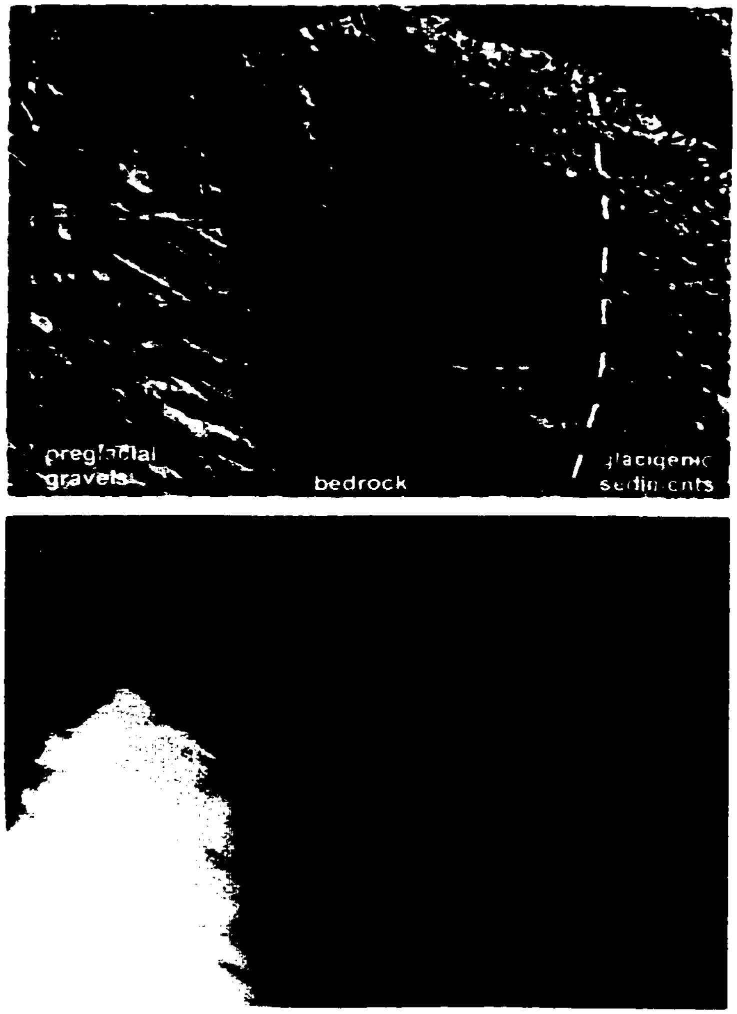

Figure 6.6: A. Hillshaded DEM showing that flutes/remnant ridges are directly transitional to hummocks. A degree of alignment can be observed in the hummocks parallel to the flutes. The dashed line marks the edge of a preglacial valley. All features are eroded into their substrate. The flutes are eroded into preglacial gravels and local bedrock (the relatively flat terrain). The hummocks are eroded into bedrock and glacigenic sediments that fill the preglacial valley (see documentation later in this paper). B. Classed greyscale DEM showing the same trends. The contour interval is 2 m in the hummocky zone and 10 m in the fluted zone.

Figure 6.7: The oldest glacigenic sediment in the region disconformably overlies preglacial gravels. The gravels are frost heaved.

there has been much argument about the age of the Labuma till, recent work north and west of the study area demonstrates that the Late Wisconsinan Laurentide glaciation was the only Laurentide glaciation in this part of North America (Liverman, et al., 1991; Young et al., 1994; Jackson et al., 1997). Thus, all glacigenic sediments associated with continental glaciation in this area are of Late Wisconsinan age.

A thick sequence (up to 60 m) of glaciolacustrine, laminated and rhythmically bedded sand, silt, clay, gravel, and diamictons overlie the Labuma Till. These sediments are located in preglacial valleys in hummocky and non-hummocky zones. They make up ~ 80%, by thickness, of all the sediment observed in the hummocks. Munro-Stasiuk (in press, a) interprets these deposits as subglacial, rather than proglacial lacustrine: their elevations relative to meltwater channels require a subglacial environment. Conformable, transitional contacts with overlying diamicton also support this conclusion. Munro-Stasiuk (in press, a) indicated that after ice advanced into the region, water accumulated beneath the ice-sheet and decoupled it from its bed. The lowermost sedimentary units in the sequence were intensely sheared, faulted, and folded during and after their deposition by ice flowing from the northeast. Deformation decreases upward in the sequence. The combination of sedimentary and structural observations documents draining of the lakes and recoupling of the ice with its bed.

Alternating beds of homogeneous clayey diamicton and sorted strata (Fig. 6.8) conformably overlie the glaciolacustrine sediments. These beds comprise the youngest unit in the hummocks: a stratified till which was deposited by direct melt-out beneath the ice (Munro and Shaw, 1997; Munro-Stasiuk, in press, b). Clasts are commonly striated and some larger boulders have sand-filled scours below them (Fig. 6.8B), indicating that the boulders were held in ice and extended downwards into flowing subglacial water (Shaw, 1982). Strongly preferred orientation of clast long axes supports a subglacial origin for this unit. Most of the 38 fabrics from this unit have strong principal eigenvalues (S_1) and K-values (the degree of clustering) (cf., Woodcock, 1977) (see Table 6.1). Mean orientations indicate ice flow from the northeast (Fig. 6.9). Eyles et al., (1999) stated that many of the properties of this deposit can be readily attributed to deformation till. However, there are no rafts of underlying strata, the diamicton and sorted sediment are stratified, not banded, and clast fabrics in deformation till are generally variable and/or weak (Dowdeswell and Sharp, 1986; Hicock and Dreimanis, 1992; Benn, 1994; Benn and Evans, 1996; Hicock et al., 1996). Also, the sorted beds intersect large boulders and if these represented banding as proposed by Eyles et al., (1999) then they would be wrapped around the clasts by rotational shear. Rather, large clasts with

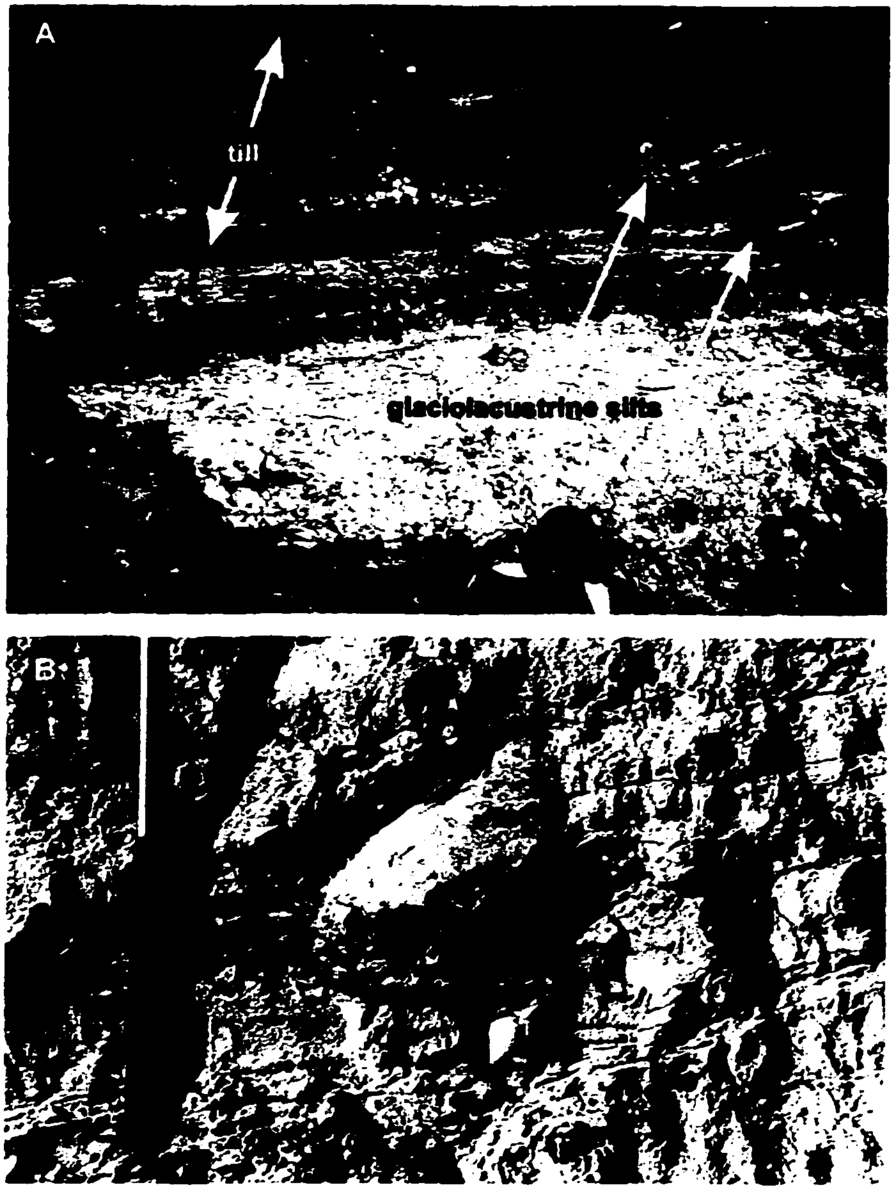

Figure 6.8: A. The contact between glaciolacustine silts and subglacial till is gradational and conformable. Typically the two sediment types are interbedded for 1.5 m. B. The till unit has sorted strata between diamicton beds, and scours below boulders suggest that melt-out was the dominant sedimentation process.

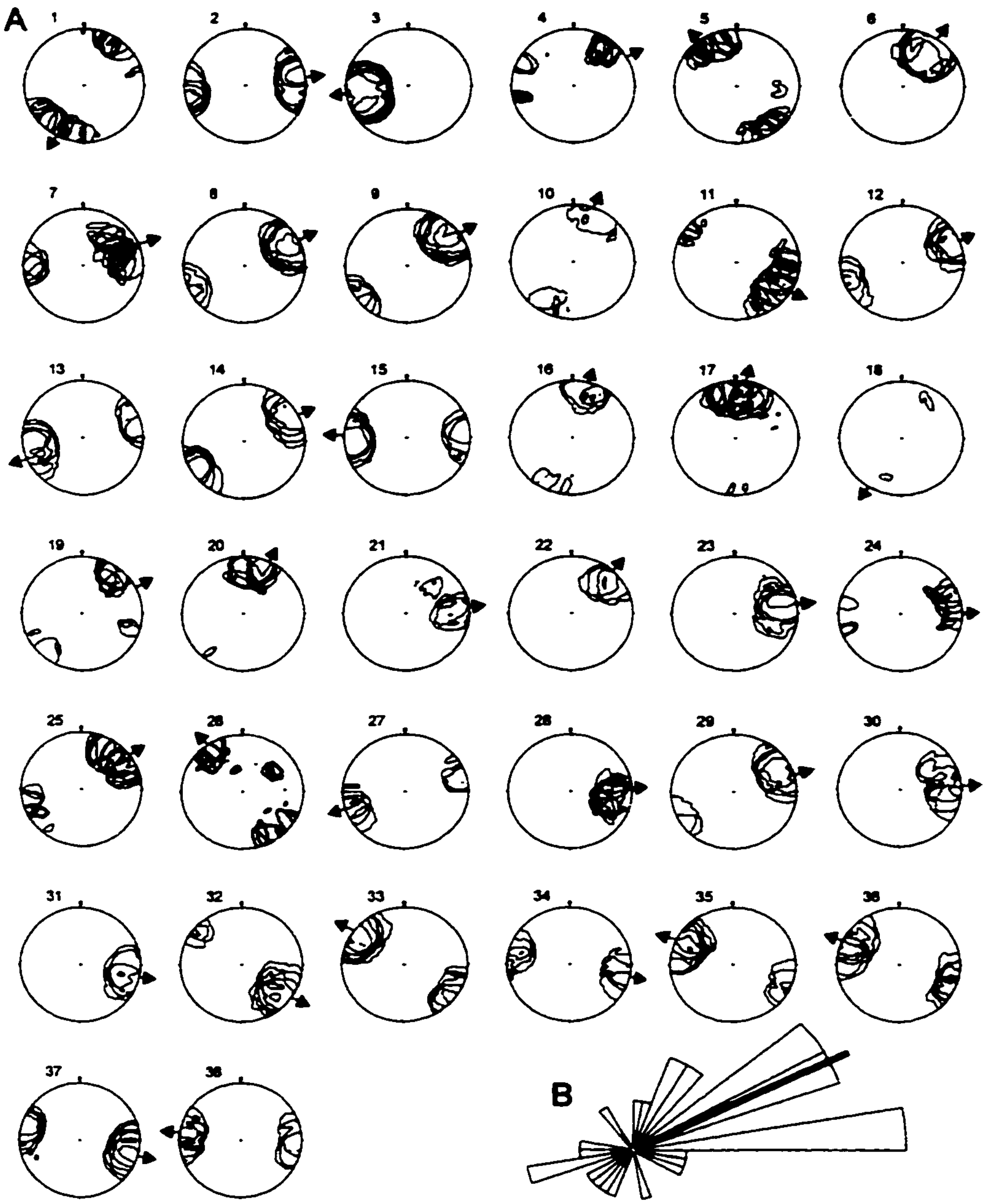

Figure 6.9: A. 38 clast fabrics from the youngest till at McGregor Reservoir. Distributions are generally unimodal. B. Mean plunge orientations are plotted on a unidirectional rose diagram. Mean plunge is toward the northeast indicating that ice moved into the area from that direction.

Sample	O	P	S1	S2	S3	K
1	209.6	5.4	0.607	0.342	0.051	0.299
2	81.4	7.9	0.784	0.185	0.031	0.803
3	261.5	28.5	0.801	0.174	0.025	0.778
4	68.4	7.3	0.489	0.424	0.087	0.090
5	324.4	0.9	0.541	0.326	0.133	0.562
6	31.2	33.2	0.693	0.266	0.041	0.512
7	68.2	15.2	0.562	0.272	0.166	1.479
8	51.5	15.2	0.803	0.135	0.062	2.268
9	161 1	17.4	0.868	0.113	0.019	1.153
10	21.6	8.1	0.528	0.334	0.138	0.523
11	119.2	16.8	0.600	0.332	0.068	0.375
12	69.9	9.0	0.716	0.199	0.085	1.510
13	253.7	10.1	0.730	0.220	0.050	0.805
14	58.8	3.6	0.794	0.142	0.064	2.142
15	275.8	6.4	0.766	0.174	0.060	1.316
16	19.1	7.5	0.635	0.220	0.145	2.563
17	7.5	19.9	0.603	0.299	0.098	0.630
18	222.8	0.3	0.448	0.382	0.170	0.198
19	52.4	8.5	0.512	0.357	0.131	0.362
20	23.2	12.6	0.546	0.324	0.130	0.572
21	83.4	26.2	0.552	0.392	0.056	0.176
22	36.0	18.7	0.575	0.326	0.099	0.472
23	86.0	26.7	0.685	0.200	0.115	2.241
24	92.9	5.8	0.533	0.354	0.113	0.355
25	59.0	11.2	0.638	0.284	0.078	0.627
26	326.5	7.1	0.422	0.354	0.225	0.394
27	258.0	4.0	0.616	0.297	0.087	0.589
28	89.4	22.1	0.550	0.261	0.189	2.329
29	64.7	10.7	0.749	0.188	0.063	1.274
30	64.9	21.8	0.661	0.276	0.063	0.590
31	103.2	15.9	0.697	0.225	0.078	1.072
32	128.2	18.9	0.716	0.279	0.105	2.625
33	301.8	8.8	0.780	0.164	0.056	1.442
34	97.6	1.3	0.620	0.221	0.159	3.159
35	295.8	13.2	0.748	0.138	0.114	8.500
36	291.9	7.8	0.776	0.152	0.072	2.185
37	97.4	5.6	0.777	0.195	0.028	0.720
38	274.0	1.9	0.681	0.248	0.071	0.816

Table 6.1: Statistics from clast fabric data. O - mean plunge orientation; P - mean plunge angle; S1, S2, and S3 - eigenvalues; K - degree of clustering.

underlying scours indicate that bed separation was more compatible with melt-out till (Lawson, 1979; Shaw, 1982).

Hummock after hummock contains the lithostratigraphic sequence described above (e.g., Fig. 6.10) which extends beneath non-hummocky terrain in nearby exposures: the surfaces of hummocks cross-cut this stratigraphy. The only significant materials overlying the terrain are surface boulders, eskers, small kames, and proglacial lake deposits. Surface boulders are up to 2 m across and are lithologically similar to cobbles and boulders in the underlying sediments, indicating that they have not traveled far. Some are heavily pitted by percussion marks (Fig. 6.11A). When observed in exposure, concentrations of surface clasts occur directly above boulder and cobble beds in the underlying sediments (Fig. 6.11B). This relationship strongly suggests that these boulders are lags resulting from the differential removal of finer sediment. In some areas, there are boulders lying on the surface, but few, or no boulders, within the sediments. Such surface boulders were probably part of a more extensive deposit, now almost entirely eroded away.

Eskers overlie hummocks at many locations and, therefore, they clearly post-date the hummocks. Most beds within the eskers arch upwards, demonstrating that they formed by paragenesis and the eskers are therefore subglacial. Up-slope palaeocurrents measured from ripples in the eskers also support a subglacial interpretation.

A few symmetrical mounds of anomalous size are found in the field area. A gravel pit in one of these mounds exposed sorted sand and silt beds which are conformable with the surface of the mound. Multiple normal faults cross-cut the beds toward the edges of the mound. This is unusual for hummocky terrain in the area (see documentation in next section), and the feature is interpreted as a subglacial or proglacial kame rather than part of the hummocky terrain tract in which it sits. Therefore, caution is called for when interpreting these single mounds, especially within extensive hummocky zones.

Several proglacial lakes were formerly present in the study area and their sediments overlie other landforms. The most prominent lake beds are represented by the relatively flat relief in the vicinity of Carmangay (Glacial Lake Carmangay), near Lethbridge (Glacial Lake Lethbridge), and immediately north of Milo (Fig. 6.1). The underlying glaciolacustrine sediments are commonly rhythmically-bedded silt and clay (< 2 m thick). Rhythmites thin upwards. A maximum of 40 rhythmites indicates that the lakes were short-lived.

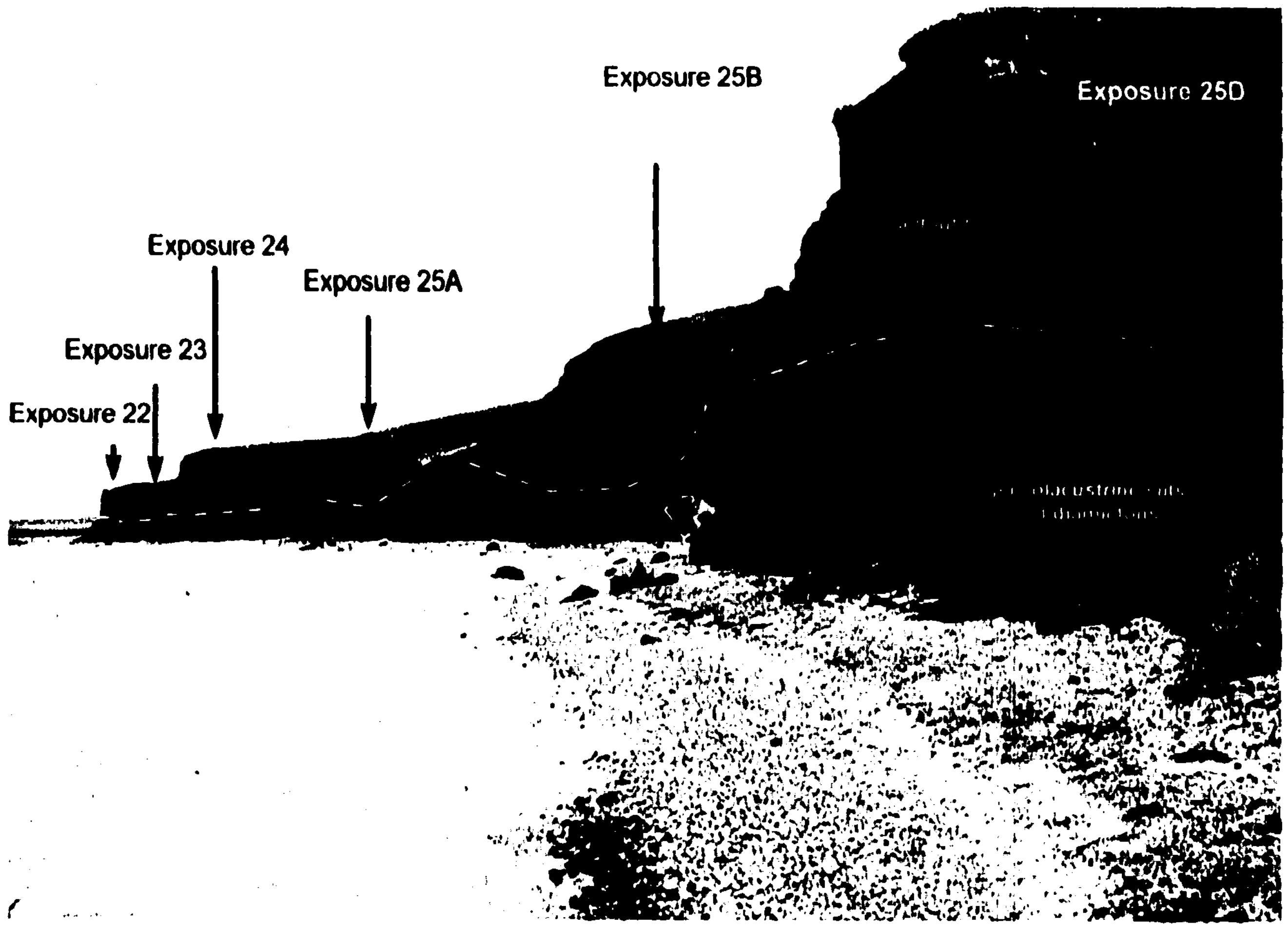

Figure 6.10: The same stratigraphic sequence can be observed in many exposures in succession. Here at least 5 individual hummocks have the same sequence: glaciolacustrine sediments conformably overlain by subglacial till.

