National Library of Canada
Bibliothèque nationale du Canada

Canadian Theses Service
Service des thèses canadiennes

Ottawa, Canada
K1A 0N4

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

NL-339 (r. 88/04) c

Canada

UNIVERSITY OF ALBERTA

LATE PLEISTOCENE GEOMORPHOLOGY OF THE HAND HILLS AREA, SOUTHERN ALBERTA

BY

ROBERT RODERICK YOUNG

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND
RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

FALL 1991

ISBN 0-315-70041-6

UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: ROBERT RODERICK YOUNG

TITLE OF THESIS: LATE PLEISTOCENE GEOMORPHOLOGY OF THE HAND HILLS AREA, SOUTHERN ALBERTA

DEGREE: MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED: 1991

PERMISSION IS HEREBY GRANTED TO THE UNIVERSITY OF ALBERTA LIBRARY TO REPRODUCE SINGLE COPIES OF THIS THESIS AND TO LEND OR SELL SUCH COPIES FOR PRIVATE, SCHOLARLY OR SCIENTIFIC RESEARCH PURPOSES ONLY.

THE AUTHOR RESERVES OTHER PUBLICATION RIGHTS, AND NEITHER THE THESIS NOR EXTENSIVE EXTRACTS FROM IT MAY BE PRINTED OR OTHERWISE REPRODUCED WITHOUT THE AUTHOR'S WRITTEN PERMISSION.

#204, 508-5 ST. N.E.
CALGARY, ALBERTA

DATE: OCT. 15, 1991

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH, FOR ACCEPTANCE, A THESIS ENTITLED, **LATE PLEISTOCENE GEOMORPHOLOGY OF THE HAND HILLS AREA, SOUTHERN ALBERTA.**

SUBMITTED BY ROBERT RODERICK YOUNG IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

R.B. Rains

R.B. RAINS
(SUPERVISOR)

J.A. Burns.

J.A. BURNS

M.M. Fenton

M.M. FENTON

DATE: Oct. 11 1991

Abstract

The discovery of prairie dog fossils and trace fossils in the Hand Hills area provided a unique opportunity to study several aspects of the region's Pleistocene history. The fossils provided organics for absolute dating, and the burrow casts provided evidence indicating the relative age of periglacial and glaciotectonic events.

The trace fossils, in the form of burrow casts, were preserved by infilling from surrounding and overlying sediments, both by inwashing and by animal activity. Bones of the extinct prairie dog, *Cynomys churcherii*, were buried during infilling, so that their former homes became their tombs. The burrow casts cross cut numerous "old" ice-wedge casts, indicating pre- Middle Wisconsinan periglacial activity. The presence of prairie dogs, and other vertebrates indicates that the area was a cool, dry, grassland during the Middle Wisconsinan. Accelerator radiocarbon dates on bone collagen show that the prairie dogs lived in the area from at least 33,000 yrs B.P. to around 22,000 yrs B.P. Analysis of burrow casts and periglacial sag structures indicates that the hills were likely not submerged by pre- Late Wisconsinan Continental ice sheets. A thick, topographically unconstrained northwest-southeast flowing sector of Laurentide ice sheet submerged the hills sometime after about 22,000 yrs B.P. The Laurentide flow is best explained as responding to pressure gradients caused by the coalescence with and deflection by lobes of the Cordilleran glaciers to the west and northwest.

The initial phases of deglaciation and ice thinning caused the Hand Hills to be exposed to periglacial conditions, causing limited ice-wedge formation. The first phases of glacial retreat allowed decoupling of the two ice sheets and establishment of a non-deflected, northeast-southwest flow pattern of the Laurentide ice sheet. A distinct band of hummocky topography likely represents the Laurentide terminus during this phase of deglaciation.