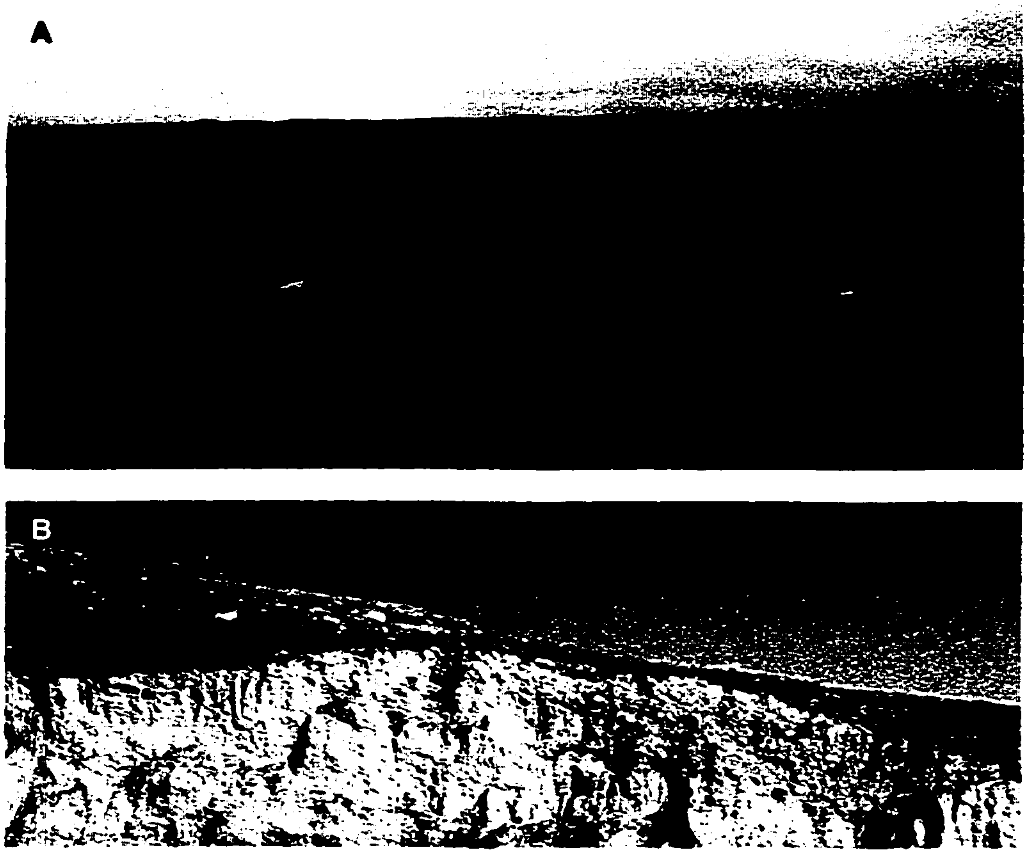

Figure 6.11: A. Boulder lag at West McGregor exposure 3. B. Boulder lag at Travers exposure 2. Boulders on the surface are clearly coincident with the underlying boulder gravel occupying a scour, suggesting that the boulders were concentrated by winnowing.

ORIGIN OF THE HUMMOCK FORM

Both internal sediments and surface morphology are important to the interpretation of hummocky terrain. The hummocks contain both deformed and undeformed sediments of variable origin. In the field area, intact stratigraphies are truncated at hummock surfaces (Fig. 6.12). Therefore, each hummock is a product of erosion, and not deposition. Bed truncation is most obvious where beds in the hummocks have been upturned (e.g., Fig. 6.12A, F, G, I). Figure 6.12 shows eight hummock exposures that contain the sedimentary sequence described in the previous section (a brief description of each sequence is given in the figure captions). All of these exposures show erosional truncation of internal sediments at the hummock surfaces and demonstrate that the hummocky landscape itself is a regional-scale erosional surface.

Thus, the widely accepted hypothesis that the hummock morphology was created by differential lowering and faulting during supraglacial let-down is contradicted by:

(i) the continuous, unfaulted strata beneath depressions at many locations;
(ii) the presence of primary subglacial melt-out till as the youngest unit in the hummocks; and
(iii) by the consistent non-conformable contacts between internal sediments and hummock surfaces.

Other hypotheses are also contradicted by observations:

(i) undisturbed sediment at some locations contradicts ice-pressing (e.g., Hoppe, 1952);
(ii) undisturbed sediment and lack of shear planes at many locations contradict a thrust origin for the hummocks (e.g., Hambrey et al., 1997);
(iii) subsurface diapirism (e.g., Boulton and Caban, 1995) does not account for hummocks as diapirs are uncommon in the centre of hummocks;
(iv) preferential lodgement (Menzies, 1982) is contradicted as lodgment till is not present in most hummocks;
(v) *in situ* sediments contradict active ice moulding (e.g., Aario, 1977);
(vi) there is no secondary reworking of sediments related to frost heaving, or frost cracking, and hence periglacial action (e.g., Henderson, 1952) was not responsible for hummock formation.

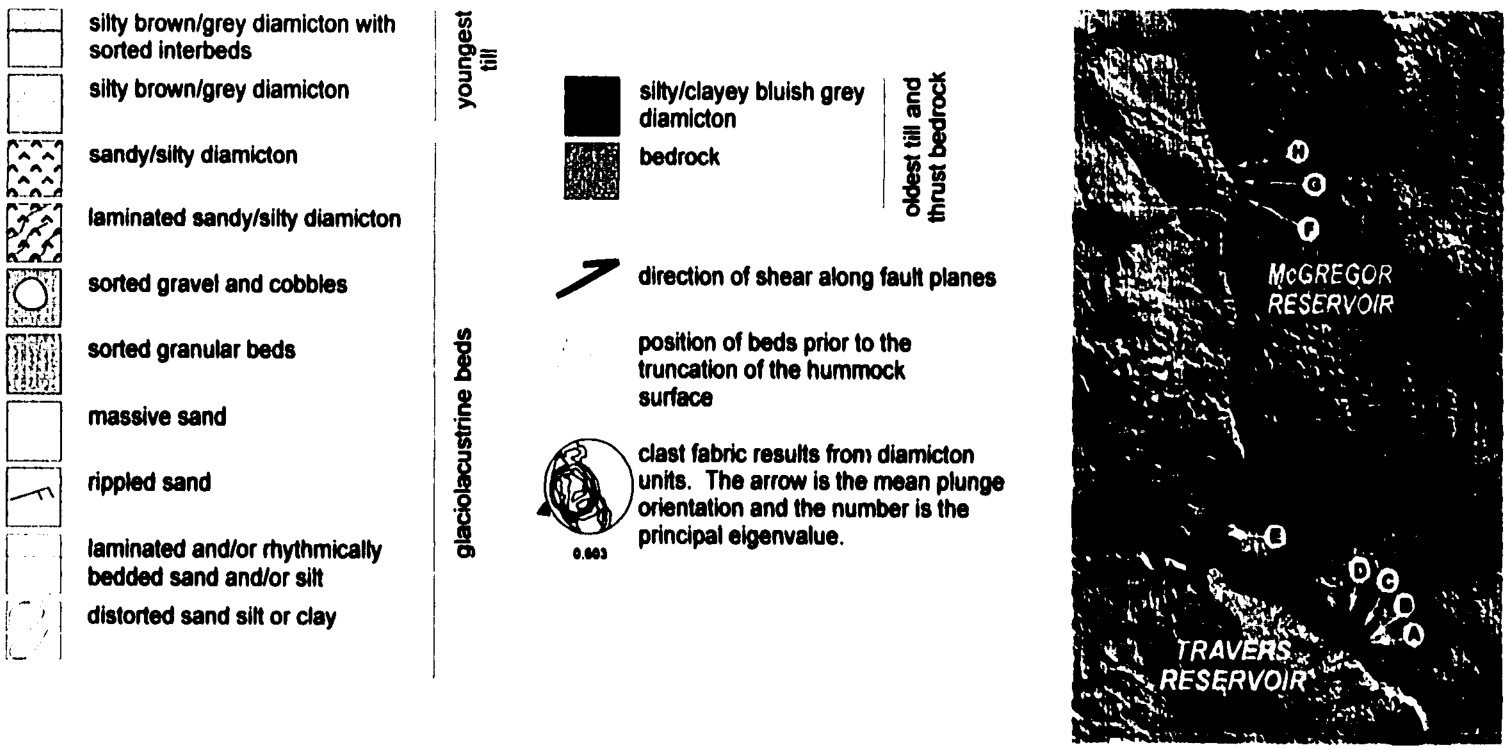

Figure 6.12: Legend for symbols used in the following exposure diagrams. Each diagram is drawn to illustrate the erosional nature of hummock surfaces. The DEM shows the location of each exposure drawn.

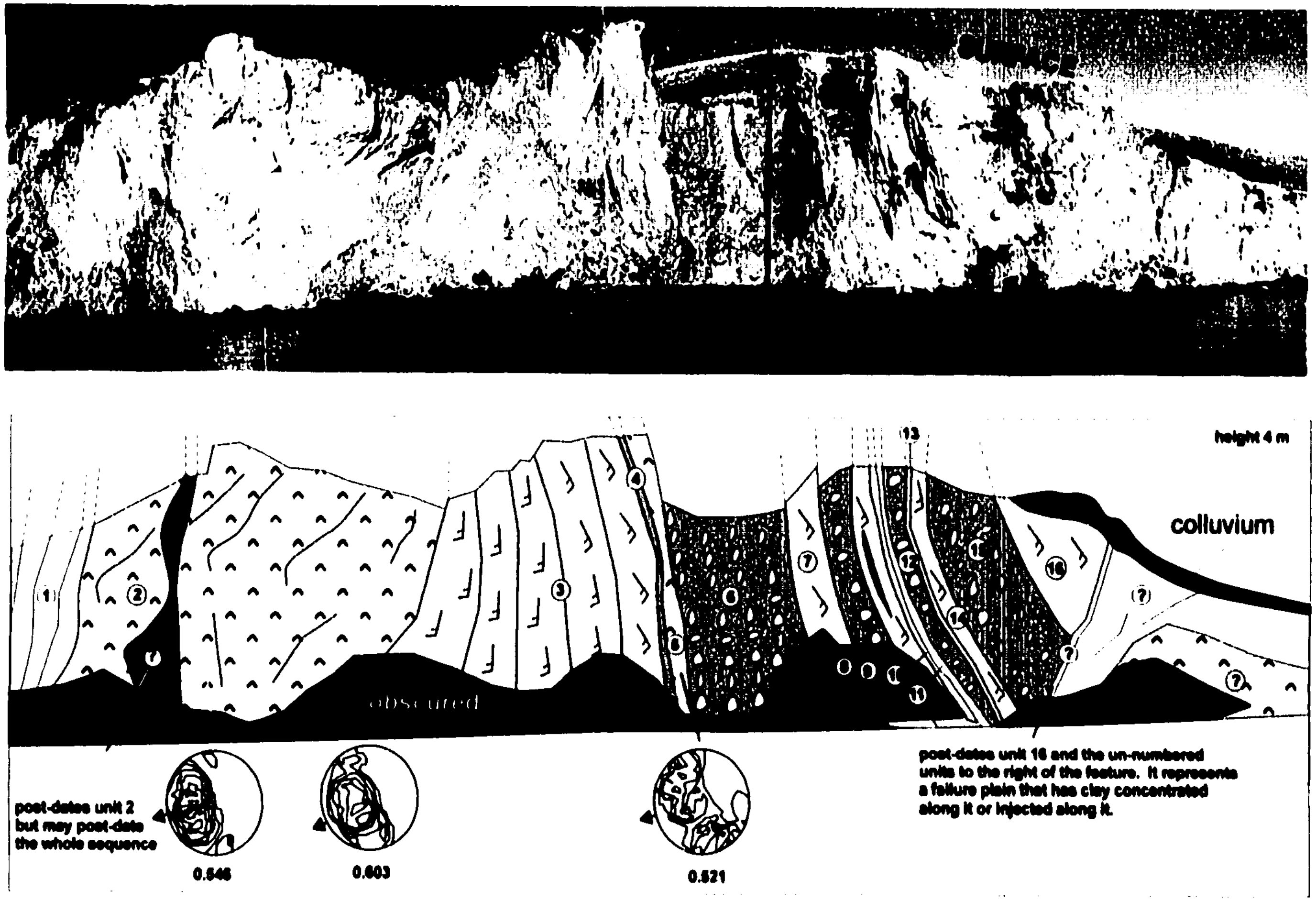

Figure 6.12A: Travers exposure 4: a symmetric hummock. Units were laid down in the order that they are numbered. Where the order cannot be determined the units are marked with a question mark. This exposure contains a thick sequence of sorted beds with some diamictons. Diamictons conformably overlie and are interbedded with the sorted beds. They therefore relate to aqueous rather than glacial deposition. The consistent mean fabric orientations and fabric shape suggest that these were laid down in the same environment by the same process. Principal eigenvalues (S_1) are low, and support a debris- or slurry-flow origin. The sequence is interpreted as distal and proximal turbidites and debris flows that were deposited in a high energy glaciolacustrine environment. These have been diapirically intruded by Labuma till, and may have been faulted. The entire sequence has been tilted and is truncated by the surface that represents the hummock morphology.

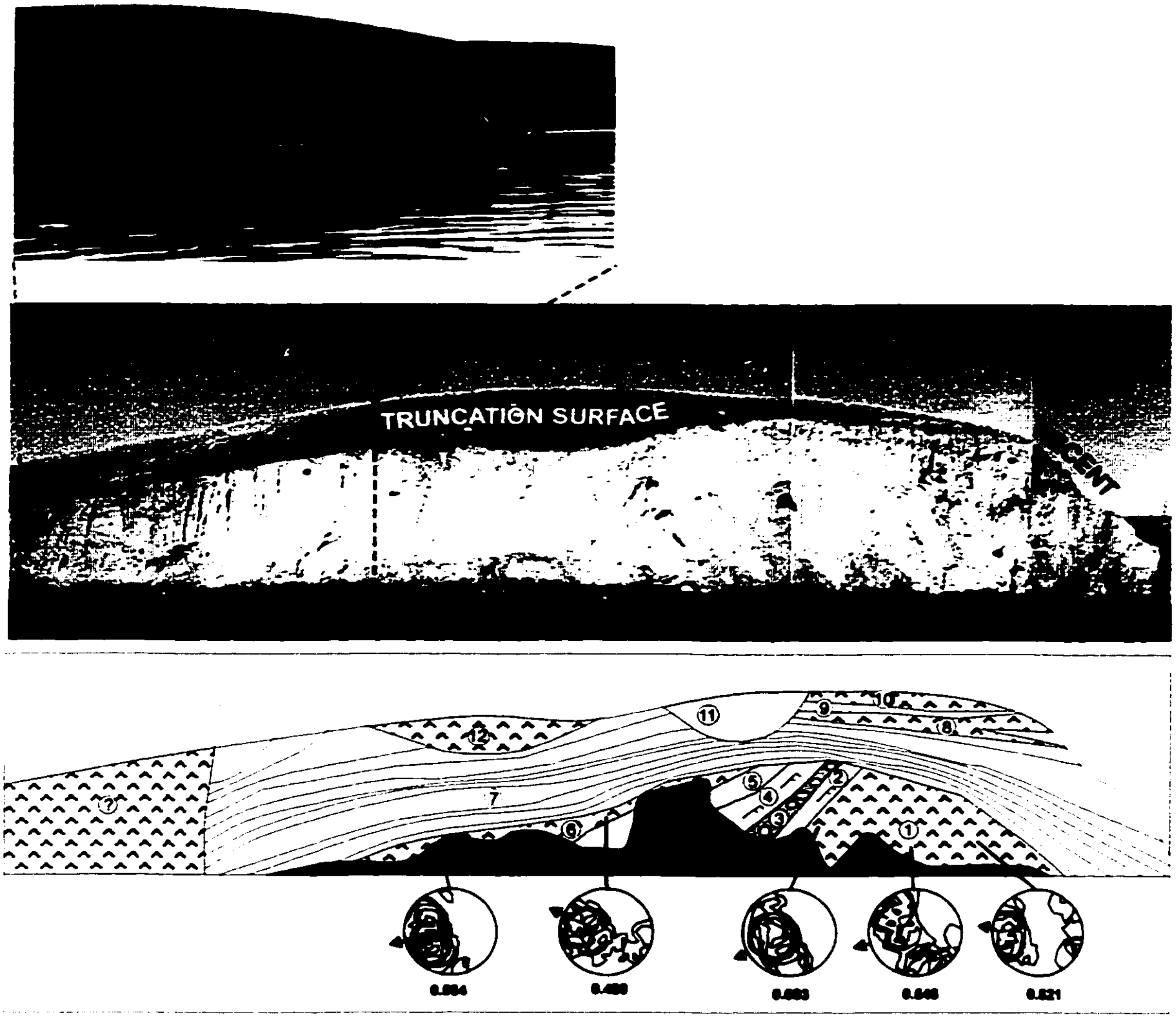

Figure 6.12B: Travers exposure 5 - an asymmetric hummock. A complex sequence of interbedded glaciolacustrine sediments dominate this exposure. Units were laid down in the order that they are numbered. Diamictons are interpreted as debris flows in a subaqueous environment as they are interbedded with sorted beds. Also, orientation strength (S_1) is low, but the fabric shape and mean plunge orientations for each bed are similar, suggesting a similar environment of deposition. Beds 1 - 6 were tilted and then eroded (thick black line) before deposition of the overlying beds. Channels are cut into this sequence (11 and 12?). It is not certain where the diamicton at the west of the exposure fits into the sequence. It may be a diapir of older sediment that has been intruded through all the overlying sediments, or it may be younger, with the contact representing a normal fault. The arching of all the sediments may represent minor folding, or post-depositional diapirism of unit 1. All units are clearly truncated at the hummock surface demonstrating that the hummock morphology is erosional.

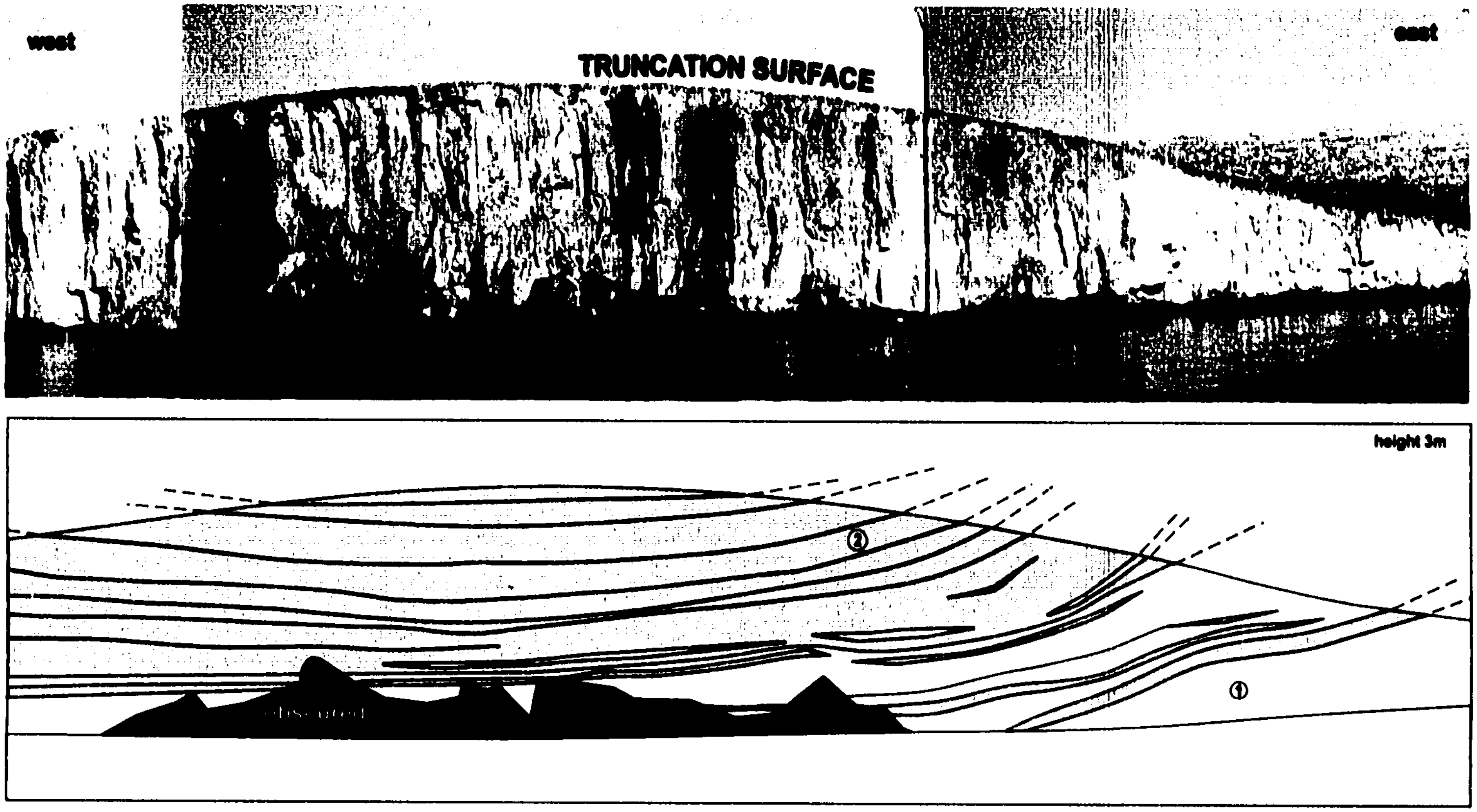

Figure 6.12C: Travers exposure 7 - a symmetric hummock. Glaciolacustrine silts grade conformably into the overlying stratified diamicton interpreted as subglacial melt-out till. Sediments have undergone minimal post-depositional disturbance. Both glaciolacustrine deposits and diamicton beds are truncated by the hummock surface.

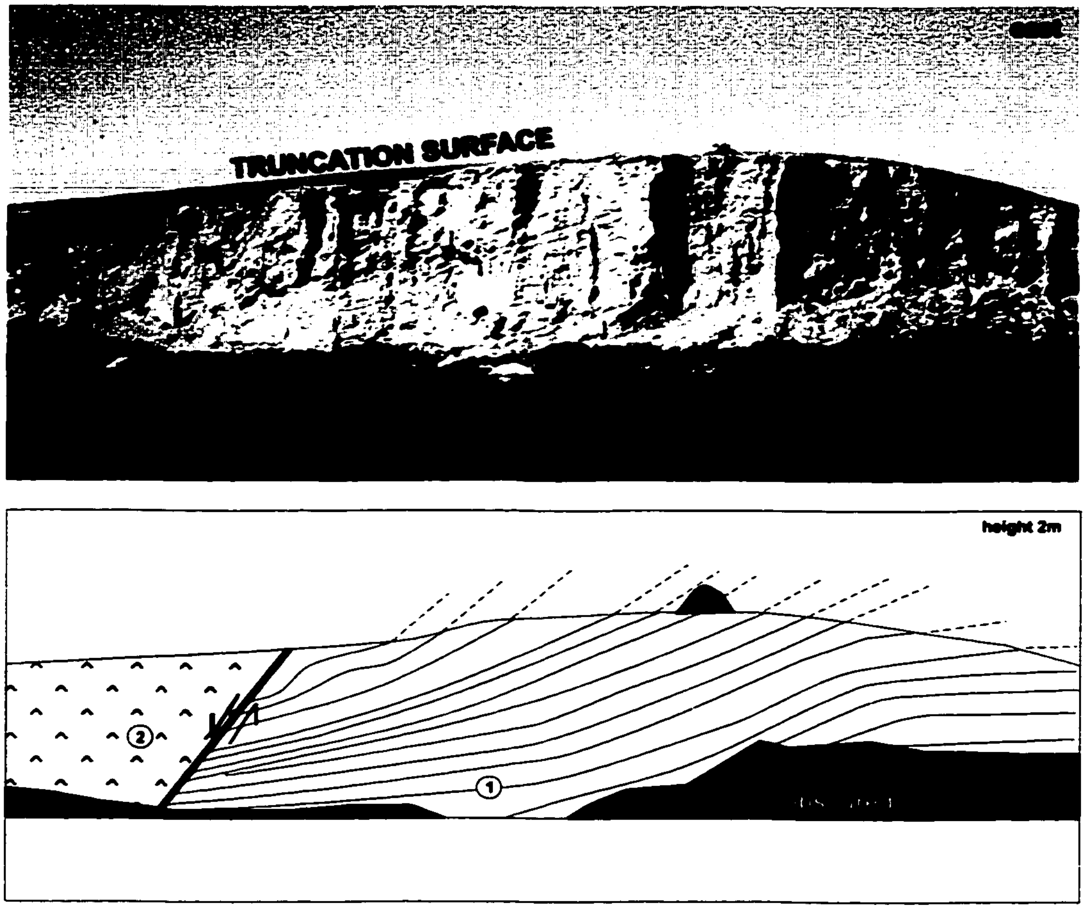

Figure 6.12D: Travers exposure 8 - an asymmetric hummock. Most of the exposure is composed of planar cross-bedded fine sand. This is typical of subaqueous fan sedimentation toward the edge of main sediment plumes. Sandy diamicton overlies the sand but has slumped down to its present position. Beds are truncated at the hummock surface. A single boulder lies on the surface and is part of a sparse lag at this location.