Acknowledgements

We usually pass through crossroads in our life without realizing it. Only later does a person recognize which events, though insignificant at the time constitute those crossroads. I am fortunate in recognizing two such events quickly enough to acknowledge them in a place where others may see the result. The events were simply walking into the offices of two men, J.A. Burns and R.B. Rains. They were similar experiences because, in each case, I found a person whose enthusiasm for their discipline was tempered by a recognition that good science takes time. My thanks to them for giving me the time to develop a project that couldn't have been done without it. I would also like to thank and recognize the contribution of many others. The Royal Canadian Geographical Society, Provincial Museum of Alberta, and Department of Geography at the University of Alberta all provided sustenance and/or field expenses at various time from 1986 to 1990. Many thanks to Dr.s Liam Kieser and Rolf Buekens at Isotrace in Toronto for their contribution to the dating of the sites. Dr. Dave Arnold at the Alberta Environmental Centre, Vegreville did some interesting experimentation with some organics found during this study. The Faculty of Graduate Studies provided travel funds to present the results.

May I join the ranks of a multitude of researchers in thanking D.B. (Tim) Schowalter for his contributions to research. His contribution to my research was to a) finding the prairie dogs in the Hand Hills, and b) providing constant encouragement, friendship, and support, particularly in the field. Tim's enthusiasm for science is at least the equal of any, and his views reinforced what I learned elsewhere.

My thanks to the people of Delia and the Hand Hills for letting me onto their land, and into their lives. I quickly found that many farmers are fascinated

with natural history, so visits were always interesting. I was fortunate to enjoy many arm-waving sessions, both in talking and listening.

A number of students and faculty in the Department of Geography have contributed by providing an atmosphere where ideas can be exchanged freely, to either grow or wilt through examination. Thanks to Bob Skoye, Barb Shaw, James Hooper, and Trevor Bell for the time they spent with my ideas. Thanks to John Shaw, Ian Campbell, Pete Kershaw and for their interest and feedback. Thanks to Fred Bachhuber of UNLV for just being Fred. Many aspects of this work were greatly improved due to the advice of Tracy Brennand.

A factor in coming back to Edmonton to return to school was that my family is here. It was a good move. Thanks especially to my brother, Ralph who introduced me to Macintosh

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

CHAPTER 2

LITERATURE REVIEW

Glacial stratigraphy and ice-sheet reconstructions in west and southwest Alberta

Laurentide processes, landforms, and sediments

Periglacial landforms and sediments

CHAPTER 3

CHAPTER 4

Summary and discussion

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

Chapter 1: Introduction

Problem statement

i. Introduction

Many vertebrate fossil sites, of Pleistocene age, in formerly glaciated areas have incomplete or extremely complex stratigraphies that were the result of glacial erosion and deposition. Others may contain fossils which lie beyond the limit of radiocarbon dating and are from sites where other radiometric dating methods cannot be used. Also, because glaciation involved massive loading of surfaces, most of the sediment overridden by ice was subjected to high normal and shear stresses - conditions not favorable to the preservation of fossils. Another problem is that where datable organics are found in glacial deposits they may have been reworked from older deposits. Thus, even when datable organics are found their actual value as a tool for paleoenvironmental reconstruction is tenuous unless the exact stratigraphy can be determined.

The challenge, then, is to extract as much information as possible from every paleontologic site. Useful information may include; evidence of the circumstances of deposition, details of site-stratigraphy, correlation with other sites having more complete stratigraphies, observation of post-depositional events as indicated in reworking of sediments, and, an appraisal of regional events based on evidence gained from available studies.

ii. Problem statement

The goal of this study was to reconstruct the Pleistocene stratigraphy associated with Middle Wisconsinan fossil prairie dog, *Cynomys churcherii*, sites in the Hand Hills, south-central Alberta. Where possible, observations were made pertaining to demonstrable pre- and post-depositional events at the study sites. Finally, these events were interpreted in context of the regional Pleistocene history of south-cental Alberta.

Location

The study area is roughly that encompassed by the 1:250,000 NTS 82 P mapsheet, south-central Alberta (Figure 1). The Hand Hills, in the east-central zone of the mapsheet area, are the primary focus but several geomorphic features in the surrounding area pertain to events in the hills.