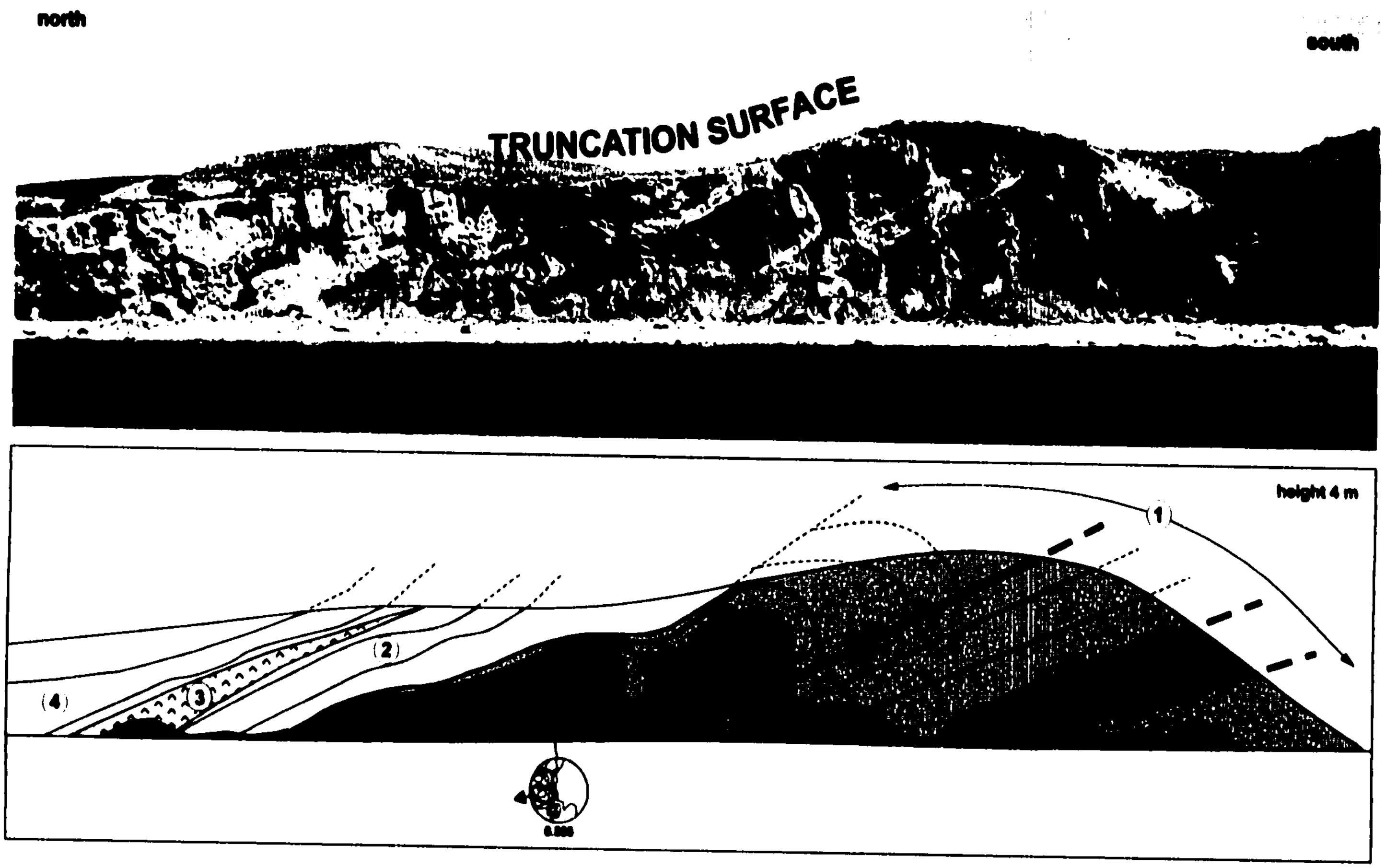

Figure 6.12E: Travers exposure 10 - a transverse hummock. This exposure demonstrates how the oldest till (the Labuma till) is folded with the local bedrock and, in places, even underlies disturbed bedrock. Overlying the sequence is bedded glaciolacustrine sediment. All units are truncated at the hummock surface.

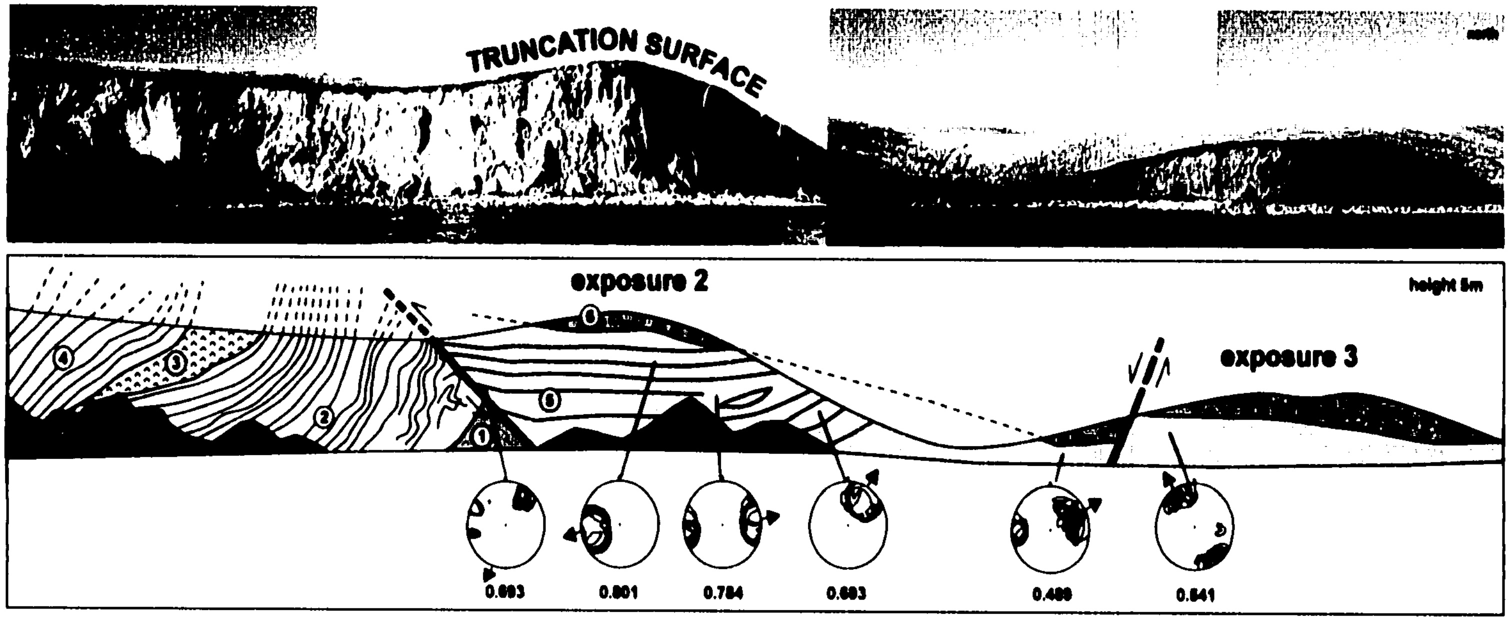

Figure 6.12F: West McGregor exposures 2 and 3 - asymmetric hummocks. These are dominated by glaciolacustrine sorted beds to the south, and till overlain by gravels to the north. The till is younger than the glaciolacustrine beds and has been displaced laterally southward. The truncation is most notable where silts have been upturned and truncated at the surface, and where the continuous gravel bed has been truncated.

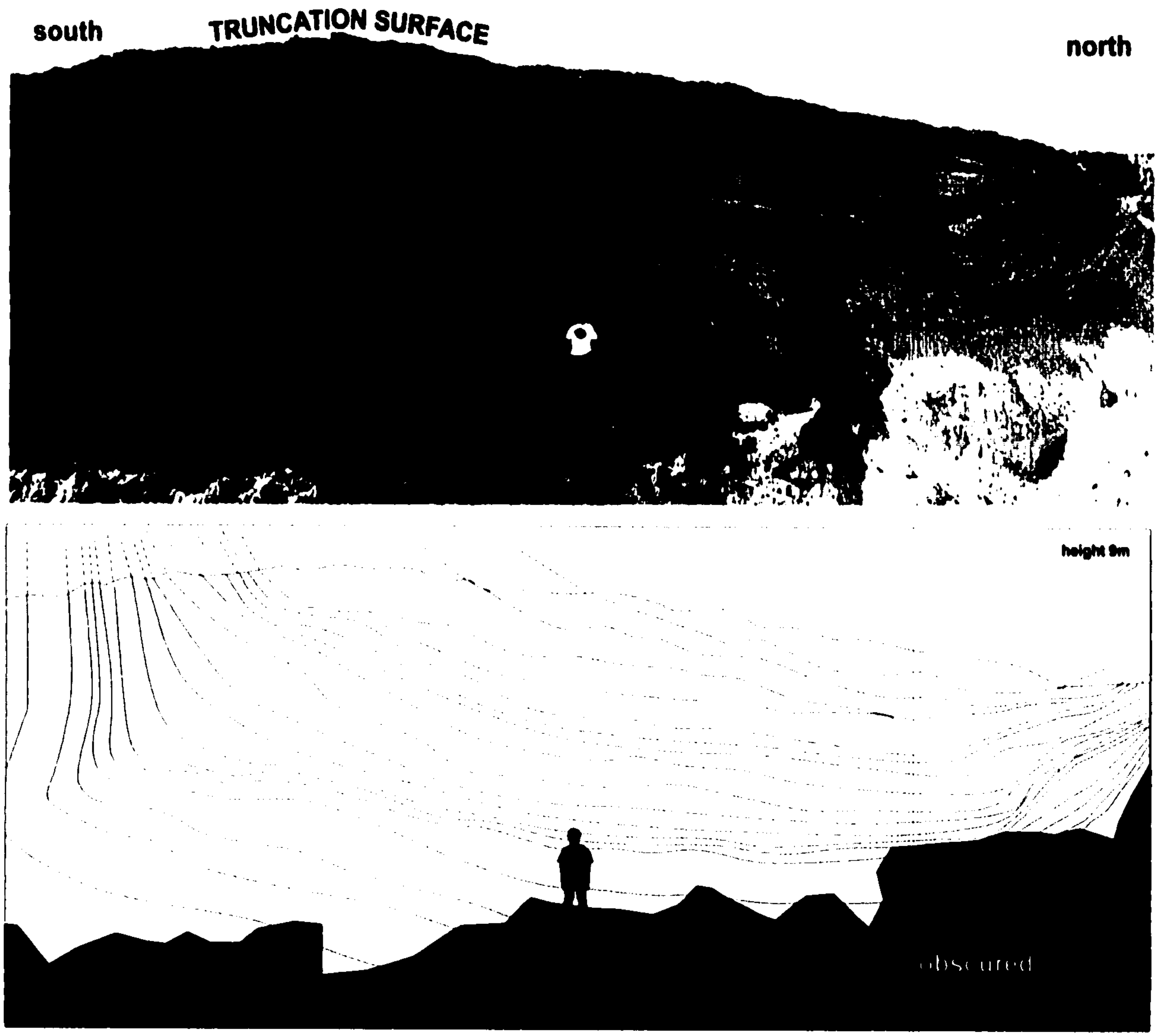

Figure 6.12G: West McGregor exposure 20 - an asymmetric hummock. Rhythmically bedded sand, silt, and clay dominates this entire exposure. Beds have undergone minor folding and then have been truncated at the hummock surface.

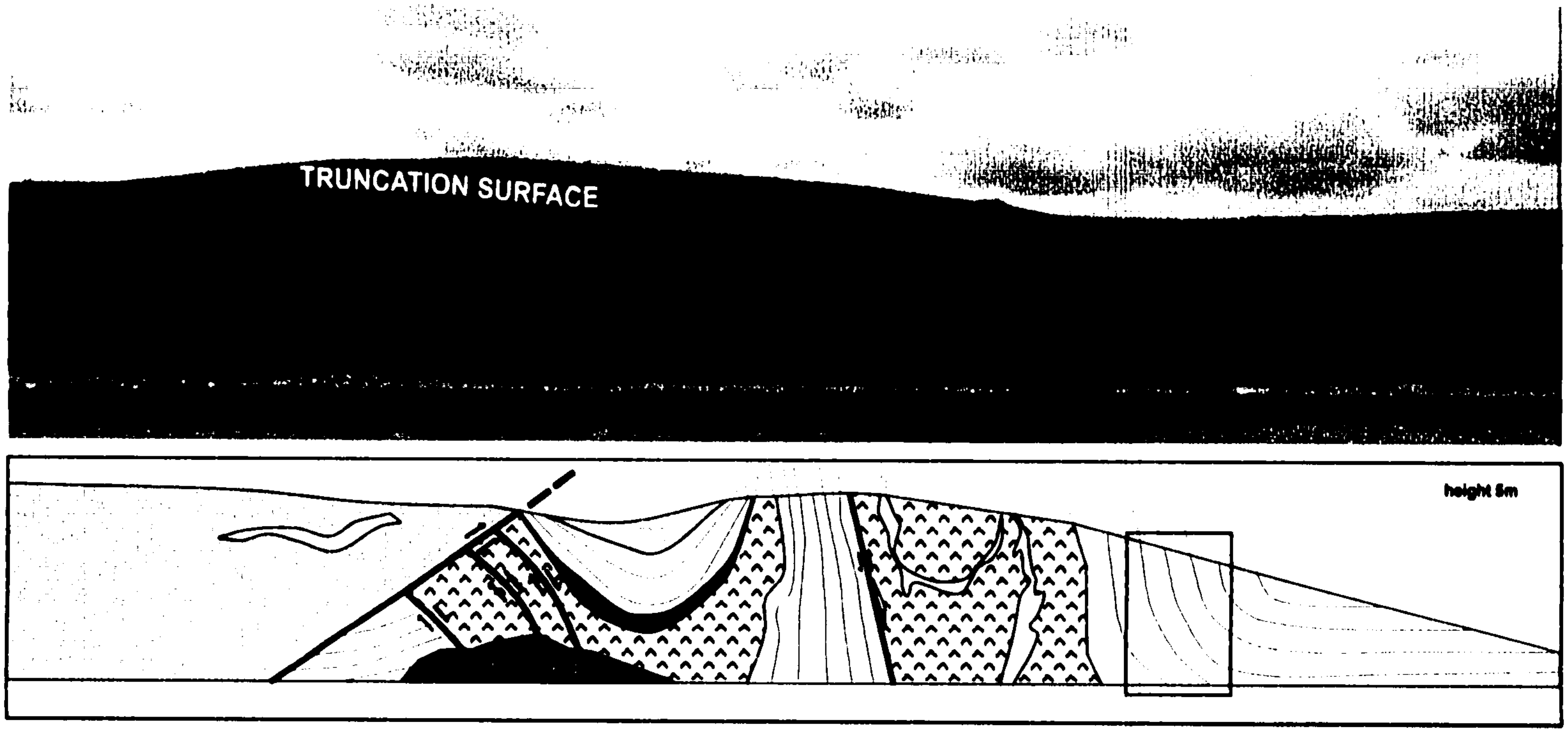

Figure 6.12H: McGregor West Exposure 32 - an asymmetric hummock. The three main glacigenic sediment types observed across the study area are present in this exposure. The oldest Labuma till is not *in situ*, rather it has been thrust up as a raft into overlying deformed lake sediments. The lake sediments are not pervasively deformed, although both extensive shearing and folding phases are present. As these cross-cut each other in places, there was more then one deformational event. The rhythmically bedded sediments at the northern extreme of the exposure are *in situ*. Beds are not numbered as they are too disturbed to determine the order in which they were deposited, but it is known that the grey unit is the youngest.

The processes inferred in each of these theories are generally based on limited sedimentary observations. Although the sediments and structures noted by other researchers are also present in the Travers/McGregor hummocks, they do not lead to a consistent interpretation explaining the erosional origin of hummocky terrain.

Since the youngest unit within the hummocks is interpreted as subglacial, and superimposed subglacial eskers are clearly younger than the hummocks, the hummock surfaces must represent subglacial rather than proglacial erosion. This erosion may be ascribed to ice (directly or by way of a deforming bed), and/or to meltwater flowing between the ice and its bed. I conclude that ice or a deforming layer were not the eroding agents for the following reasons:

1. The presence of pervasively deformed sediment may provide evidence of deformable bed conditions (e.g., Hart, 1995; Boulton, 1996). However, there are no deformation tills or pervasively deformed sediments directly beneath the hummock surfaces. Although pervasively deformed material is present low in the stratigraphic sequence in the lake beds, it passes upwards to undeformed sediments formed by passive deposition of melt-out till, and short-lived meltwater events (Munro-Stasiuk, in press b). Thus the erosional event was preceded by sediments associated with stagnant ice.

2. Neither ice erosion nor deforming-layer erosion can account for boulder lags on the hummock surface: neither have the capability of preferentially removing fines. In glacial environments, concentration of clasts as boulder pavements has been attributed to clast ploughing during lodgement (e.g., Clark and Hansel, 1989). to subglacial deformation (Hicock, 1991), or to selective lodgement of coarse clasts accompanying removal of fine particles during lulls in till deposition (Johansson, 1972; Stea and Brown, 1989). Yet, such pavements commonly have >50% silt and clay in the matrix and are usually composed of faceted clasts which are striated on their upper surfaces (Clark, 1991; Hicock, 1991). The boulders described here are unfaceted, sub-rounded to rounded, with no surrounding matrix. They show evidence of water transport (see below), and thus they are considered to be glaciofluvial lags.

3. Between 1 and 20 m of sediment have been removed to form the interhummock depressions. As well, moraine plateaux indicate that the whole hummock landscape has been denuded. The eroded material has been transported downflow (toward the southeast), yet expected downflow

depositional features (moraines, till blankets, outwash, or glaciolacustrine beds) within or beyond the zone of hummocky erosion are lacking. Ice itself can only move the eroded sediment to the ice margins. Ice-marginal deposits or end moraines are not recognized beyond the hummocky zone (Beaney, 1998).

4. Fabrics from the youngest sediment in the hummocks, a melt-out till, document ice flow from the northeast (Fig. 6.9), highly oblique to the flow direction indicated by hummock surface orientation (Figs. 6.3, 4 and 5), and other oriented landforms such as flutes/remnant ridges (Fig. 6.1). If ice had eroded these surfaces, the fabric patterns near the surface should be more variable and perhaps even be partly re-aligned with the direction of ice movement.

For the following reasons evidence suggesting that meltwater eroded the hummock surfaces is most convincing:

1. Abrupt erosion surfaces (Fig. 6.12) are readily explained by meltwater erosion involving sediment removal clast by clast and grain by grain. Hence, there is minimal disturbance of underlying strata.

2. Surface boulders are best explained as lags, left behind during glaciofluvial transport, where flowing water had the competence to remove all but the largest boulders. The coincidence of surface lags and underlying coarse gravel supports this winnowing explanation (Fig. 6.11B). Percussion marks on the boulders attest to clast to clast collisions during transport. The lags are unlikely to represent minor subaerial erosion (cf., Wright et al., 1973) because there are no complementary deposits in the swales between hummocks. As well, stratigraphic relationships suggest that erosion was subglacial, and uphill flow in some hummocky terrain requires pressurized conditions in a subglacial environment.

3. Subglacial and extraglacial water flows may have transported the predominantly fine-grained sediment over large distances, perhaps as far as the Gulf of Mexico (Shaw et al., 1996). Thus, the lack of deposits complementary to hummock-forming erosion is better-explained by the meltwater hypothesis.

4. The hummock erosional surface resembles bedforms (Figs. 6.3 and 4). For example, transverse hummocks resemble fluvial bedforms (e.g., Allen, 1982) and erosional marks formed beneath river ice (Ashton and Kennedy, 1972). They also resemble megaripples in form and scale, and streamlined loess hills which were sculpted by catastrophic floods in Washington and Montana. The latter "Channeled Scabland" remnant features maintain undisturbed internal stratigraphy (as in the Travers-McGregor hummocks) despite erosion by the Lake Missoula floods (Bretz, 1969). Some erosional forms in scabland basalt resemble hummocky terrain (Baker, 1978), indicating that meltwater erosion is a plausible explanation for hummock formation. Also, horseshoe-shaped depressions around the upflow-facing slope of some hummocks are well explained as products of horseshoe vortices wrapping around bluff obstacles (e.g., Shaw, 1996). Furthermore circular erosional depressions are comparable to giant potholes formed by kolks.

DISCUSSION

Hummocky terrain along McGregor and Travers reservoirs is clearly a product of erosion. This conclusion is supported by the widespread truncation of beds within hummocks. The evidence suggests that hummocks were formed subglacially, most likely by meltwater. The total amount of erosion is unknown, but between 1 and 20 m of sediment must have been removed from between the hummocks as the hummocks themselves are denuded. As well, sediment may have been removed prior to and during hummock formation. If the surfaces of moraine plateaux represent the pre-erosion land surface (Rains et al., 1993), then an additional 1-5 m of sediment must have been removed.

As the trends in hummocky alignment consistently indicate flow to the southeast, and there are no cross-cutting features, it is assumed that all hummocks formed contemporaneously. In my preferred interpretation, southeasterly currents in meltwater crossed and submerged hummocky terrain. To account for the hummock field, flow must have been at least 70 km wide. Since it is difficult to envisage piecemeal formation of wide bands of similarly oriented hummocks by narrower flows, the hummocks are assumed to have formed beneath a broad coherent flow. Thus meltwater must have been stored upglacier from and, even in the area of hummocks, and then released catastrophically to account for the amount and extent of erosion.

If the interpretation that water eroded the hummocks is correct, and the boulders left on top of the hummocks are glaciofluvial lags, then it is possible to estimate the entrainment velocity of those boulders, and hence, obtain a maximum velocity for the flow that eroded the hummock surfaces. Costa (1984) gives a relationship between grain size, flow depth, and flow velocity for flow with high sediment concentration:

$$V = 3.5\, d^{0.17}\, D^{0.33}$$

where V is the mean velocity (ms $^{-1}$), d is half the flow depth (m), and D is the diameter of the boulder (m). The range of flow depth is estimated at 10 m to 130 m. A 10 m deep flow would overtop most, but not all, hummocks. A 130 m deep flow would overtop the largest hills in the region. The observed range of clast sizes is between 10 cm and 2 m. Using the relationship above, the minimum and maximum flow velocities across the study area are 2 m s $^{-1}$ and 7.5 m s $^{-1}$ (Table 6.2).