The Hand Hills are two gravel-capped uplands commonly mapped together since they are conveniently outlined by the 914 m (3,000 ft) contour (Figure 1). The highest point on the eastern upland is about 90 m (~300 ft) lower than on the western. The Hand Hills lie between 51°15'40' and 51°31'10" north latitude and 111°58'00" and 112°23'00" west longitude. The Hand Hills area is split almost equally between the Municipal District of Starland and Special Areas # 2. It is located approximately 30 km northeast of Drumheller, and an equal distance southwest of Hanna. The city of Calgary is about 110 km to the southwest. The mapped area of the Hand Hills delineates about 51,000 hectares. The plateau of the hills (above the 990 m (3,250 ft) contour) encompasses only about 13,000 hectares of which nearly 11,000 hectares are located on the western upland.

Physiography of the study area

The study area is dominated by a plain which dips to the northeast at about 0.5 m per kilometre. Elevation of the plain varies from about 1,005 m (3,300 ft) asl around Calgary to approximately 820 m (2,700 ft) asl in the northeast. The nearly flat-topped Hand Hills and Wintering Hills are the most prominent and important of a number of hills in the study area (Plate 1). The relatively flat topography directly east and west of the Hand Hills tends to make them visually striking, especially when they are observed from the west. The steepest slopes exhibiting the greatest relief occur on the northwest sides of both the

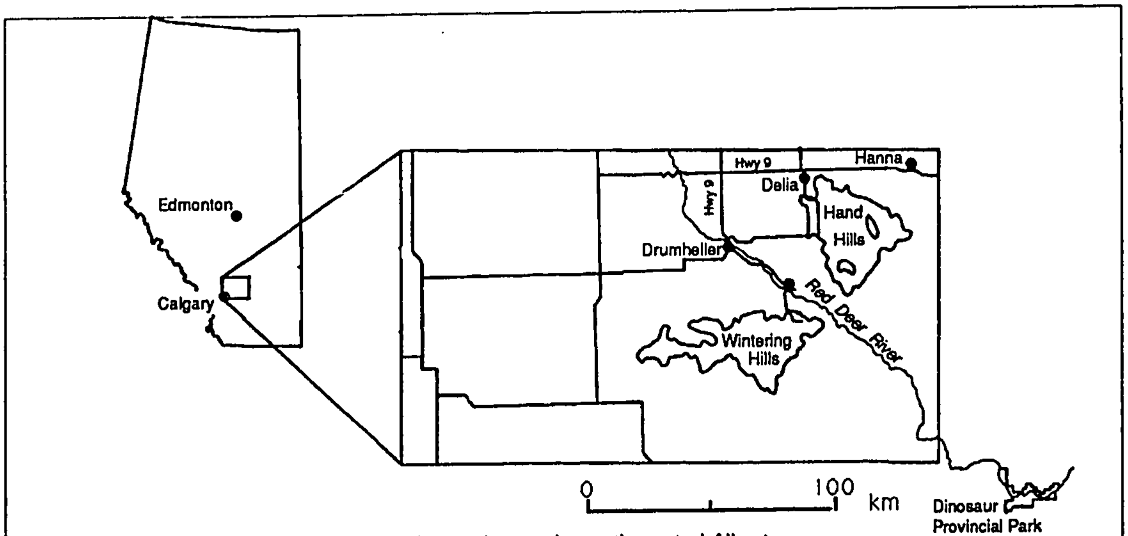


Figure 1: Location of the study area in south-central Alberta.

Wintering and Hand Hills.

A relatively narrow (only ~3 km wide in places) belt of hummocky topography interrupts the almost continuous plain around the Hand Hills (Plate 2). The belt extends from the north-central zone eastward to the northern tip of the eastern Hand Hills (Plate 1). The hummocks become more subdued around the hills' perimeter, but are more prominent on the southeast corner of the Hand Hills. They can be traced across the Red Deer River valley and south, out of the study area.

Successive authors have each discovered landforms thought to be oriented parallel to glacial flow. Stalker (1973) mapped numerous northwest-southeast trending flutings, drumlins, and "murdlins" primarily in the western part of the study area (Plate 1). Recently, Shetsen (1987) identified northwest-southeast oriented landforms on and around the Hand Hills, and on Surprise Hill (about 15 km north of the Hand Hills). Northeast-southwest oriented landforms also exist in the study area but are far less numerous, have low relief, and are primarily located in the central and northeastern zone. Skoye (1990) identified a number of previously unrecognized, long, low-amplitude flutings northeast of the

Plate 1: Surficial Deposits and Physiographic Features

Plate 2: Looking north from the northeast corner of the eastern member of the Hand Hills. The hummocky topography continues north, out of the study area.

Hand Hills (Plate 1). The flutings are not visible on standard air photographs but are revealed by satellite imagery taken during January 1984, when conditions of snowcover and low sun angle fortuitously permitted. Oriented landforms that display an intermediate or southerly orientation occur in the south-central and southwestern part of the study area, but the southeast and southwest trending features are more numerous. Shetsen (1987) also mapped several types of features oriented transverse to assumed ice movement. These include small ridges, elongated hummocks and depressions, as well as ice-thrust ridges. Again, two dominant suites of orientation are apparent, relating to either northwest-southeast or northeast-southwest glacial flow.

Meltwater channels of varied scales are common throughout the study area. Large northwest-southeast trending channels, some occupied by misfit streams, occur to the west of the Hand Hills, and are interspersed with drumlins and flutings maintaining the same trend (Plate 1). Some authors (e.g. Bryan *et al.* 1987) think that certain reaches of the Red Deer River may have been initiated by similar-trending spillways during the early phases of deglaciation. Eskers are also common features, especially in western sectors of the study area. They are most prolific in elevated areas that have thin or discontinuous Quaternary deposits (Plate 1). Stalker (1973) identified several "esker channels" — small, narrow channels connected to proximal and/or distal ends of eskers. The basin that was occupied by glacial Lake Drumheller is approximately in the middle of the study area (Plate 1). Shorelines are not immediately evident, but the northern shore may often be inferred from the presence of somewhat rounded or muted hummocks when seen on air photos.

Several other landscape features are notable in the study area. Hand Hills Lake is located in a depression on the low plateau between the two uplands of the Hand Hills, about 13 m (50 ft) above the surrounding plains (Plate 1). Little Fish Lake is located on the plains about 3 km southwest of the hills. The Red Deer River is about 10 km south of the hills and flows from northwest to southeast. The Wintering Hills (gravel-capped uplands) are located about 15 km south of the Red Deer River, and nearly 30 km southwest of the Hand Hills. They reach nearly the same elevation as the eastern Hand Hills.

Immediately to the west of the study area are two features which pertain to events and landforms/sediments being examined. First, the foothills erratics train and associated tills (Stalker 1956) denote an area of mixed Cordilleran and Continental glacial deposits (not shown). These erratics and tills can be found from the Jasper area along the foothills and into Montana. Farther to the west are streamlined landforms, formed under Cordilleran ice, mainly trending northwest-southeast, almost parallel to the structural grain of the landscape. They also occur discontinuously from the Jasper area in west-central Alberta southeastward down the foothills (Roed 1975, Shetsen 1987, 1990).

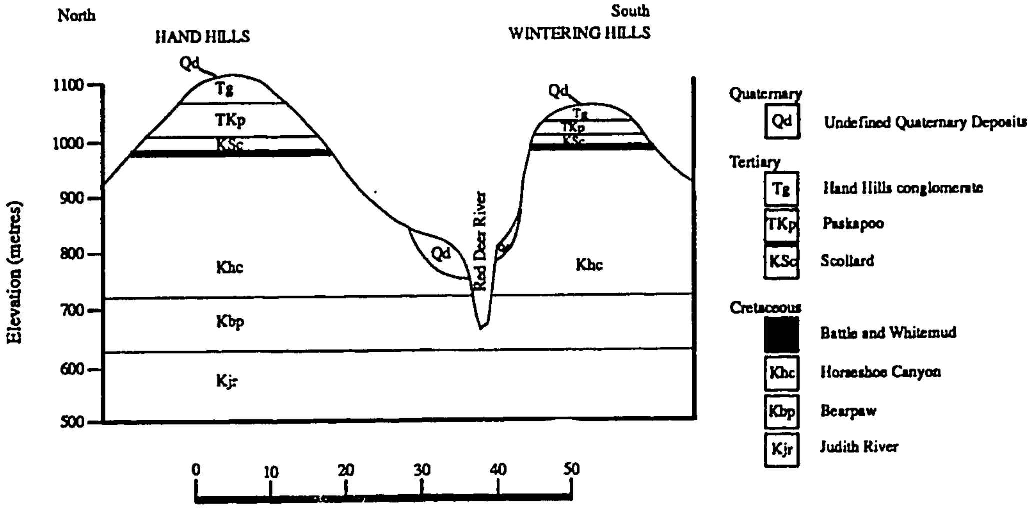
Bedrock geology and stratigraphy of the study area