Taking the relationship further, if the flow dimensions are known and the entrainment velocity is known then discharge rates can be determined (Table 6.2). If the flow was of the width of the hummocky zone only, then it was 70 km wide. Larger scale fluting in the areas north of the Little Bow River and in the Blackspring Ridge flute field also show northwest to southeast trends (Fig. 6.1). Munro and Shaw (1996) proposed that the Blackspring Ridge flutes represents sheetflow erosion at least 50 km wide. Flutes are transitional to hummocks, hence it is likely that these features formed contemporaneously and flow may have been as wide as 120 km accounting for the full suite of landforms. Using the same flow depths and the velocities determined for boulder entrainment, the total discharges range between 1.4 x 10^{6} m^{3} s^{-1} and 1.4 x 10^{8} m^{3} s^{-1}. These numbers are comparable to the discharge of 6 x 10^{7} $m^{3}s^{-1}$ conservatively estimated for the

	Boulder size 0.1 m		**Boulder size 2 m**	
flow dimensions	**velocity**	**discharge**	**velocity**	**discharge**
d = 10 m, w = 50 km	2 m s^{-1}	1.4 x 10^{6} m^{3} s^{-1}	5.8 m s^{-1}	4.1 x 10^{6} m^{3} s^{-1}
d = 10 m, w = 120 km	2 m s^{-1}	2.3 x 10^{6} m^{3} s^{-1}	5.8 m s^{-1}	7 x 10^{6} m^{3} s^{-1}
d = 130 m, w = 50 km	3 m s^{-1}	2.7 x 10^{7} m^{3} s^{-1}	9 m s^{-1}	8.7 x 10^{7} m^{3} s^{-1}
d = 130 m, w = 120 km	3 m s^{-1}	4.5 x 10^{7} m^{3} s^{-1}	9 m s^{-1}	1.4 x 10^{8} m^{3} s^{-1}

Table 6.2: Mean flow velocities calculated for minimum and maximum sized clasts in boulder lag, and minimum and maximum depths of flow. Discharges are calculated for minimum flow widths (across the hummocky terrain only), and maximum flow widths (across the hummocky and fluted terrain).

Livingstone Lake drumlin field (Shaw, 1996) which lies upstream along a distinctive flood swath (Rains et al., 1993).

Interestingly, since reservoirs are required for outburst floods, Munro-Stasiuk (in press, a) demonstrated that subglacial lacustrine sediments in hummocks at McGregor and Travers Reservoirs were deposited subglacially. Based on the areal extent of the lake sediments and the depth of the water required for their deposition, the estimated volume of water stored at McGregor Reservoir ranged from 8 km^3 to 10 km^3, and at Travers Reservoir, from 10 km^3 to 16 km^3. These numbers are comparable to the volume stored at Grimsvötn, Iceland, prior to jökulhlaups (Gudmundsson et al., 1995). Although the McGregor subglacial lake had drained prior to the erosion of the hummock surfaces, as documented by the deposition of melt-out till, drainage durations are calculated based on Travers subglacial lake draining only, and both lakes draining. Assuming that these lakes were full just prior to the outburst that eroded the landforms, and using the discharge estimates from Table 6.2, drainage duration ranges from ~ 2 minutes to just over six hours (Table 6.3). Using only the Travers subglacial lake, which is more likely to have existed at the time of the outburst, the drainage duration was ~ 1 minute seconds to just over 3 hours. The implications are that the reservoirs were likely orders of magnitude too small to account for the erosional landforms, as the drainage durations are short (even using absolute minimum flow velocities and flow dimensions). Therefore, much larger reservoirs of water had to have existed upstream from this site.

volume (from Munro-Stasiuk, in press, a)		**discharge**	**time to drain**
Travers only	10^{10} m^3	1.4 x 10^6 m^3 s^{-1}	119 min
		1.4 x 10^8 m^3 s^{-1}	71 s
	1.6 x 10^{10} m^3	1.4 x 10^6 m^3 s^{-1}	190 min
		1.4 x 10^8 m^3 s^{-1}	114 s
Travers and McGregor	1.8 x 10^{10} m^3	1.4 x 10^6 m^3 s^{-1}	214 min
		1.4 x 10^8 m^3 s^{-1}	128 s
	3.1 x 10^{10} m^3	1.4 x 10^6 m^3 s^{-1}	369 min
		1.4 x 10^8 m^3 s^{-1}	221 s

Table 6.3: Calculated drainage times for minimum and maximum volumes for the Travers subglacial lake and combined Travers and McGregor subglacial lakes, using the minimum and maximum discharge values from Table 6.2.

IS THIS FIELD AREA UNIQUE?

The sites at Travers and McGregor Reservoirs are unique in that the quality and number of exposures are exceptional. They also appear to be unique in that these are the only documented sites, to date, that record a continuous erosional surface defining the hummocky terrain. This erosional surface rules out depositional theories of hummocky terrain genesis, although some theories such as ice-pressing and active ice moulding do recognize that sediment within hummocks must predate the hummock form. It has been normal practice to interpret hummocky terrain based on small exposures of hummock materials. Unfortunately such exposures are generally poor and restricted to minor road and river cuts. Where glaciolacustrine sediments, or debris flows have been observed, it has been customary to interpret hummocks as the product of supraglacial letdown. Where subglacial sediments have been observed, it has been customary to interpret the features as the product of ice pressing or moulding. Although the consequences of an erosional origin of hummocks have not been clearly set out, they are fundamental: ***if erosion is the main mechanism of much hummocky terrain formation, then hummocks may contain any surficial sediment or rock type and many structural elements.*** The critical observation is that the internal architecture or structure is truncated at the hummock surface. Hummocks at four locations outside the field area further illustrate this point.

Hummocks in the BLM near Stettler, central Alberta (Fig. 6.2) are dominated entirely by thrust bedrock (Fig. 6.13). Thus, Stalker's (1960b) observations indicating that many of the features are composed predominantly of till (6 - 16 m) are incomplete. The hummocks with bedrock were not recognized and were identified as thrust ridges by Tsui et al., (1989). Although thrusts formed ridges oriented approximately NW to SE, the land surface has been modified by erosion to create the modern hummocky landscape. The folded beds are truncated, and reconstruction of the folds indicates several metres of erosion. The near-absence of sediment on the hummocks refutes hypotheses invoking thick supraglacially derived sediments.

Near the northern limit of the Viking "moraine" (Fig. 6.2), Sjogren (1999) observed morphologically similar hummocks to those described from the southern BLM. He noted that the hummocks contain glaciolacustrine and glaciofluvial sediments, diamicton (till), and bedrock. Like the BLM hummocks, materials are deformed or *in situ*. Most importantly, Sjogren (1999) reports truncated beds at the hummock surfaces and boulder lags on the erosional plane. At least one hummock reported by Sjogren (1999) contains intact and *in situ* Cretaceous bedrock with bed truncation at the surface.

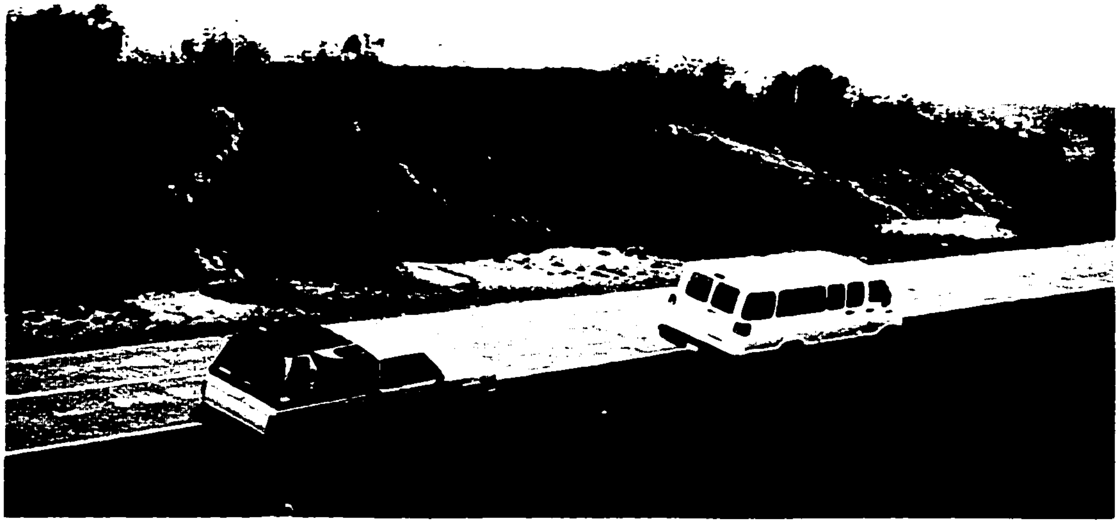

Figure 6.13: Exposure through part of the Buffalo Lake Moraine near Stettler central Alberta. Bedrock was glaciotectonically thrust and has been truncated at the hummock surface. No significant glacigenic sediments overlie the bedrock.

The "Duffield moraine" near Heatherdown, northwest of Edmonton, Alberta (Fig. 6.2) is composed of *in situ* and thrust bedrock with well-developed lags overlying that surface (Fig. 6.14). Hummocks range from 1 - 25 m high and some display surficial sediment of only ~ 20 cm thick. Thus, in some cases a thin unit of diamicton, overlies the boulder lag, and in other cases a thin bed of gravel overlies the bedrock. As these features are composed primarily of bedrock their origin must be erosional.

One exposure in the "Eastend moraine" near Swift Current, southern Saskatchewan, reveals up to 30 m of rhythmically bedded sand, silt, and clay. These are horizontal and undisturbed (Fig. 6.15). Beds are truncated at the hummock ground surface. The hummock relief involves excavation to a depth of about 5 m at hummock depressions.

Although the four sites discussed above have far less spectacular exposures than those at Travers and McGregor Reservoirs, the sediment/landform surface relationships are identical for all the hummocks. Importantly, sediment genesis and hummock genesis are clearly unrelated. Thus the so-called "morainal belts" are not moraines formed of glacial sediment at the margins of the Laurentide Ice Sheet. Further detailed analysis of other exposures in other regions will test the general applicability of these conclusions.

CONCLUSIONS

Hummocky terrain in the southern BLM is clearly the product of erosion into pre-existing sediments and bedrock. This erosion in the subglacial environment, and the resulting morphology, are best explained by the action of meltwater rather than ice. Importantly, if hummocks in the BLM are erosional, and may have formed many hundreds of kilometers behind the ice margin, then the BLM is not a moraine, and cannot be used to delineate a significant stillstand of the disintegrating Laurentide Ice Sheet. This appears to hold true for the "Viking moraine", the "Duffield moraine", and the "Eastend moraine". The hummocky landscapes in these are dominated by landforms of similar form, magnitude, and pattern as in the southern BLM, and most importantly, internal materials are truncated at the landform surfaces. Thus, the large hummocky terrain belts observed in the prairie regions are unlikely to be true moraines. Consequently, reconstructions of Laurentide ice sheet deglaciations are questionable (e.g., Clayton and Moran, 1982; Dyke and Prest, 1987). In general, authors of maps, reports, and papers refer to "hummocky moraine," "stagnation moraine," and "ice-stagnation topography." This terminology mistakenly assigns hummocky terrain to stagnant ice in marginal or near-marginal positions. According to the interpretation presented

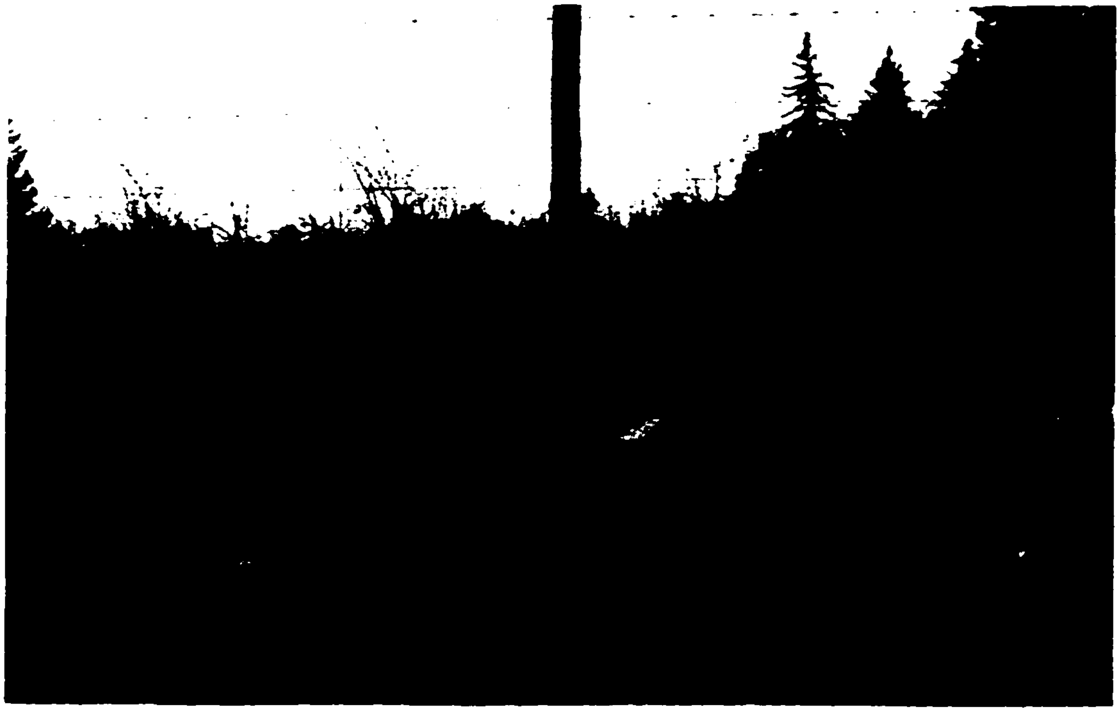

Figure 6.14: Exposure through the top of one hummock in the Duffield Moraine (Fig. 6.2). This hummock is composed of in-situ bedrock overlain by a boulder lag and thin veneer of diamicton. It is unsure whether the diamicton is till.

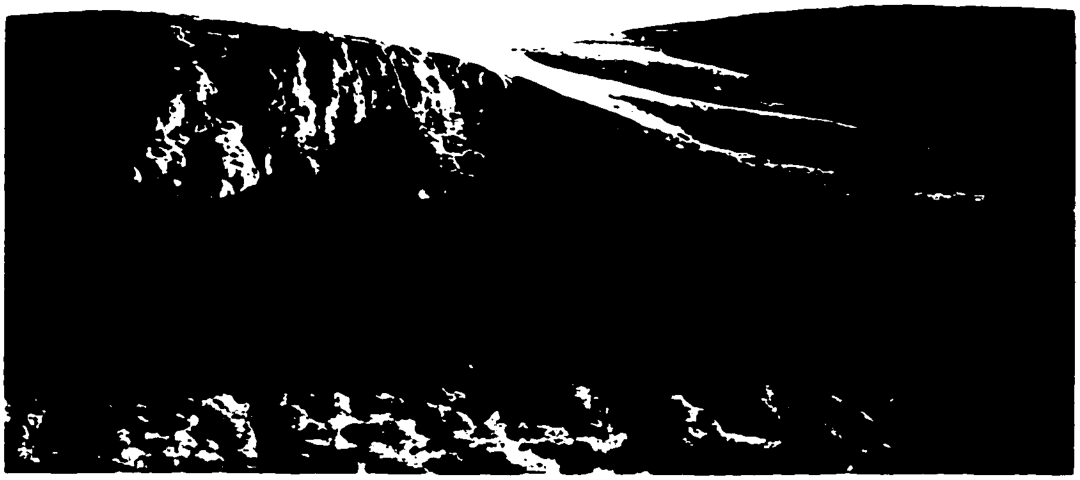

Figure 6.15: Exposure through the “Eastend moraine”, southwest Saskatchewan (north of the Cypress Hills). Intact horizontally-bedded glaciolacustrine rhythmites are truncated by the surface that represents the hummock morphology.

here, such terminology does not apply when hummocky terrain of the Great Plains is examined in detail. Such genetic terminology should be abandoned and "hummocky terrain" should be classified in descriptive terms only.

In light of this research many questions still remain unanswered. For instance, the detailed mechanics of hummock formation by meltwater erosion are not well understood. The exact scale of the proposed flow, how the meltwater interacted with different substrates-regardless of the scale of the flow, relationships between form and substrates, and the locations of the deposits related to large-scale erosion, are some matters of speculation. Also, moraine plateaux remain enigmatic landforms. Detailed sedimentary observations and interpretations are an essential step in determining if moraine plateaux are also erosional residual remnants, or if they post-date hummock formation and do represent stagnation features, as suggested by some researchers (e.g., Clayton, 1973). Moraine plateaux are found only within hummocky zones. Therefore, given this association, their genesis is *probably* linked to hummock formation. As well, sediment ridges forming rings around circular depressions (Fig. 6.3D) invite detailed scrutinization.

The hummocky terrain discussed here is confidently inferred to be a product of subglacial erosion, most likely meltwater erosion. Consequently, the implied presence of enormous volumes of meltwater beneath the Laurentide Ice Sheet has a direct bearing on reconstructions of ice-flow regime, ice thickness, and ice extent. These conclusions carry major implications for ice-sheet modeling.

On a final note, it must be stated that hummocks are polygenetic and erosion cannot account for all hummocky terrain. For example, subaqueous outwash can appear hummocky (Rust, 1977); ice-stagnation hummocks occur in front of many modern glaciers (e.g., Sharp, 1985); and moraines produced by thrusting of debris onto the ice surface and then melting out have also been observed in modern environments (e.g., Hambrey et al., 1997). Consequently, a genetic landform classification scheme relating hummocks to primary mechanisms (e.g., erosion, glaciotectonism, letdown) remains an important goal for understanding and reconstructing landscapes produced by the mid-latitude, Pleistocene ice sheets.

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CHAPTER 7: EVOLUTION OF A SUBGLACIAL LANDSCAPE, SOUTH-CENTRAL ALBERTA

INTRODUCTION

This chapter concisely examines the evolution of the subglacial landscape in south-central Alberta. It brings together the data presented in the previous five chapters. The approach used is to consider the contemporary landscape (Fig. 7.1) as a product of spatial and temporal events, based on sedimentary, stratigraphic, and landform relationships. Some events were depositional, resulting in thick sedimentary sequences. Some were erosional, thus cutting into the sedimentary sequences and into the underlying bedrock. Each event is illustrated in its regional context, and hence a map displays either the distribution of sediments associated with a depositional event, or the distribution, or orientation, of landforms associated with an erosional event. The emergent picture is astonishing and calls into question ice sheet reconstructions based on landforms and sediments.

EVENT 1 - INITIAL LAURENTIDE ICE INVASION

Event 1 is the first glacigenic event in the region. It is marked by the stratigraphically youngest unit in the region that contains clasts from the Canadian Shield: the "Labuma Till" (Chapters 3, 4 and 6). This till is distinctive because of its blue-grey colour and fine clayey matrix (Stalker, 1960). It is most prominent in preglacial valleys where it disconformably overlies preglacial gravels (no clasts from the Canadian Shield are present). This initial Laurentide ice invasion took place at some time after 22,000 BP, documented by multiple radiocarbon dates on Pleistocene fauna from preglacial sediments upglacier from the present site (Young et al., 1994). Therefore, all glacial events in the region occurred during the Late Wisconsinan.

In the study area, the Labuma till is commonly associated with glaciotectonically thrust bedrock (Fig. 7.2). Thrust ridges associated with the event are observed at the modern landscape surface. These are generally oriented NW-SE (Figs. 7.2 and 7.3), and fold noses in the ridges point southwestward (Fig. 7.2B). Thus, ice invaded the area from the northeast. Although the Labuma till is observed extensively in exposure, only a few ridges of thrust bedrock associated with the advancing ice are observed at the landscape surface.

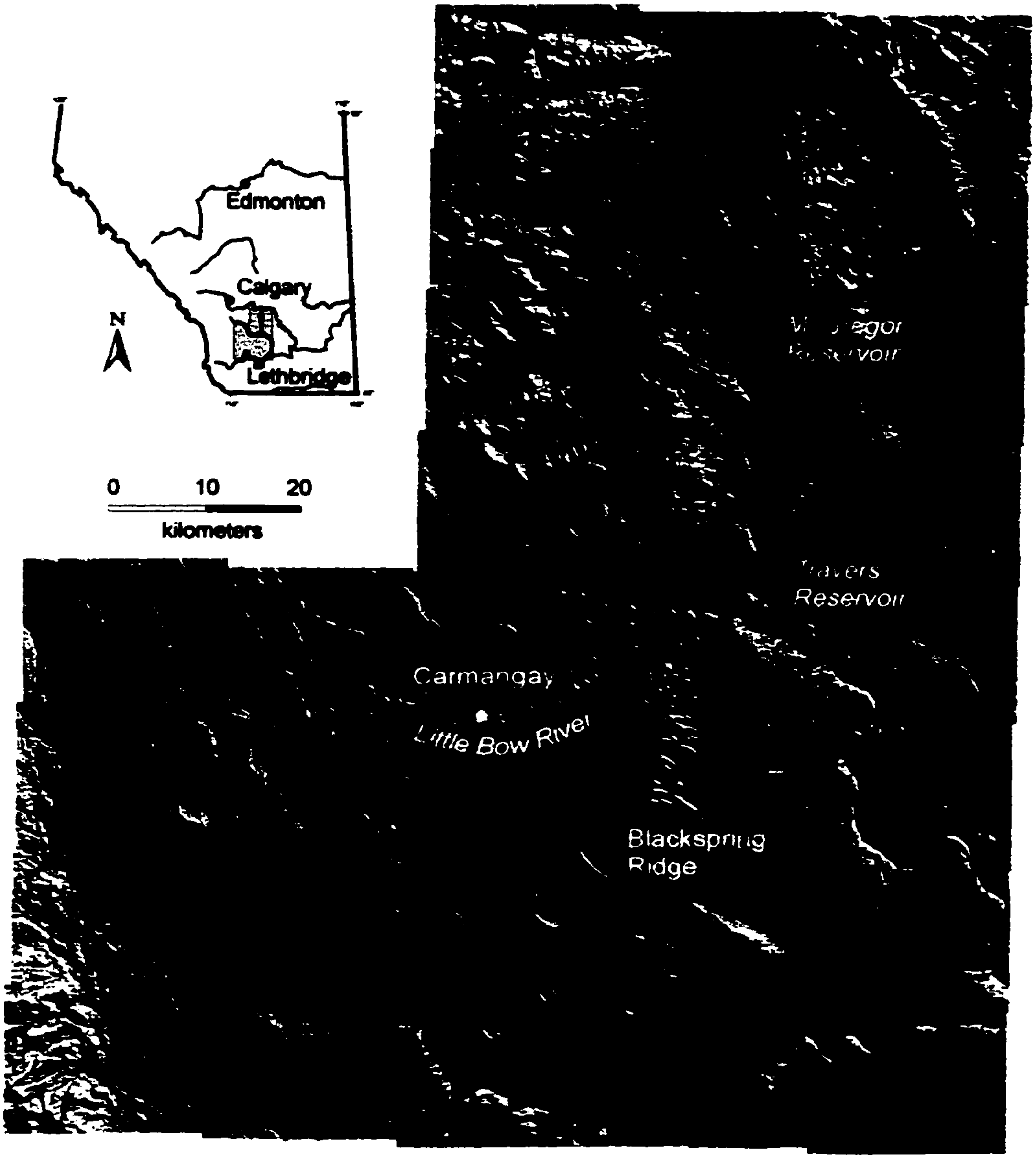

Figure 7.1: Hillshade digital elevation model (DEM) of the McGregor and Travers area in south-central Alberta. All mapping is based on the area shown on this figure.