Aspects of the bedrock geology (Figures 2 and 3) in the area have been intensively studied because of the wealth of vertebrate fossils contained there. The oldest sedimentary rock exposed in the study area is the Bearpaw Formation. It outcrops along the Red Deer River valley bottom in the southeast of the study area (Figure 2). The beds consist mainly of dark grey to brownish-grey marine clay shales and silty shales. The formation is estimated to be about 200 m (650 ft) thick, but only the upper 140 m (450 ft) are exposed (Braman and Eberth 1988).

The Edmonton Group conformably overlies the Bearpaw Formation and is the most common bedrock throughout the eastern half of the area. It consists of four formations; the Horseshoe Canyon, Whitemud, Battle, and Scollard (Figure 2). Rock types include fossiliferous interbedded sandstones, siltstones, claystones, coal and a variety of diagenetic products (ironstone and smectite clays). The Horseshoe Canyon Formation comprises about two-thirds of the thickness of the entire Edmonton Group in the Red Deer River valley. The Whitemud and Battle Formations are gradational units related to delta and coastal plain progradation punctuated by sudden marine transgressions. Some Scollard Formation outcrops contain palynofloral changes, and the well-known iridium anomaly, which mark the Cretaceous/Tertiary boundary. The upper Scollard Formation is therefore Paleocene in age (Braman and Eberth 1988).

The Edmonton Group is conformably overlain by the Paleocene Paskapoo Formation. The formation includes gray-greenish, brown, and black shales, mudstones, siltstones, and sandstones. The depositional environments were likely slowly flowing streams, shallow lakes, and swamps (Fox 1988).

References to a nearly continuous gravel cap on the Hand Hills were

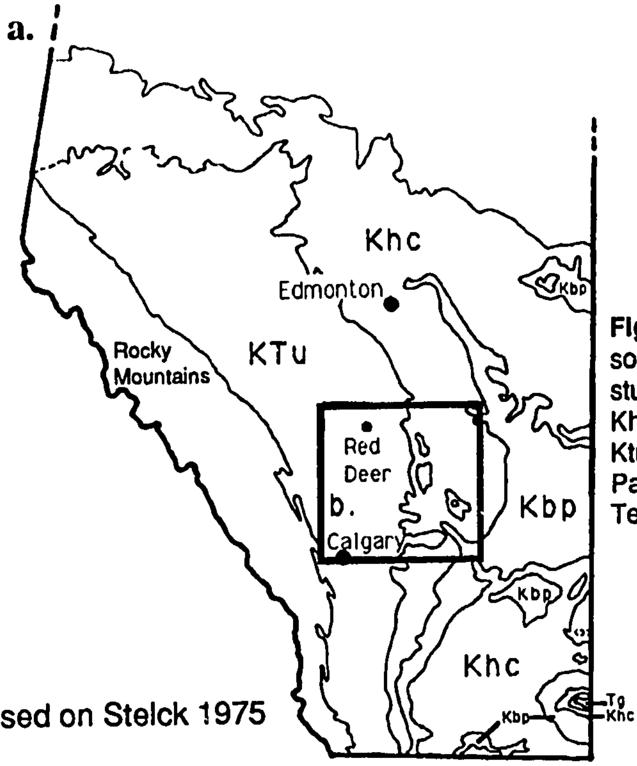


VE = 80

Figure 2: Geological cross-section of the Hand Hills region

based on Glen, pers. comm.