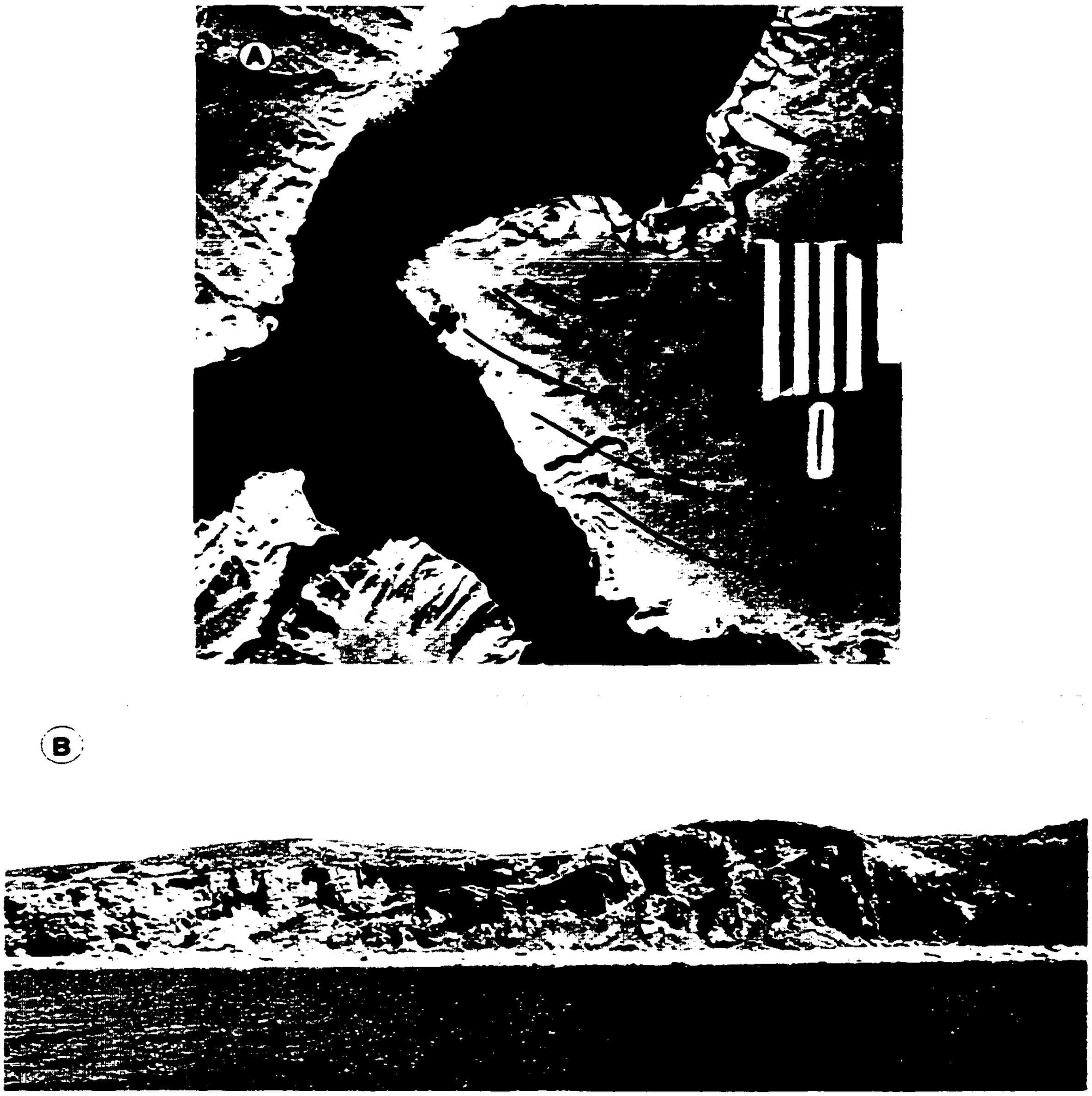

Figure 7.2: A. Aerial photograph showing thrust ridges associated with event 1. The asterix marks the location of 2B. B. Fold nose in bedrock (light coloured material) and till (dark coloured material).

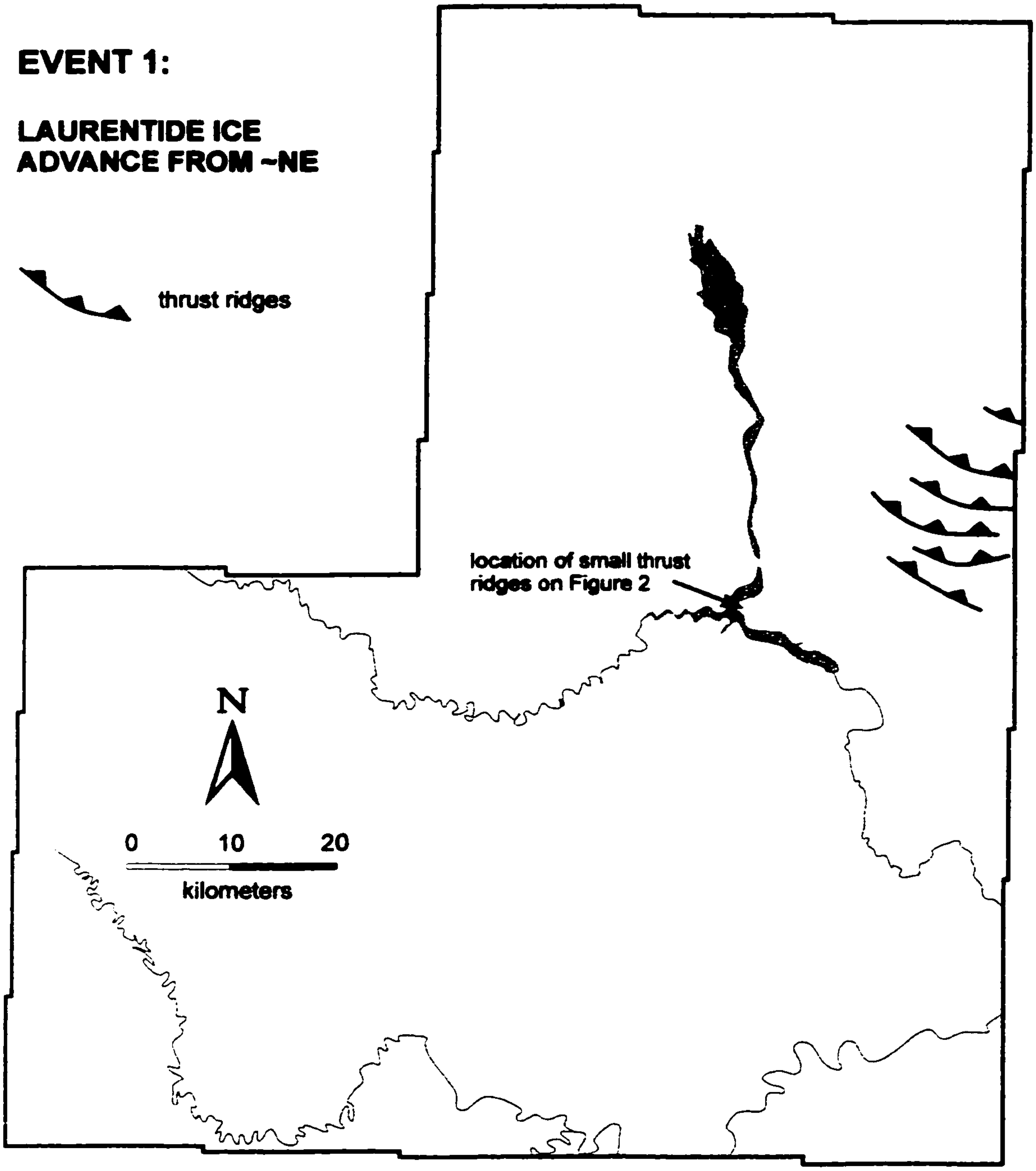

Figure 7.3: Distribution of thrust ridges documenting ice flow into the study area.

EVENT 2 - SUBGLACIAL LAKE DEVELOPMENT

After the Laurentide Ice Sheet advanced into the region, it became decoupled from its bed over topographically low areas (mainly preglacial valleys). Large volumes of meltwater were delivered to the bed at these locations. This is documented by the change from subglacial till sedimentation to glaciolacustrine sedimentation (Chapters 4 and 5; Munro-Stasiuk, in press a; in press b). Up to 60 m of glaciolacustrine beds associated with this event are observed at some locations (Fig. 7.4). The water could only have been stored subglacially because the elevation of the deposits relative to the topography would have resulted in southward and eastward drainage of the lakes (Chapter 5; Munro-Stasiuk, in press a). Also, conformable and interfingering relationships with the overlying subglacial till (see event 3) strongly support a subglacial origin for the lake sediments (Chapters 4 and 5; Munro-Stasiuk, in press a; in press b). This event was primarily depositional and was regionally extensive within the preglacial valley network (Fig. 7.5).

This subglacial lake event can be divided into two stages. The first stage is that of multiple lake-filling and drainage cycles. This is documented by extensive cross-cutting shear planes in the lowermost lake beds. Therefore, ice had to be in contact with the lake bed on several occasions to account for shearing. By inference, the lakes must have drained on several occasions (Chapter 5). Stage 2 is marked by the decreasing frequency of shearing and deformation upwards in the sequence. Similarly, the frequency of thick diamicton beds, turbidite beds, and sand and silt beds also decreases (Chapters 3 and 5). These thick beds grade into thin silt and rhythmically-bedded sand, silt, and clay. Thus, ice movement was beginning to cease, the lakes were beginning to drain less frequently, or there was a decrease in sediment supply. A combination of these factors may have led to the change in sedimentation (Chapter 5).

EVENT 3 - DRAINAGE OF THE McGREGOR SUBGLACIAL LAKE

Event 3 marks a change in sedimentation style at McGregor Reservoir and hence, also a change in subglacial conditions. Lake sediments grade into subglacial melt-out till (Fig. 7.6A). Sorted beds, scours below boulders and well-developed fabric patterns support a subglacial melt-out origin for the till (cf., Shaw, 1982; Chapter 4; Munro-Stasiuk, in press b). Thirty eight clast fabrics obtained from the melt-out till are well oriented, and have high principal eigenvalues and high K-values. Importantly when all preferred plunge orientations are plotted on a unidirectional rose diagram, a well-defined pattern emerges, documenting ice flow from ENE. This is the direction in which ice was moving prior to stagnation and deposition of the melt-out till.

Figure 7.4: sixty metres of subglacial lake sediments at Carmangay, south-central Alberta. Only the lightest coloured material at the top represents proglacial lakes. The contact between the two is an unconformity which is overlain by a boulder lag.

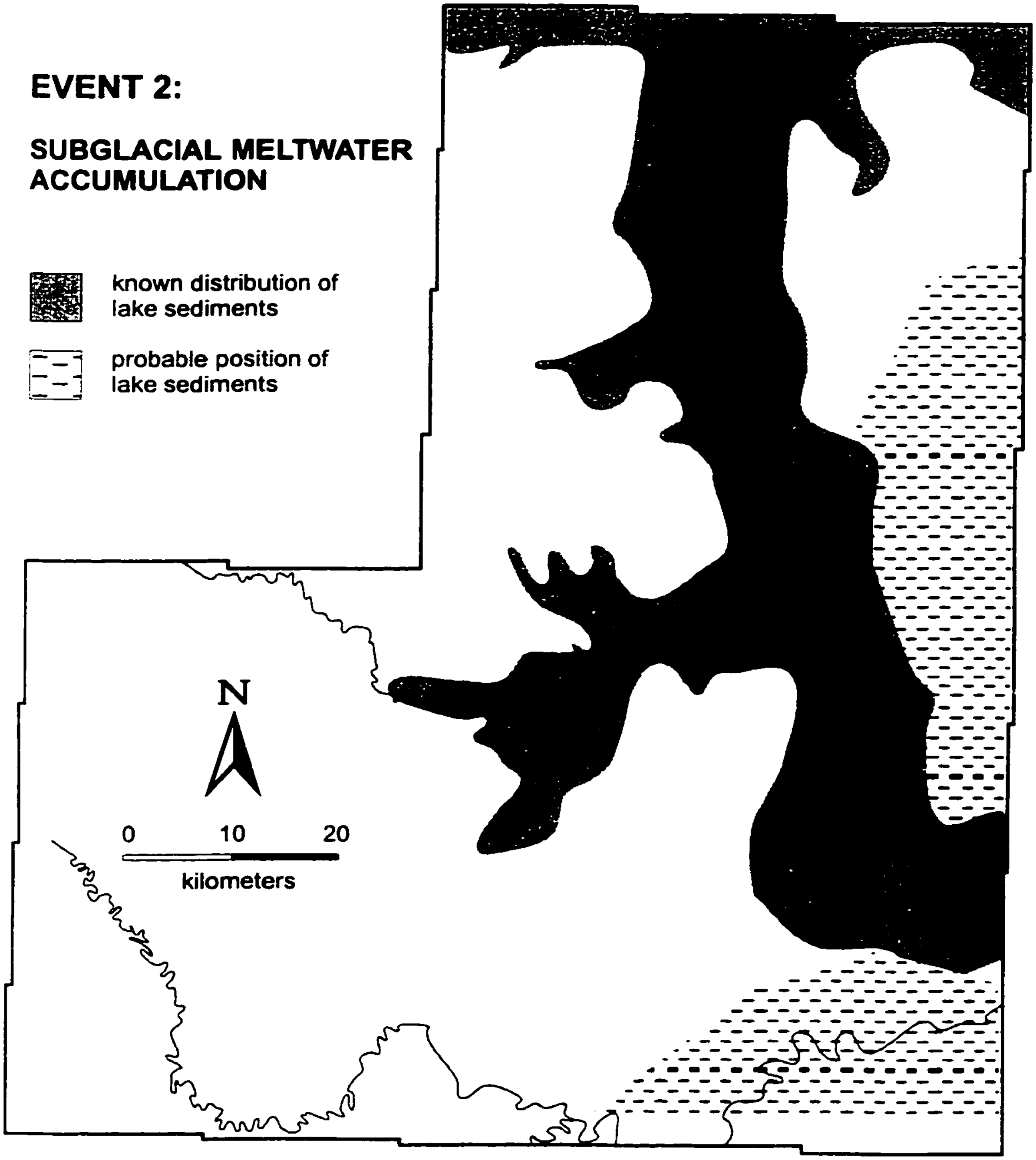

Figure 7.5. Distribution of lake sediments mapped as subglacial. The dashed areas likely contain lake sediments because of their topographically low settings, but this has not been confirmed by fieldwork.

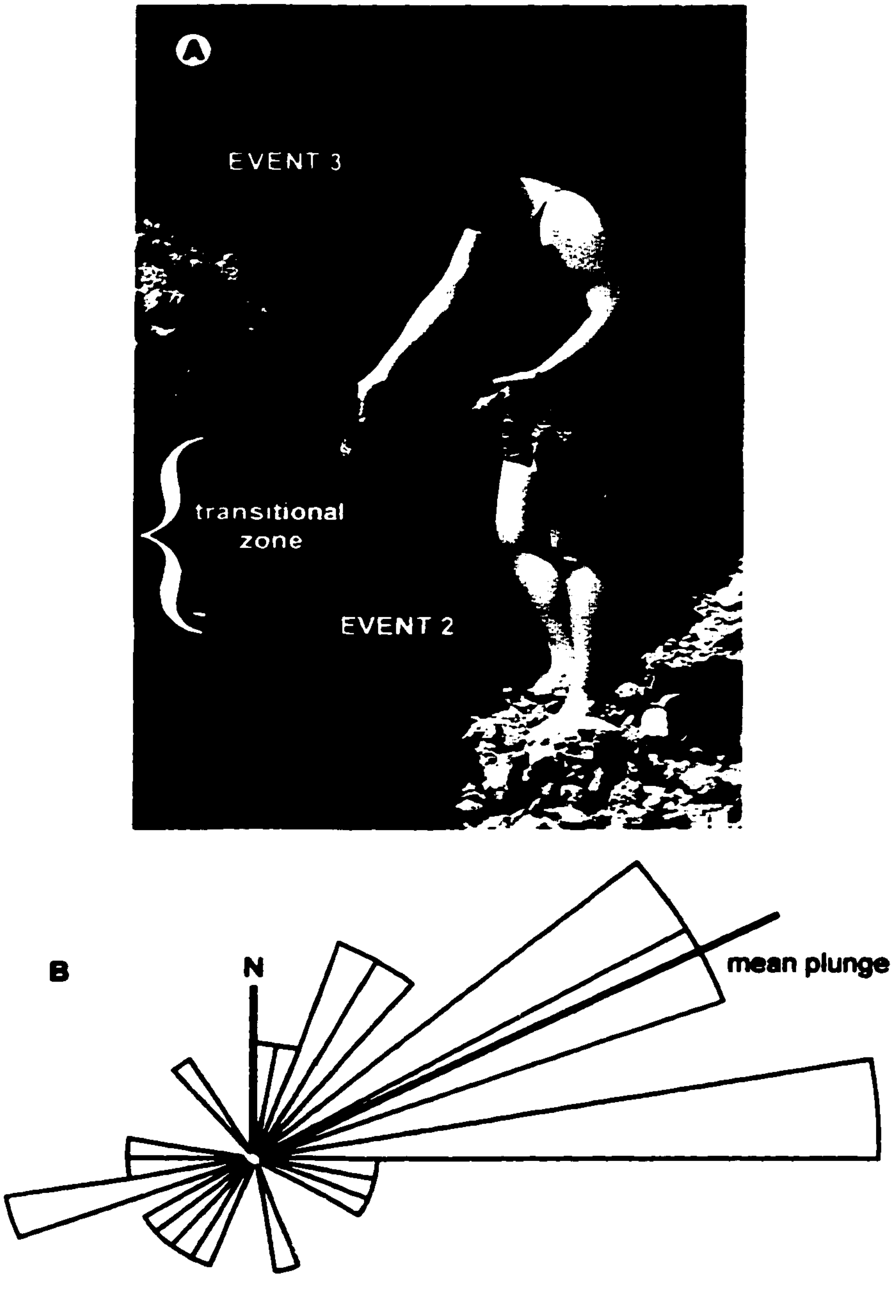

Figure 7.6: Event 3 is marked by melt-out till deposition at McGregor Lake. A. Subglacial lake sediments (event 2) give way gradually to the melt-out till (event 3). B. Synthesis of all fabric data from the melt-out till plotted on a Rose diagram. The principle direction of ice movement prior to depositing the till was from ENE documented by an average clast plunge in that direction.

The change in sedimentation from glaciolacustrine beds to melt-out till at McGregor Lake indicates that ice came back down onto its bed and, hence, the subglacial lake had drained. Interfingering of glaciolacustrine sediments with the till indicates that the draining was gradual and comprised several fill and drain cycles, each decreasing in volume over time. Eventually, till sedimentation dominated and the lake completely disappeared. Water, however, continued to be delivered to the bed on a much smaller scale: sedimentary structures suggest that a thin layer of water (~20 cm) was stored beneath the ice and then released. This storage/release cycle occurred repeatedly, resulting in a remarkable rhythmically-bedded till sequence (Fig. 7.6A). Rhythmites may be annual layers (Chapter 4; Munro-Stasiuk, in press b). The deposition of this melt-out till indicates that the ice was beginning to stagnate. In the Travers preglacial system a large subglacial lake was maintained shown by the fact that no till overlies the glaciolacustrine sediments there (Fig. 7.7).

EVENT 4 - WIDESPREAD EROSION BY A MELTWATER SHEET

Event 4 was erosional and is marked by a regional unconformity observed across the entire study area. This event was the most dramatic of all landforming events and was responsible for both flute and hummock formation. Flutes/remnant ridges (Fig. 7.8), most notable on the Blackspring Ridge, are eroded into local bedrock or undisturbed preglacial Tertiary gravel (Chapter 3). All flutes/remnant ridges are oriented WNW to ESE. Hummocks are eroded into many different sediment types and bedrock. Two types of hummocks, transverse (Fig. 7.9A) and longitudinal (Fig. 7.9B), also document flows that moved from WNW to ESE. Erosional landforms are obvious in exposure where ***all*** materials are truncated by the surface that represents the regional erosion, regardless of the genesis of those materials (Fig. 7.10).

Direct erosion, or deformation, by ice are discounted as:

1. Most of the sediment below the erosion surface is undeformed, and there is no "deformation till" in the hummocks or remnant ridges.
2. The erosion surface is abrupt.
3. The only extensive sediments directly overlying the erosion surface are boulder lags which cannot be accounted for by direct ice erosion or deformation.
4. There are no end moraines, or sediment blankets that can account for the volume of sediment removed.

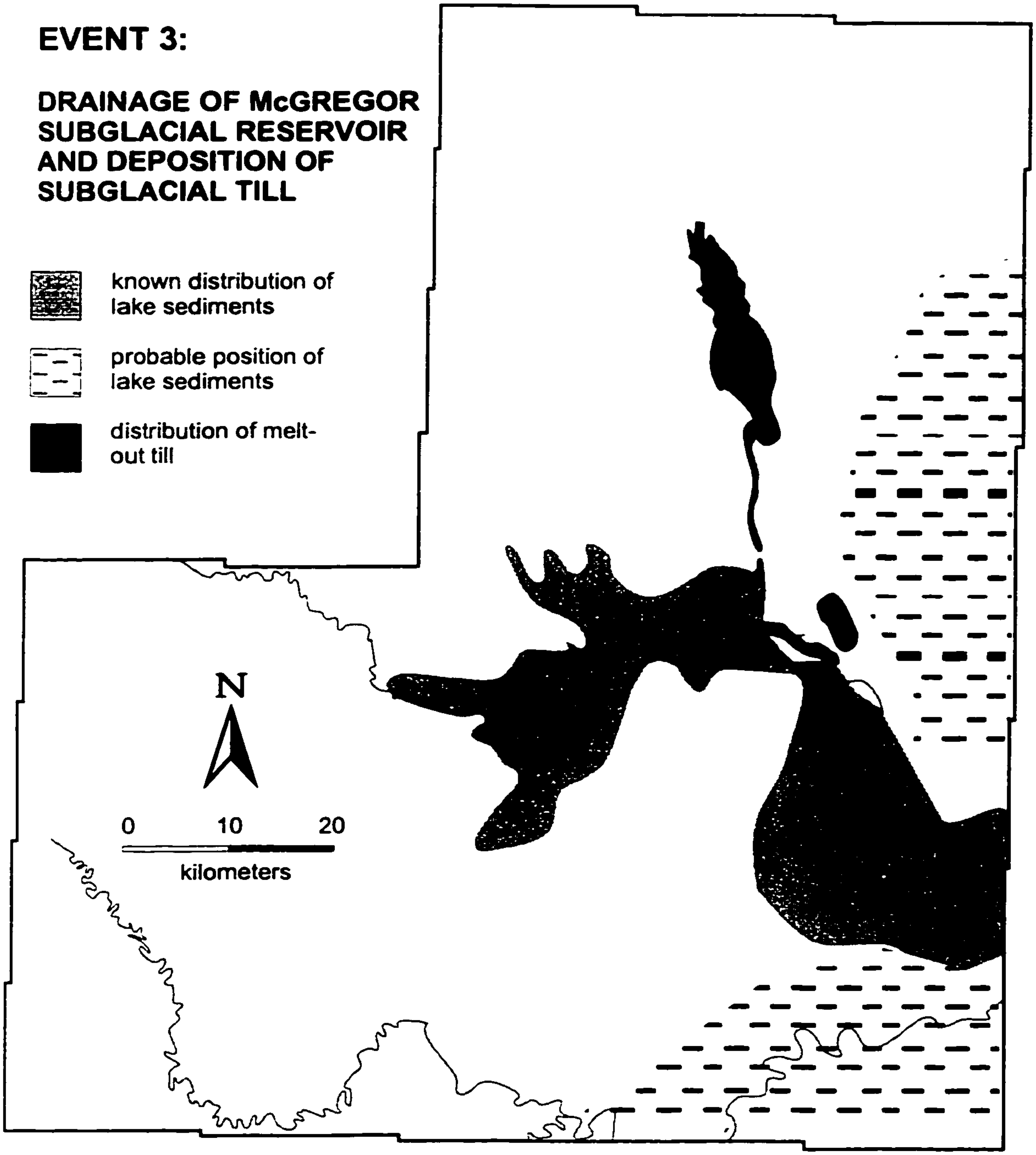

Figure 7.7: Distribution of melt-out till deposited during event 3. While till was being deposited at McGregor Lake, a subglacial lake was maintained at Travers Reservoir.

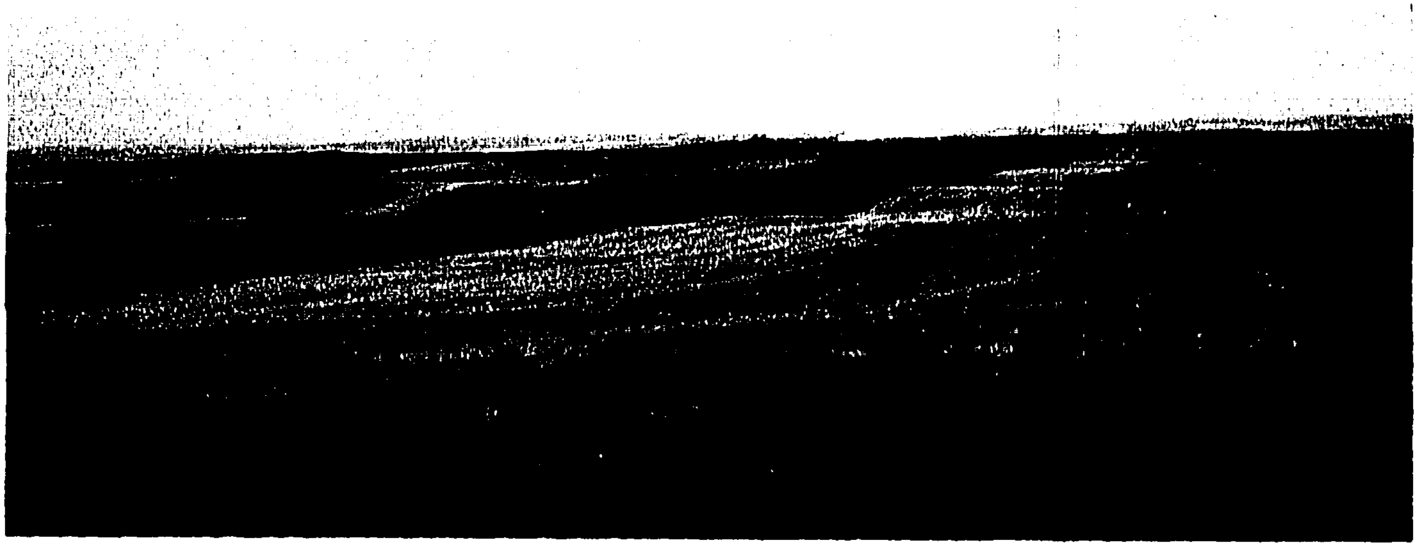

Figure 7.8: The fluted surface on Blackspring Ridge is easily observed through the undulating crop marks.

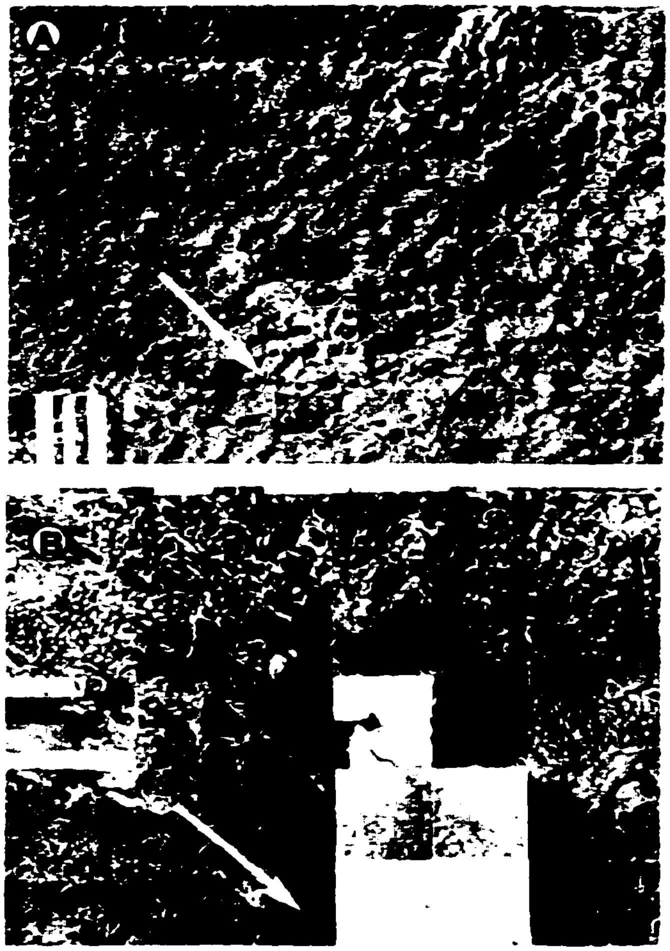

Figure 7.9: Aerial photographs illustrating erosional hummocky terrain (A and B). A illustrates transverse hummocky terrain, while B illustrates longitudinal hummocks. Trends from the hummock types are plotted on Figure 7.12.

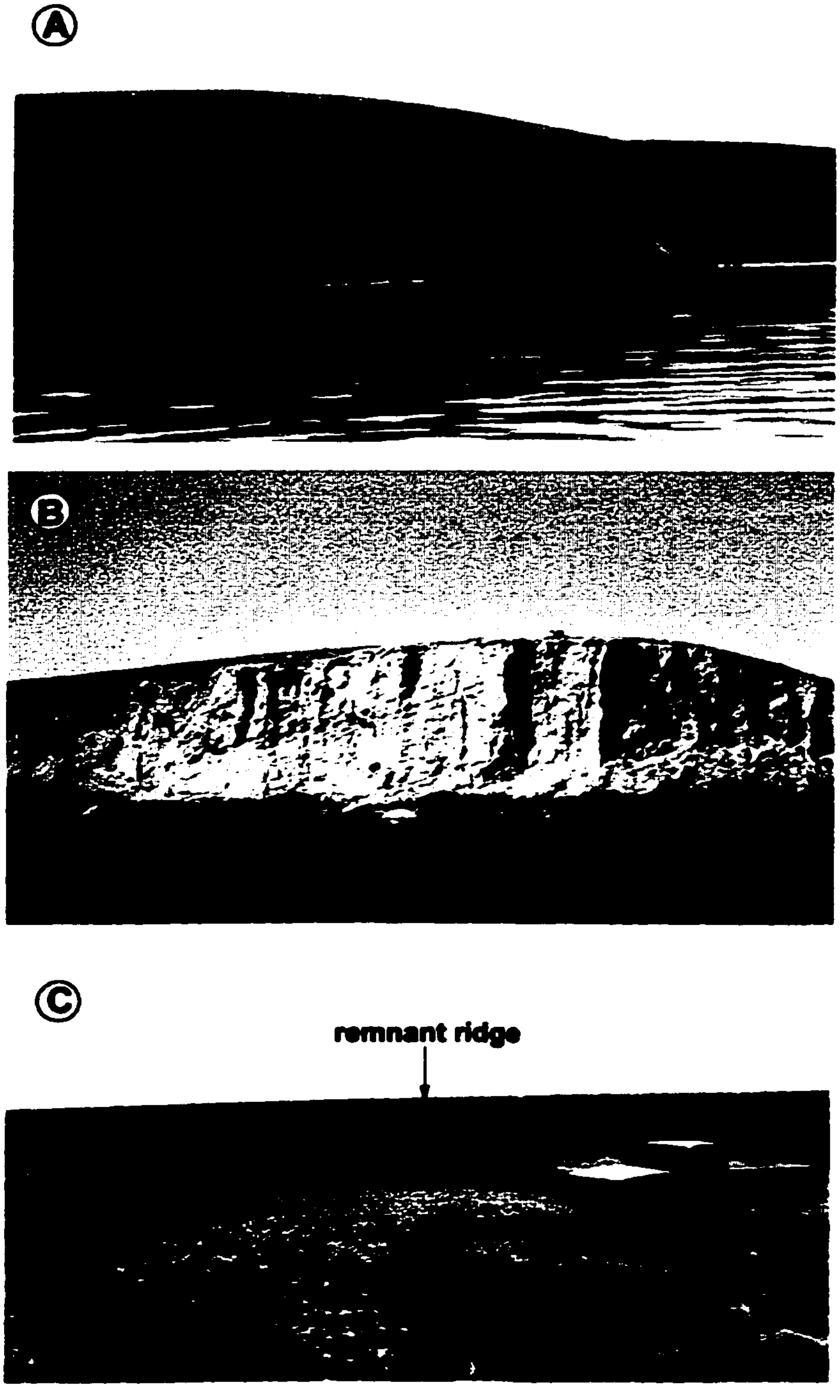

Figure 7.10: Photographs illustrating that hummocks (A and B) and flutes/remnant ridges (C) are erosional features. The hummocks are eroded into (A) glaciolacustrine sediments with diapiric intrusions, and (B) dune foreset beds. Flutes/remnant ridges (C) are eroded into undisturbed gravel that predates Laurentide glaciation in the region.

The only widespread sediments overlying the erosion surface are boulders. These lie on top of many, but not all, hummocks (Fig. 7.11). This is a function of underlying sediment type: where there are boulders below the surface, boulders also lie on the surface. This indicates that the boulders are lags and were not simply deposited on the surface of the hummocks after the hummocks were eroded. The boulder lags are crucial in determining the nature of the erosion responsible for hummock and flute/remnant ridge formation. The lags are best explained as the product of fluvial transport, where flowing water was able to remove all but the largest boulders. Ice is incapable of removing sediment sizes preferentially. Water erosion and sediment transport also explain percussion marks on the boulders, attesting to clast-to-clast collisions during transport, the abrupt erosion surface (erosion involved removal of sediment grain by grain, and clast by clast), and the lack of depositional products of the erosion. Unlike ice, water can remove the eroded sediment and transport it far beyond the ice margins and hence, it may never be deposited as moraines. The distribution of landforms (WNW - ESE) over a 120 km wide swath, suggests that water moved across the entire area as a sheet, also 120 km wide. Erosion was subglacial, with upslope water flow, requiring the water to be pressurized. Also, the youngest sediments in the hummocks are subglacial (Chapters 4 and 6) and subglacial eskers overlie the hummocks. Therefore, hummock erosion was probably also subglacial (Chapter 6).

Sediments in erosional landforms either predate local Laurentide glaciation (i.e., they are older than 22,000 BP), or they represent events 1, 2, or 3. Strikingly, the youngest sediment in the hummocks, the melt-out till (event 3), documents ice flow from the ENE. All landforms mapped for event 4 trend transverse to that ice flow direction. This demonstrates conclusively that the event responsible for eroding these features was unrelated to, and independent of the earlier depositional events.

EVENT 5 - CHANNELIZATION OF THE SHEET FLOW

Event 5 marks the collapse of the sheetflow in the region. As water sheets are unstable they must eventually collapse and break down into channels (Walder, 1982). Channels are observed extensively in the study area cross-cutting hummocky and fluted terrain. They are often lined with imbricate boulder gravels (Fig. 7.13). Although it cannot be demonstrated for all channels, many do cross-cut topographic highs such as at the south end of McGregor Reservoir and in the central area of the Blackspring Ridge (Figs. 7.1 and 7.14), hence, they are of subglacial origin. Channels are generally wide, but shallow, and range from complex anabranching networks to individual

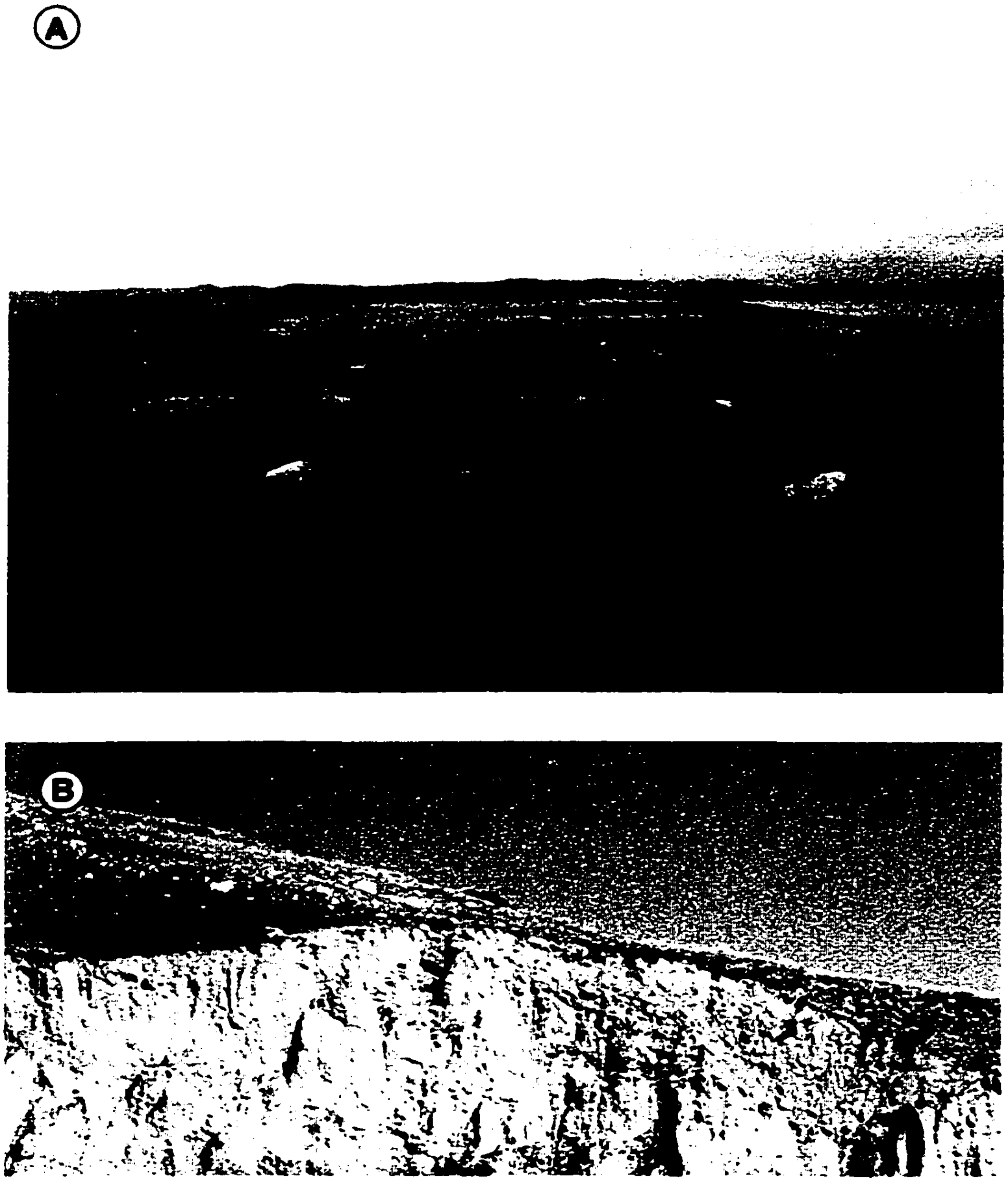

Figure 7.11: Boulder lags at McGregor Reservoir (A) and Travers Reservoir (B). B illustrates that where gravel is extensive below the hummock surfaces, lags lie on the surface. The lags are best explained as the result of fluvial transport where water had the competence to remove all but the largest boulders.

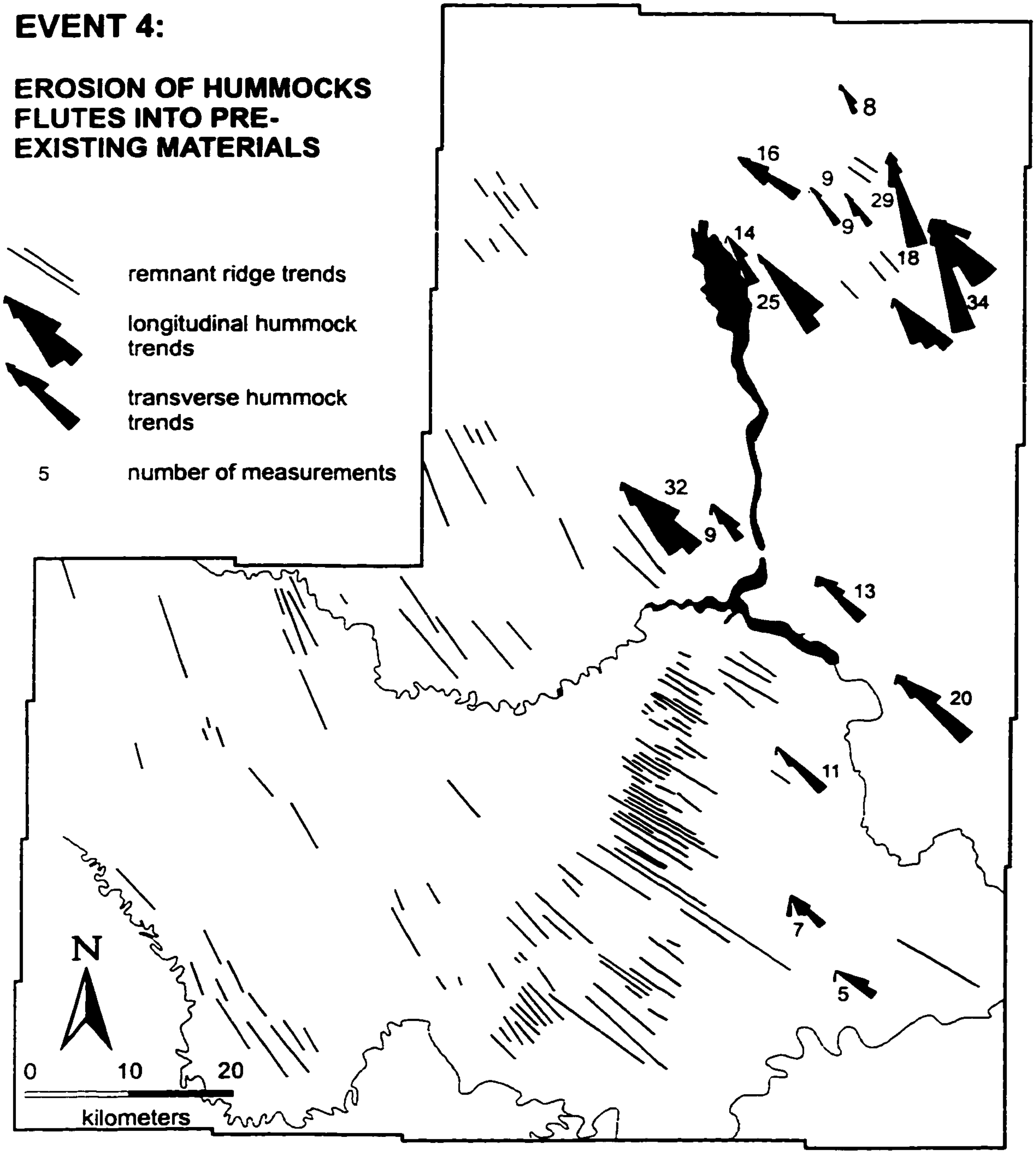

Figure 7.12: Patterned hummocky terrain and fluted terrain display northwest to southeast trends. These features dominate the contemporary landscape and document a single meltwater sheet flow that crossed the entire region and cut bedforms into pre-deposited sediments and bedrock.

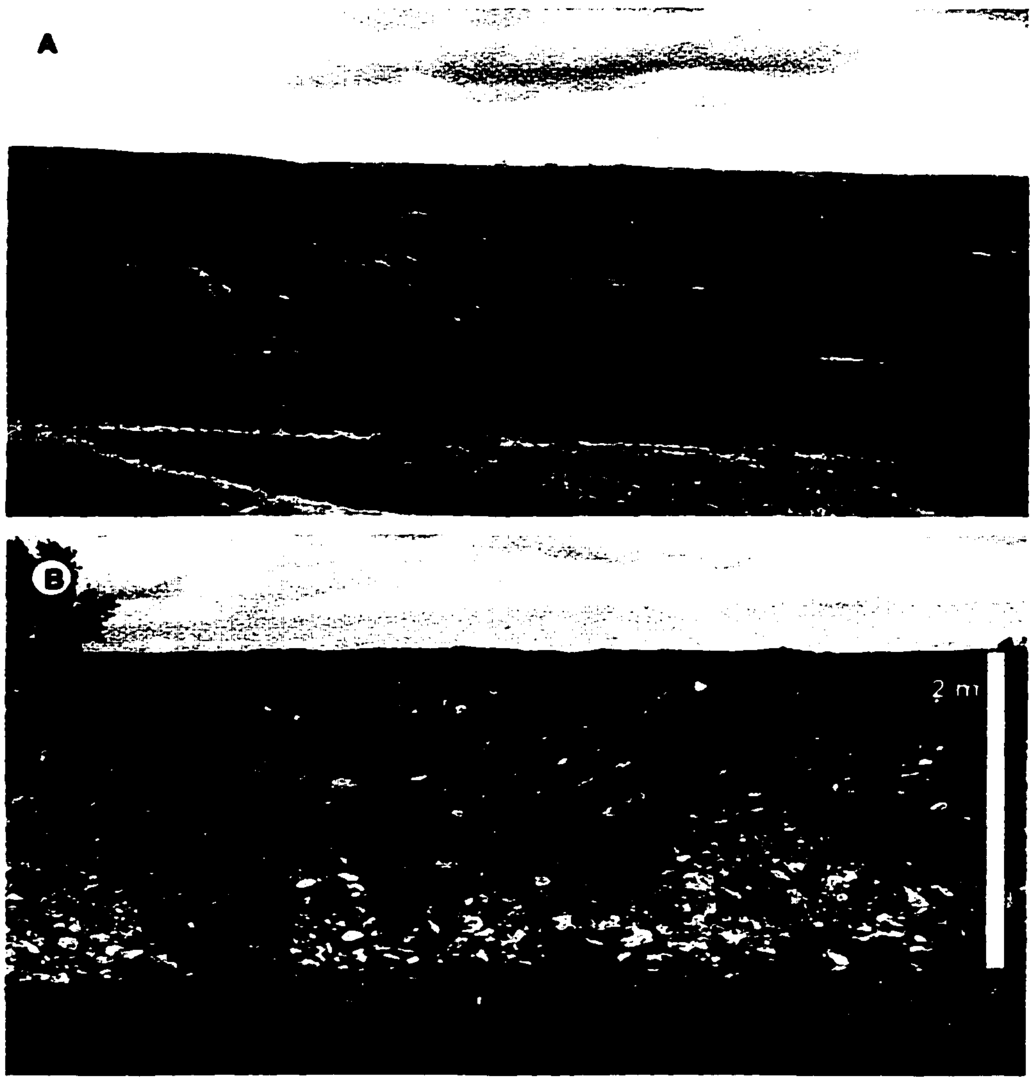

Figure 7.13: A. Photograph looking westward along a channel south of Blackspring Ridge. B. Imbricate boulders on terrace above channel east of Travers Reservoir.