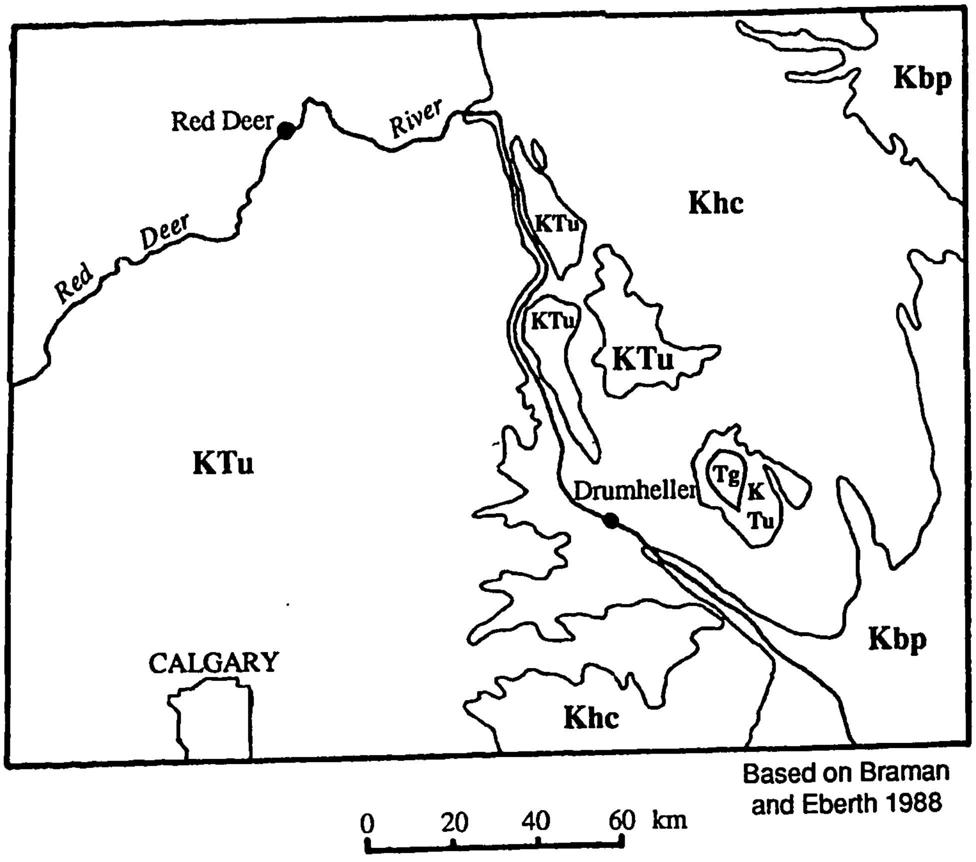
a.



based on Stelck 1975

Figure 3: Bedrock geology of; a. the southern Alberta plains, and b., the study area. Kbp - Bearpaw Formation; Khc - Horseshoe Canyon Formation; Ktu - Whitemud, Battle, Scollard and Paskapoo Formations undivided; Tg Tertiary gravel.

b.