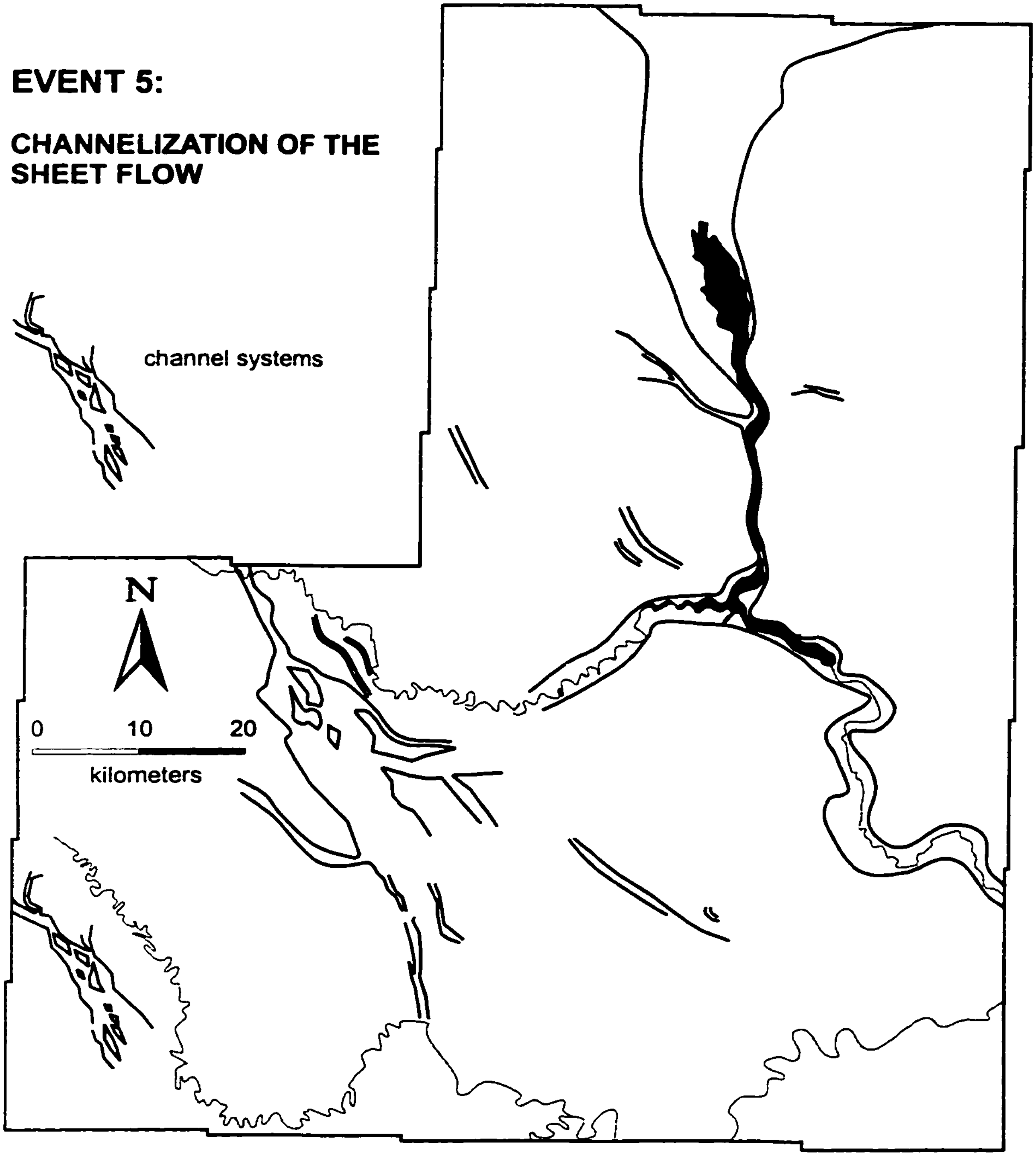

Figure 7.14: Distribution of meltwater channels that cut through the fluted and hummocky terrain.

channels. The anomalously deep, yet narrow channel that joins McGregor Lake to Travers Lake may have been partly formed during the subglacial lake phases when the McGregor subglacial lake drained southward on several occasions (Chapter 5).

EVENT 6 - REORGANIZATION OF THE SUBGLACIAL HYDROLOGY

Apart from boulder lags, many eskers and two large fans are the only sediments (and landforms) that overlie a landscape almost entirely dominated by erosion. Eskers lie in the bottom of many of large channels cut during event 5 (Figs. 7.1, 7.15 and 7.16), and hence they post-date the channels. Intact beds that arch upwards within the eskers demonstrate that they are subglacial. The fans are intimately associated with the eskers, but it cannot be conclusively demonstrated that the fans were deposited subglacially or whether they were deposited at the ice margins.

Unlike the landforms of events 4 and 5, eskers are not all oriented WNW to ESE. The large eskers to the west of the study area maintain this orientation but the topography is relatively flat there. Where there is more relief many of the eskers have orientated themselves towards the larger channels (e.g., at McGregor Reservoir). This demonstrates two points. First the hydrostatic head was no longer high enough to drive meltwater up and over topography of varying relief. This is probably due to a flatter ice surface profile, which would have resulted from the zero basal shear stress associated with the sheetflow of event 4 (Chapter 5). Second, some of the larger channels still maintained water flow as eskers were diverted towards them (cf., Röthlisberger, 1972).

EVENT 7 - STAGNATION OF THE LAURENTIDE ICE SHEET

Almost the entire modern landscape in south-central Alberta was eroded during event 4 outlined above. The relatively minor events, 5 and 6, resulted in some modification in terms of channels cut into the erosional surface of event 4, and eskers overlying the erosional surface of event 4. Apart from these, there was little later modification of the erosional landscape. Thus, there was no further movement of ice, only stagnation. Some lake beds associated with proglacial lakes during ice stagnation are observed at Carmangay (Fig. 7.17). No further glacigenic sediments are present.

SUMMARY AND CONCLUSIONS

The events that occurred in the study region can be summarized in the following order:

Event 1 - Laurentide ice first invaded the region from the northeast sometime after

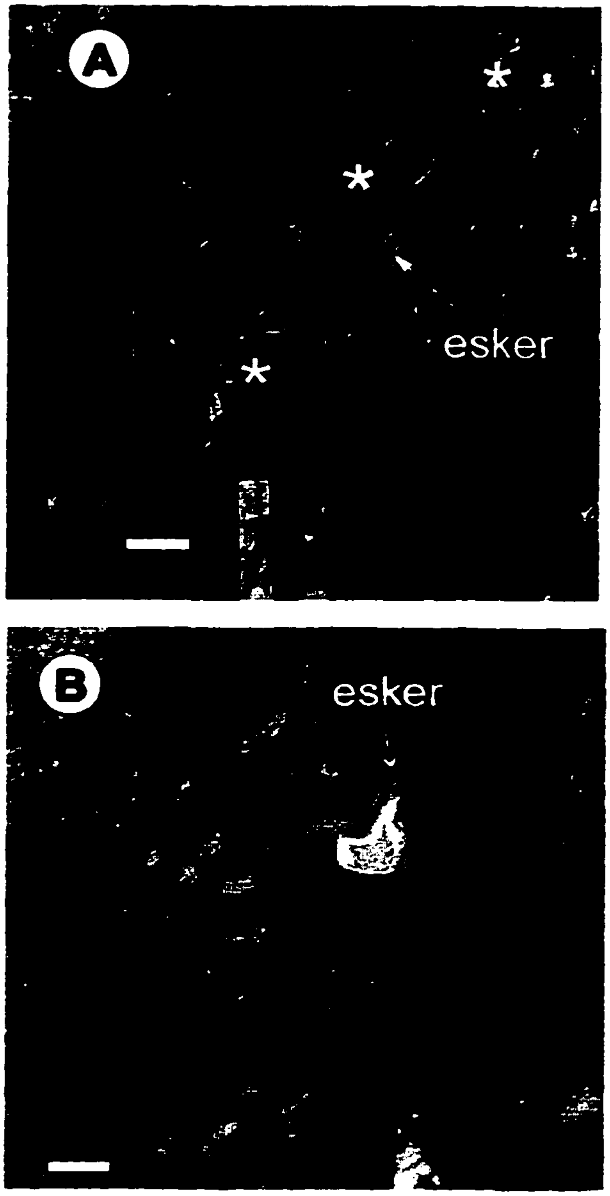

Figure 7.15: Aerial photographs showing eskers overlying hummocks.

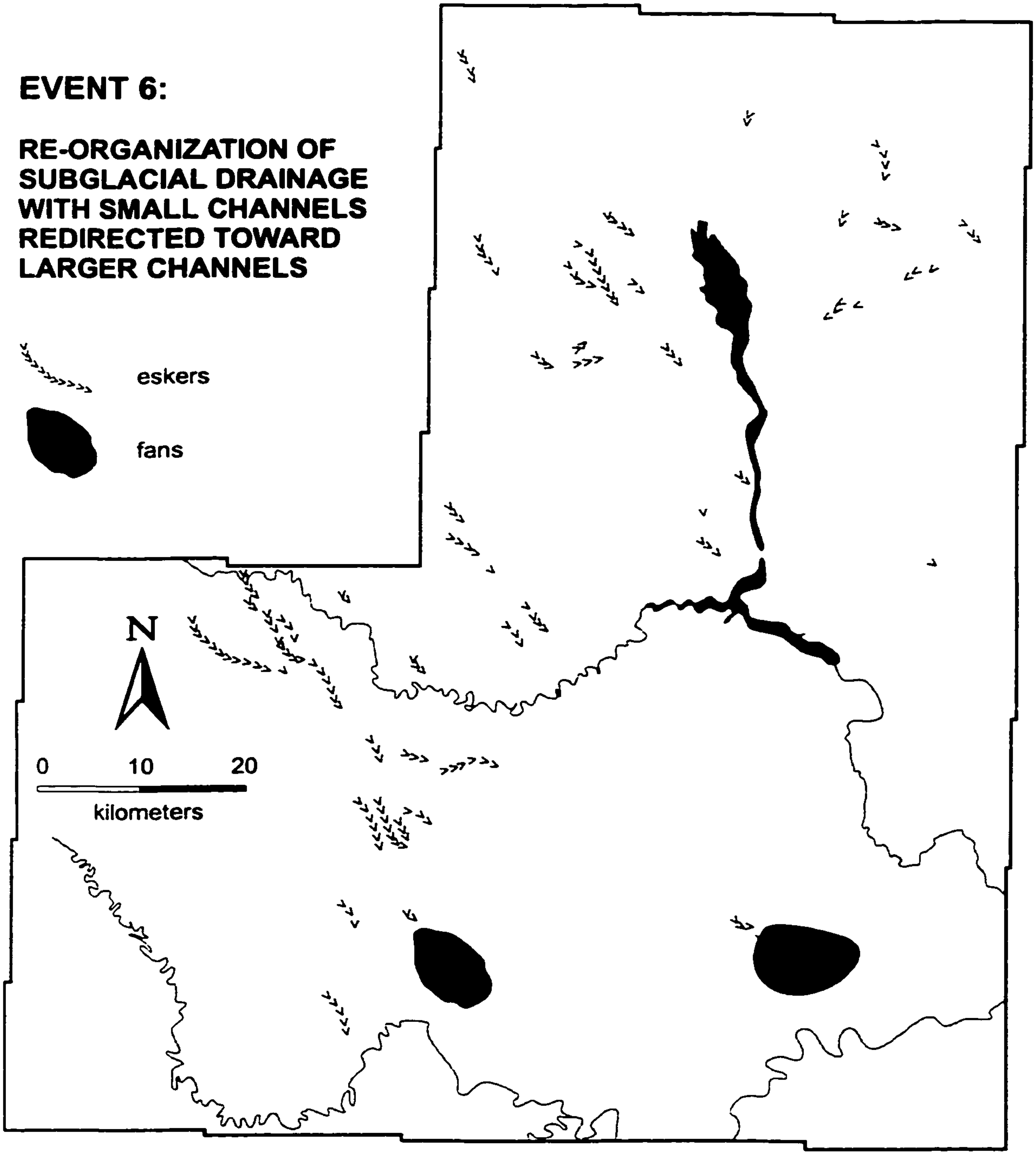

Figure 7.16: The last documented subglacial event was the deposition of eskers. As fans are depositional they are likely related to this event, but may predate or postdate esker formation.

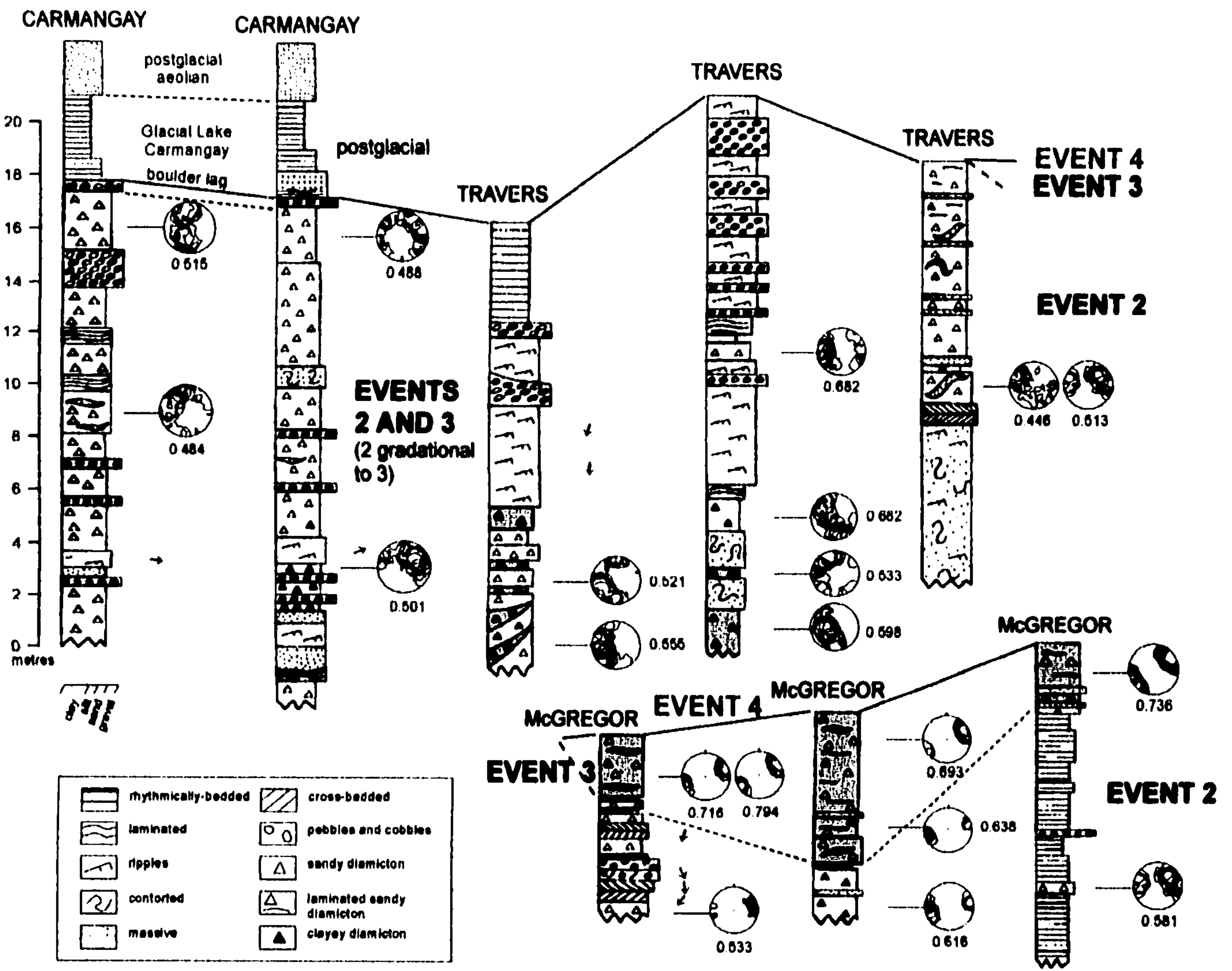

Figure 7.17: Not all events can be observed at all locations. However, sedimentary transects from Carmangay, Travers Reservoir, and McGregor Reservoir document at least 3 events (and the two stages of event 2).

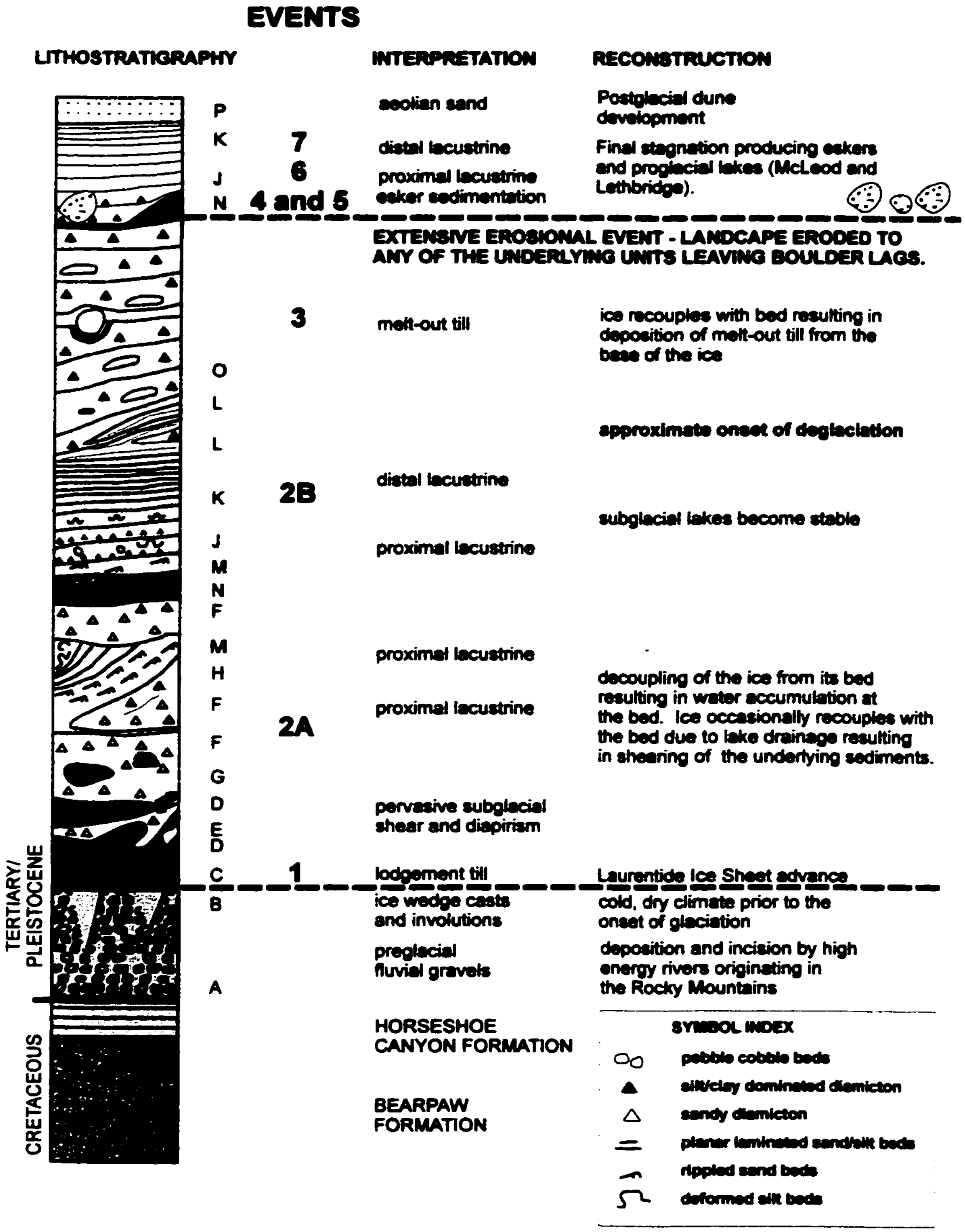

Figure 7.18: Simplified composite diagram of the stratigraphy of the preglacial valley fills of south-central Alberta (from Chapter 3). Glacigenic events are shown in thick black letters.

22,000 BP.

Event 2 - Subglacial water began to accumulate at the bed, creating two subglacial lakes, one in McGregor preglacial valley, and one in the Tee Pee preglacial valley. Sedimentation was initially chaotic but gave way to more passive sedimentation towards the end of the lake phases.

Event 3 - The McGregor subglacial lake drained and ice came to rest on the bed, resulting in the deposition of melt-out till.

Event 4 - A large meltwater sheetflow crossed the entire study area from WNW to ESE, documented by oriented flutes, remnant ridges, and hummocks.

Event 5 - Sheetflow collapsed to channels.

Event 6 - Channels gave way to minor tunnels which reoriented themselves relative to the local topography.

Event 7 - Ice stagnated and no further glacigenic landscape modification of consequence occurred.

Although it has been demonstrated that the landscape in southern Alberta is dominated by a wide array of landforms and sediments, the processes of sediment deposition and landform formation were quite independent of each other. Sediment deposition occurred over a relatively long period of time, resulting in thick sedimentary sequences (events 1 - 3) (Fig. 7.17, 7.18). The expression of this deposition on the landscape is barely visible. Instead, that landscape is dominated by flutes/remnant ridges and hummocks (event 4) which are cut into the sediments of events 1 to 3, or are cut into the local bedrock or preglacial gravels. This event, however, was short-lived, up to 20 days (based on modern jökulhlaup duration). Two further events, channel cutting (event 5), and esker deposition (event 6), had little impact on the landscape although these landforms are locally important relative to the regional erosional unconformity.

In general, hummocks in south-central Alberta contain sediments that are genetically unrelated to the landforms that contain those sediment. Landform creation was, therefore, independent of sediment deposition . This calls into question models that seek to explain the genesis of subglacial landforms based on processes inferred from the sediments contained within those landforms.

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CHAPTER 8: CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

CONCLUSIONS

This thesis has focussed on hummocky terrain in south-central Alberta. This analysis is significant as the exposures examined are, to the best of my knowledge, the most extensive within hummocky terrain in the world. Therefore, they should be instructive on the genesis of hummocky terrain. Surprisingly, those exposures revealed that hummock morphology is largely unrelated to the sediments in the hummocks: units, structures, and architecture are all truncated by the surface that represents hummock and trough forms. This conclusion is in direct contrast to all existing hypotheses of hummocky terrain formation, including the accepted supraglacial letdown hypothesis. The results presented in this thesis unequivocally support an erosional hypothesis for much hummocky terrain formation. Specifically, this erosion was by subglacial meltwater. This requires the storage of enormous volumes of water on and/or below the Laurentide Ice Sheet, and catastrophic release(s) of that water.

Importantly, if hummocks in the “Buffalo Lake moraine” are erosional then it cannot be a moraine, and it cannot be used to delineate a significant stillstand of the disintegrating Laurentide Ice Sheet. This also appears to hold true for the “Viking moraine”, the “Duffield moraine”, and the “Eastend Moraine”. Thus, the large hummocky terrain belts observed in the prairie regions are unlikely to be true moraines. Consequently, accepted reconstructions of Laurentide ice sheet deglaciations are questionable. In general, authors of maps, reports, and papers refer to "hummocky moraine," "stagnation moraine," and "ice-stagnation topography." This terminology mistakenly assigns hummocky terrain to stagnant ice in marginal or near-marginal positions. According to the interpretations presented here, such terminology does not apply when hummocky terrain of the Great Plains and Prairies is examined in detail. Such genetic terminology should be abandoned and hummocky terrain should be classified in descriptive terms only.

SUGGESTIONS FOR FUTURE WORK

Results presented in this thesis strongly advocate subglacial meltwater erosion as the process responsible for creating hummocky terrain. This controversial idea is supported by sedimentary and geomorphological studies. However, it also raises as many questions about hummocky terrain genesis, as it answers. These questions must be addressed by future research, if we are to gain a better understanding of ice sheet dynamics. Four major aspects of this research should be extended:

detailed mechanics of meltwater erosion must be better understood; the origin of certain hummock types must be determined; the extent of subglacial meltwater storage must be determined; and all these result must be taken into consideration in ice-sheet modelling.

First, and foremost, the exact scale and dimensions of the proposed meltwater flow are unknown. Criteria provided in this thesis should aid in the identification of regional unconformities. From that, it should be possible to map the areal extent of landscape unconformities, and hence it would be possible to calculate the width of the proposed flow. The exact mechanics of subglacial meltwater sheetflow erosion, regardless of flow dimensions, are also not well understood at the present time and may never be. How meltwater interacted with different substrates is unknown. Varied substrates must exerted some control on the types and degrees of erosion. For example, bedrock must be more resistant to erosion than laminated clays. Systematic mapping of hummock types and internal sediments may help to identify relationships between forms and substrates.

No exposures were observed in moraine plateaux. Hence it is undetermined whether these landforms are the product of erosion or not. The plateaux stand higher than surrounding hummocks, and hence some researchers may argue that they were deposited over the hummocks. As moraine plateaux are found only within hummocky zones, then their genesis is ***probably*** linked to hummock formation. Detailed sedimentary analysis should aid in solving this problem.

Much of the sediment discussed in this thesis was deposited in subglacial reservoirs that occupied preglacial valleys. Although only two preglacial valleys were studied, the preglacial drainage network in central and southern Alberta was extensive. If many valleys stored water below the Laurentide Ice Sheet, then these would have had significant influence on the dynamics of the Laurentide Ice Sheet. Therefore, sedimentary studies are recommended to estimate the regional significance of subglacial reservoirs.

Finally, the inferred enormous volumes of meltwater episodically present beneath the Laurentide Ice Sheet had direct bearings on ice-flow regimes, ice thicknesses, and ice extents. These conclusions carry major implications for ice-sheet modeling and reconstruction, and must be implemented in models if we are to move towards a more realistic understanding of Laurentide Iie sheet dynamics during the Late Wisconsinan glaciation.

APPENDIX A

Erosional origin of hummocky terrain in south-central Alberta, Canada

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ABSTRACT

We propose that hummocky terrain in south-central Alberta is the product of subglacial erosion rather than supraglacial letdown during ice disintegration (a common view of hummock formation). Extensive exposures in hummocks contain sediments marking the history of Laurentide ice advance and deglaciation in the region. Regardless of the genesis of those sediments, units are abruptly truncated at the surface that represents the hummock and trough morphology, indicating that the hummocks are the product of differential erosion. Subglacial sediments predating the erosion and subglacial eskers overlying the erosion surface suggest that the erosion was also subglacial. Hummock morphology, lithostratigraphy correlated from hummock to hummock, truncation at the land surface, and widespread coarse boulder lags support a glaciofluvial origin for hummocky terrain in this region.

INTRODUCTION

Hummocky terrain is composed of tracts of hillocks and depressions of variable size and shape, and occurs in areas that have been glaciated. It is especially extensive in the northern Great Plains and occurs in large belts in the Canadian Prairies (e.g., Shetsen, 1987, 1990; Klassen, 1989), and the northwest United States (e.g., Clayton and Moran, 1974; Johnson et al., 1995). The terrain is commonly believed to represent the final stages of ice stagnation, when debris on the surface of the ice was slowly lowered as the ice ablated in marginal parts of the ice sheet (e.g., Gravenor, 1955), and hence is often used to reconstruct recessional patterns of the Laurentide ice sheet in North America (e.g., Dyke and Prest, 1987; Klassen, 1989). Some geomorphologists have noted, however, that not all hummocks are composed of sediments released at the ice surface (e.g., Hoppe, 1952; Menzies, 1982). On the basis of results presented here, we propose that many areas of hummocky terrain are the product of subglacial erosion, and not supraglacial letdown during ice stagnation. Consequently, we prefer to use the nongenetic term "hummocky terrain" throughout this paper, because it simply describes landscape topography and does not imply genesis.

The study area is in south-central Alberta, Canada (Fig. 1). The damming of McGregor Lake and the Little Bow River (now Travers Reservoir) in the 1960s resulted in extensive shoreline erosion, creating more than 100 hummock exposures in a major north-south–trending hummocky zone, the Buffalo Lake moraine. Stalker (1977) thought that this "moraine" marked the western extent of the late Wisconsinan Laurentide ice, but it was later reinterpreted as an interlobate stagnation feature and renamed the McGregor moraine (Shetsen, 1984). Exposures range from 2 to 25 m high; to the best of our knowledge, no glaciogenic hummock exposures of comparable quality or quantity exist worldwide. The main aim of this paper is to demon-

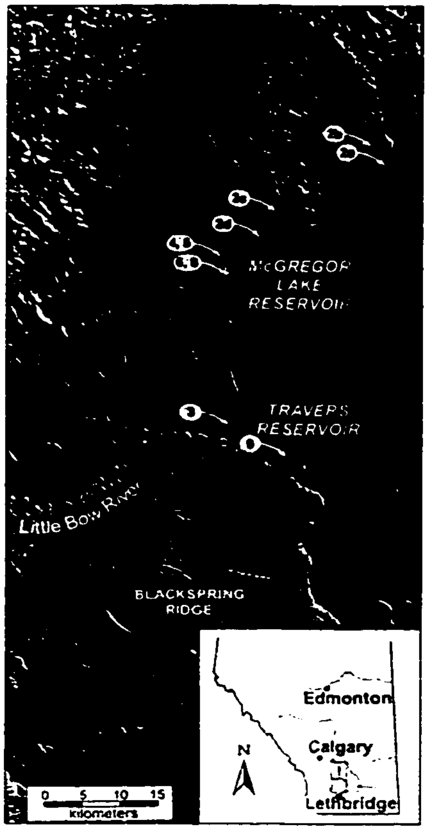

Figure 1. Digital elevation model of study area. Majority of hummock terrain occurs north of Little Bow River and Travers Reservoir. Fluted terrain on Blackspring Ridge grades southeastward into hummocky terrain. Circled numbers represent locations of other figures.

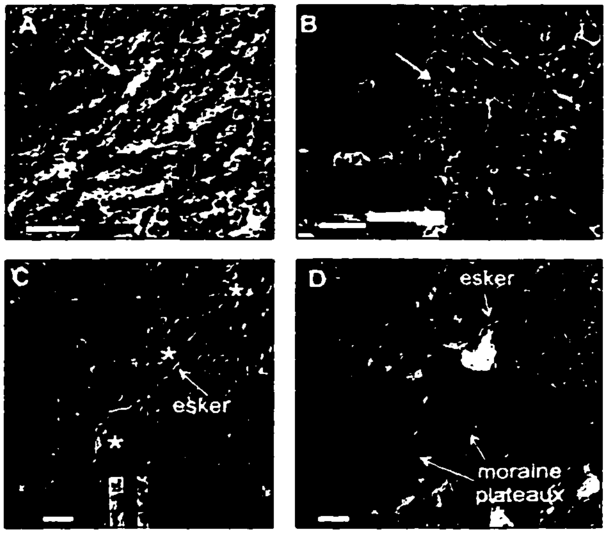

Figure 2. Types of hummocky terrain observed in study area. A—transverse ridges and depressions; B—longitudinal ridges and depressions; C—symmetric and asymmetric hummocks with eskers overlying them (indicated by asterisks); D—moraine plateaus (note esker). Scale bars represent 1 km. Arrows in A and B indicate flow trends.

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strate and document the erosional nature of the Travers-McGregor hummocks.

GEOMORPHOLOGY AND SEDIMENTOLOGY

Hummocks in the study area have a variety of forms typical of many other hummocky regions in the Great Plains. These forms include: symmetric and asymmetric circular mounds that in places contain central depressions; transverse ridges that resemble giant ripple marks; elongate streamlined hummocks; linked hummocks; and moraine plateaus (Fig. 2). Most hummocks are between 1 and 50 m high and between 25 and 300 m wide. Slopes are in the range of 1° to 25°. Each hummock type occurs in tracts, and in each tract features are of similar dimensions. For example, transverse ridges occur together (Fig. 2A), and all ridges are of similar shape and size. Similarly, this applies to elongate mounds (Fig. 2B), and to symmetric and asymmetric mounds (Fig. 2C). Types are, however, transitional to each other. Similar patterns and trends have been noted in hummock distributions by other researchers and are explained as subglacial bedforms (e.g., Lundqvist, 1981).

Sediment in the hummocks includes a basal unit of tectonized lodgment till, usually associated with bedrock thrust by ice moving from the northeast (Fig. 3). This till is the oldest glaciogenic deposit and records initial Laurentide advance into the area. Subsequent decoupling of the ice from its bed, or ice retreat, resulted in deposition of thick sequences of subglacial or ice-proximal glaciolacustrine sediments (diamictons, gravels, cross-laminated and graded sand, and rippled, laminated, and rhythmically bedded sand, silt, and clay). These beds were subjected to intense shearing, faulting, and folding after their deposition by ice moving from the northeast (Figs. 4 and 5). Some rafts of the underlying lodgment till lie along shear planes (Fig. 4). Conformably overlying the glaciolacustrine sediments is the youngest unit in the hummocks: a stratified till that was probably deposited by direct melt-out at the base of the ice. It consists of homogeneous clayey diamicton containing undisturbed and approximately equally spaced interbeds of sand (Fig. 6). The sand laminae are truncated at hummock surfaces, but the same sequence can be recognized in one hummock after another. Clasts are commonly striated, and some larger boulders have sand-filled scours below them (Fig. 6), indicating that the boulders were held in ice and extended downward into flowing subglacial water (Shaw, 1982). Also supporting a subglacial origin for this unit is clast fabric analysis. Most of the 27 fabrics from this unit have strong principal eigenvalues (S1) and K values (degree of clustering) (cf. Woodcock, 1977) (see Table 1). Mean orientations indicate ice flow from the northeast (Fig. 7). Hummock after hummock contains the same lithostratigraphic sequence described above (Fig. 8), and that sequence can also be found under nonhummocky terrain at adjacent exposures.

Boulder lags (Fig. 9) and esker (Fig. 2C) sediments are the only significant materials overlying hummocky terrain in the region. Boulders in the lags are as much as 2 m across; some are heavily pitted by percussion marks, and they are lithologically similar to cobbles and boulders in the underlying sediments, indicating that they have not moved significantly. They are most numerous in areas underlain by boulder-rich sediment (Fig. 9), with sparse lags overlying finer grained sediments. The eskers contain intact arched sediments; in places, upslope paleocurrents indicate a subglacial origin.

NATURE AND ORIGIN OF THE EROSION SURFACE

Because the youngest unit within the hummocks is interpreted as subglacial, and subglacial eskers are superimposed on and are, therefore, younger than the hummocks, it is reasonable to assume that hummock surfaces represent subglacial erosion. The alternative that the hummock morphology was created by differential lowering and faulting during supraglacial letdown is contradicted by the continuous, unfaulted strata beneath depressions at some locations (e.g., Fig. 8). Moreover, erosion by surface processes is unlikely because downslope accumulation of sediments in the troughs between hummocks is minimal.

In a subglacial environment, ice, subglacial deformation, and water are all possible agents of erosion. The sharp erosion surface, boulder lags, lack of deformed material (deformation till) near the surface and, in places, intact sedimentary architecture make subglacial deformation the least likely of these possibilities. Direct erosion by ice is also unlikely because the expected downflow depositional products in the form of moraines, till

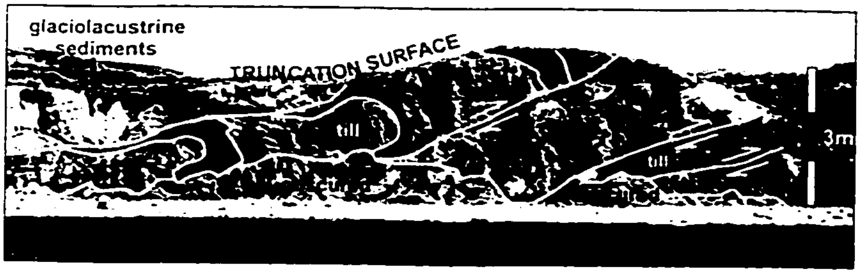

Figure 3. Oldest Quaternary unit in hummocks is lodgment till associated with thrust bedrock. All unmarked units are bedrock; darker units are coal-dominated. All units are truncated at hummock surface (including glaciolacustrine silts).

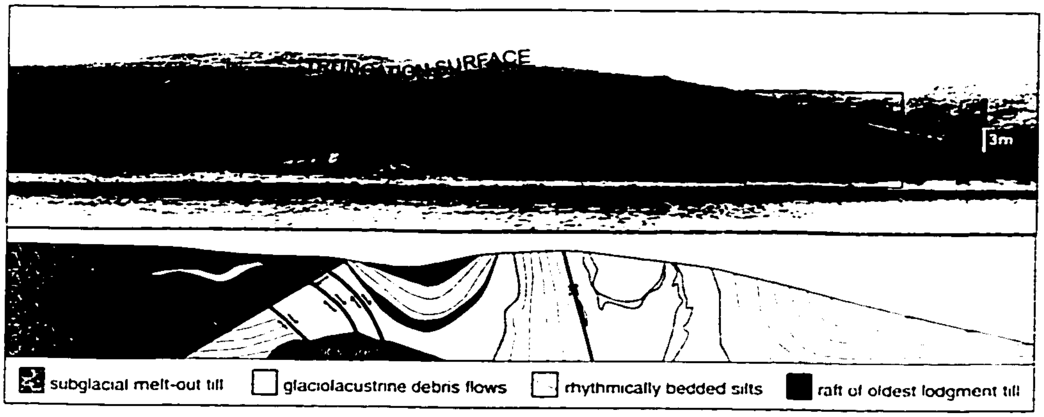

Figure 4. All three units are visible in this one exposure at McGregor Lake. Units have been faulted, folded, and sheared. Truncation of upstanding beds and synclines clearly documents erosional surface that delineates hummock form.

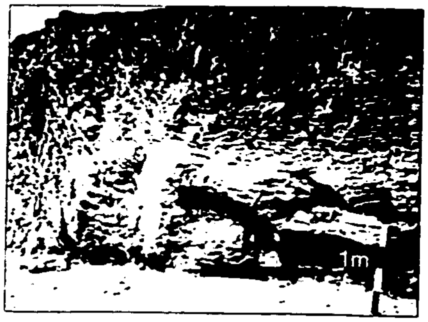

Figure 5. Close-up of truncated, rhythmically bedded silts and clays in Figure 4.

blankets, or glaciolacustrine materials beyond or within the zone of erosion are lacking. In addition, fabrics from the youngest till unit indicate ice flow from the northeast (Fig. 7, Table 1). This direction is oblique to the direction of flow indicated by fluting and oriented hummocks (see Figs. 1 and 2).

Evidence suggesting that meltwater eroded the hummock surfaces is much more convincing to us. First, surface boulders are best explained as lags left during fluvial transport, where flowing water was able to remove all but the largest boulders. Percussion marks on the boulders attest to possible clast-to-clast collisions during transport. The lags are unlikely to represent minor subaerial erosion (cf. Wright et al., 1973), because there are no deposits in the swales between hummocks. Moreover, stratigraphic relations suggest that the erosion was subglacial, and uphill trends in some of the hummocks indicate that erosion by meltwater could have occurred only in the subglacial environment. Subglacial and extraglacial water flows can transport sediment over large distances, perhaps as far as the Gulf of Mexico (Shaw et. al., 1996), thus explaining the scarceness of till above the erosion surface and the lack of complementary deposits immediately downflow. Some erosional forms in basalt scoured by the Lake Missoula floods are morphologically similar to hummocky terrain (Baker, 1978), indicating a strong plausibility that hummocky terrain can be the product of meltwater erosion. Also, streamlined loess hills in the Channeled Scabland, Washington, maintain undisturbed internal stratigraphy (like the Travers-McGregor hummocks), despite erosion by the Lake Missoula floods (Bretz, 1969).

TABLE 1. ORIENTATION DATA FROM CLAST FABRIC ANALYSIS ON THE MELT-OUT TILL UNIT

S1	S3	K	O
0.607	0.051	0.299	209.6
0.784	0.031	0.803	81.4
0.801	0.025	0.778	261.5
0.489	0.087	0.090	68.4
0.693	0.041	0.512	31.2
0.644	0.122	1.550	201.8
0.468	0.147	0.200	68.2
0.562	0.166	1.479	68.2
0.803	0.062	2.268	51.5
0.868	0.019	1.153	161.1
0.528	0.138	0.523	21.6
0.600	0.068	0.375	119.2
0.521	0.065	0.126	218.9
0.716	0.085	1.510	69.9
0 730	0.050	0.805	253.7
0.794	0.064	2.142	58.8
0.766	0.060	1.316	257.8
0.635	0.145	2.563	19.1
0.512	0.131	0.362	52.4
0.685	0.115	2.241	86.0
0.638	0.079	0.627	59.0
0.616	0.087	0.589	258.0
0.749	0.063	1.127	64.7
0.661	0.063	0.590	84.9
0.697	0.078	1.072	103.2
0.581	0.130	0.876	70.1
0.699	0.053	0.671	64.4

Note: S1 is the principal eigenvalue; S3 is the third eigenvalue; K is the degree of clustering; and O is the mean orientation.

DISCUSSION AND CONCLUSIONS

Hummocky terrain along McGregor and Travers reservoirs is clearly the product of erosion. This conclusion is supported by the widespread truncation of beds within hummocks. The evidence suggests that this erosion was subglacial, most likely by meltwater.

The amount of erosion is unknown, but formation of troughs between hummocks involved between 1 and 20 m of sediment removal. Trends in hummock form and flow directions inferred from aligned hummocks suggest that water flowed across the entire region from the northwest to the southeast. This was likely in the form of a large sheet flow. Although this cannot be proven, it is difficult to envisage piecemeal formation of wide bands of similarly oriented hummocks by narrower flows, and it is the best explanation for the wide array of sediments and morphological features observed. To account for the amount and extent of erosion, we propose that meltwater must have been stored upglacier from and, perhaps, within the hummocky zone, and then released catastrophically. The exact location and size of the reservoir(s) are unknown. Larger scale fluting in the areas north of the Little Bow River and in the Blackspring Ridge flute field also show northwest-southeast trends (Fig. 1). We have proposed (Munro and Shaw, 1996) that the Blackspring Ridge flutes represent sheetflow erosion at least 50 km wide. If the hummocks formed during the same meltwater erosional event as the fluting, flow may have been as wide as 120 km to account for all the erosional landforms. The scale and location of this proposed flow may support the idea that the study area was scoured by a branch of the subglacial Livingstone Lake megaflood (Rains et al., 1993). The detailed mechanics of this meltwater erosion are not well understood, and many questions remain. For example, we do not know the exact scale of the proposed flow, how the meltwater interacted with different substrates regardless of the scale of the flow, if different hummock forms are related to different substrates, or the locations of the removed sediment.

We realize that hummocks are polygenetic and that erosion cannot account for all hummocky terrain. For example, subaqueous outwash can appear hummocky (Rust, 1977), and ice-stagnation hummocks occur in front of many modern glac-

Figure 6. Youngest unit is interpreted as subglacial melt-out till. Thicker strata in this photo are clay-dominated diamicton. Sand strata are continuous for hundreds of meters and likely document periodic small-scale storage and release of subglacial meltwater. Sand-filled scour below boulder indicates that boulder must have been suspended from subglacial ice as water was flowing below it. Strata above scour are continuous to edge of boulder, indicating that boulder remained partially suspended from ice as adjacent strata were deposited. Finally, melt-out of boulder resulted in draping by overlying sediments.

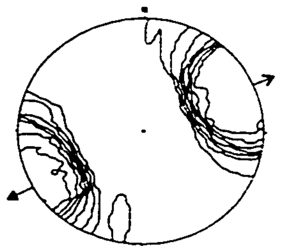

Figure 7. Clast fabric stereoplot for melt-out till in study region. Mean orientations indicated in Table 1, along with mean dips, are reanalyzed as composite sample and plotted on equal projection stereonet. Resultant principal eigenvector azimuth is 64° (line-head arrow), with S1 value of 0.773, and K value of 1.053. These values are statistically significant and indicate ice-flow direction toward southwest (solid-head arrow).

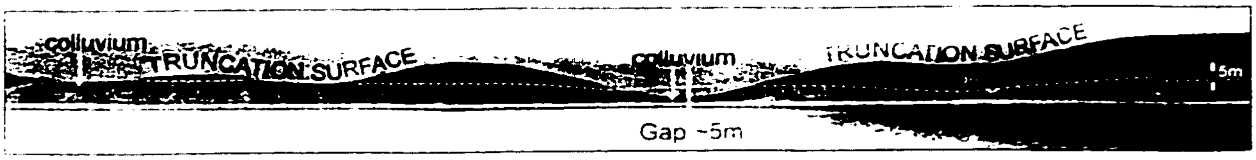

Figure 8. Two exposures at McGregor Lake clearly document continuous stratigraphy between mounds. Lower light colored unit is deformed lacustrine sediment, whereas upper dark unit is melt-out till shown in Figure 6. Dotted parts of lines indicate where units would have extended between hummocks.

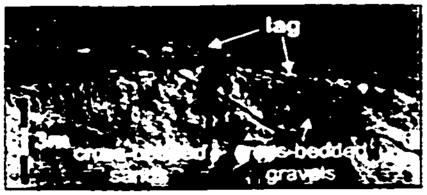

Figure 9. Study area has extensive boulder lags. They are most prominent where they overlie glaciofluvial sediments.

iers (e.g., Sharp, 1985). In general, though, authors of maps, reports, and papers refer to these features as "hummocky moraine," "stagnation moraine," and "ice-stagnation topography." This terminology assigns hummocky terrain to stagnant ice in marginal or near-marginal positions. According to our interpretation, such terminology does not apply to many hummocky areas of the Great Plains. For example, the McGregor moraine is not a moraine, and hence it should not be used to reconstruct ice margins. This conclusion must also stand for other hummocky landscapes that are dominated by landforms of similar form, magnitude, and pattern. The hummocky terrain discussed here is the product of subglacial erosion, most likely meltwater erosion. Because basal conditions have a direct bearing on ice-flow regime, ice thickness, and ice extent, the results of this paper also have major implications for ice-sheet modeling and ice-sheet reconstruction.

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