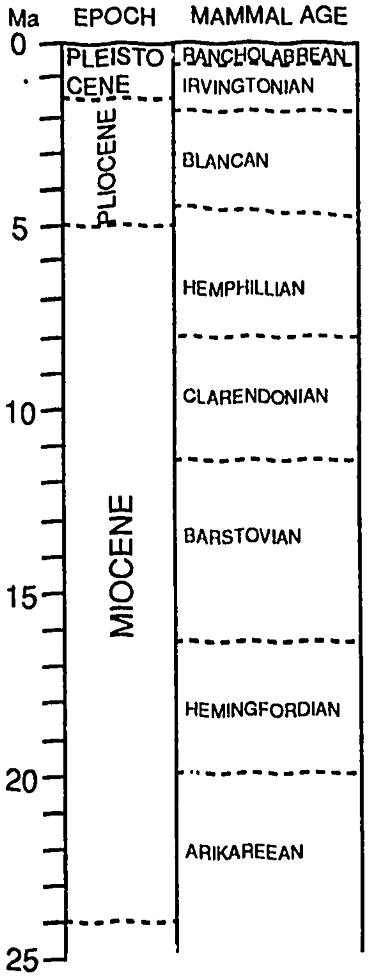


Based on Braman and Eberth 1988

made by some of the earliest geologists in Alberta (Dawson and McConnell 1885, Tyrrell 1887). The Hand Hills gravels were initially correlated with the Oligocene gravels located on top of the Cypress Hills to the southeast. On the basis of elevation, Warren (1939) correlated the Hand Hills gravels to the Flaxville Plain, an erosional surface in northern Montana. It occurs 180 to 460 m (600 to 1,500 ft) below the elevation of the Cypress plain, at about 790 m (2,600 ft) asl. Fossils from the Flaxville gravels indicate their age to be "not older than Miocene or younger than Lower Pliocene" (Figure 4) (Warren 1939, p. 343), indicating a probable similar age for the deposition of the Hand Hills gravels. Allan and Sanderson (1945, p. 100) referred to the gravel as "Oligocene (?) Formation". Russell (1958) suggested a Pliocene, or at least a late Tertiary, age for the gravels on the basis of biostratigraphic correlation of a horse astragalus found out of context in a gravel pit on "Mother's Mountain", the highest point on the Hand Hills, at NW $^1/_4$, S 32, T 29, R 17, W4 (Plate 3). The specimen was well-mineralized and had staining similar to the gravel. He used the informal term Hand Hills conglomerate, whereas Harington (1978, p.43) capitalized "Conglomerate". Stalker (1973) used the formal name Hand Hills Formation. Storer (1976) identified fossil mammals of two different ages from what he also termed the Hand Hills Formation at a site in S 16, T 30, R 17, W4 (Table 1a and 1b). He considered the Hand Hills Formation to be a single unit including, in places, an overlying till. He noted a "disturbed" zone several centimetres thick at the gravel - till contact, and concluded that the disturbance marked an unconformity. He speculated that the unconformity likely marked a period during which the gravel was uplifted and eroded. The formation apparently contained a mixed mammalian fauna whose temporal components were not separated by a stratigraphic marker. Exact provenances of much of the fossil material found at his site are unknown as this was found in piles of gravelly overburden removed from the pit

Plate 3: A view to the west from the top of "Mother's Mountain", the highest point in the Hand Hills. Shield erratics (e.g. left foreground) on the hills are common. Note the Rocky Mountains in the distance.

Figure 4: A chart of North American mammal ages for the late Cenozoic.



Based on Woodburne 1987

area during its opening. Where provenance was known, Pleistocene fossils were found in the till or above the gravel, and late Tertiary fossils were found in the gravel. Storer (1976) felt that although it would be tempting to conclude the till was Pleistocene, and the gravel Mio-Pliocene, evidence from another pit called this into question. He reassigned a Pleistocene age to Russell's (1958) horse astragalus on the basis of size comparisons with Pleistocene horses. Since the astragalus clearly came from the gravel unit, he concluded that the gravel contained two faunas that were mixed. He theorized that the glacier depositing the till probably worked some Pleistocene material into the Plio-Miocene gravel, and picked up some older fossils and incorporated them into the till. Sedimentologic evidence of mixing of the gravel (such as folding or faulting) was not reported. There is as yet no answer to this conundrum.

Table 1a and 1b: Vertebrate species from the Sinclair Site; a Barstovian or Clarendonian (middle Miocene) locality with capping fossiliferous sediments of Rancholabrean (late Quaternary) age (after Storer 1976)

Table 1a: Mio-Pliocene fauna of the Hand Hills Formation.

Taxon	Known temporal range
Merychippus sp.	Hemingfordian to Clarendonian
Hipparion sp.	Barstovian to Blancan
Camelidae, gen. et sp. indet.	-
Sciurinae, gen. et sp. indet.	-
Copemys sp.	Barstovian to Hemphillian
Pseudadjidaumo cf. *russelli*	Late Barstovian

Table 1b: Pleistocene fauna of the Hand Hills Formation.

Taxon	Known temporal range
Elephantidae, gen. et sp. indet.	Irvingtonian to Holocene
Equus cf. *conversidens*	Irvingtonian to Holocene
Spermophilus cf. *richardsonii*	Irvingtonian to Present
Microtus cf. *pennsylvanicus*	Irvingtonian to Present
Geomys sp.	Blancan to Present
Leporidae, gen. et sp. indet.	-

Burns and Young (1988) and Burns and Voorhies (in prep.) contributed evidence and analysis to support the idea that the Hand Hills fauna embraced components of two distinct ages. The discovery of three, *in situ*, diagnostic taxa from two locations (Table 2) seems to firmly date the older fauna and the gravel as Hemphillian, or latest Miocene to earliest Pliocene. Since *Teleoceras* (and all other rhinoceroses) became extinct at the end of the Hemphillian (about 4.8 Ma) in North America (Tedford *et al.* 1987), its presence in the Hand Hills sediments indicates a similar minimum age for the gravel. The presence of *Dipoides* and study area. The beds dip gently to the west and southwest, in the same direction that the land surface rises. Because of the structure, units generally thicken to the west. Generally, younger sedimentary rocks outcrop westward (Figure 3).

Quaternary stratigraphy and deposits

Single sites with a long Quaternary record are not known in the study area although glacial deposits occur almost everywhere, even on the highest points (Plate 3). Stalker (1973) attributes the attenuated Quaternary record to the fact that there are relatively few east-trending preglacial valley systems that would be good locations for deposition and preservation of Quaternary sediments. A few extensive deposits of buried gravel and local occurrences of till do exist in the preglacial valleys found in the area. The gravel is thought to be "preglacial" and therefore part of the Saskatchewan gravels and sands as defined by Stalker (1968). The mineralogy of these gravel deposits is similar to those found on top of the Hand and Wintering Hills. It is also similar to that of the modern Bow River, indicating that the ancestral river flowed more directly east than at present. The ancestral rivers farther south, in the Oldman basin, have red and green argillites, Crowsnest volcanics, sill-type intrusives, and purplish quartzites and sandstones (Stalker 1973). More northwesterly ancestral rivers (Red Deer and North Saskatchewan) have greater percentages of dolomite. Overall, there is a change in composition of the ancestral Bow gravels from west to east as limestone and dolomite percentages decrease. These clasts do not survive well in fluvial conditions. There is some conjecture concerning the origin of the buried gravel deposits. Rutherford (1937 cited in Stalker 1973) stated that:

Plesiogulo, that invaded North America about 6.7 Ma at the beginning of the Hemphillian (Repenning 1987), indicates a probable maximum age for the gravel. Burns and Young (1988) feel that the Pleistocene age assignment by Storer (1976) was tenuous, and the gravel is very likely Hemphillian in age.

Table 2: Late Hemphillian (latest Miocene) vertebrates from two sites in the Hand Hills near Drumheller, Alberta. (Unpublished identifications by James A. Burns and Michael R. Voorhies)

RUSSELL PIT
- **Perissodactyla**
  - Equidae sp. in doubt, large (see Russell 1958)
  - *Teleoceras* sp., small rhinoceros

COURTNEY PIT
- **Lagomorpha**
  - ?*Hypolagus vetus* (Rabbit)
- **Rodentia**
  - *Dipoides* sp. (a small beaver)
- **Artiodactyla**
  - *Neotragocerus* sp. (enigmatic antelope-like bovid)
  - cf. *Megatylopus* (large camel)
  - Camelidae (yet unidentified camel)
- **Perissodactyla**
  - *Nannippus lenticularis* (three-toed horse)
  - *Neohipparion eurystyle* (another)
  - *Dinohippus leidyanus* (one-toed horse)
  - Equidae (yet unidentified horse)
- **Carnivora**
  - *Plesiogulo* cf. *P. marshalli* (wolverine)

In summary, the bedrock geology is dominated by late Cretaceous sedimentary rocks in the eastern third of the study area (Figure 3). In the northeast and southeast are outcrops of the marine shales of the older Bearpaw sea. The remainder of the Cretaceous sediments are predominantly of the Horseshoe Canyon Formation. Overall, these rocks are not very resistant and are easily eroded. Relics of more resistant early and late Tertiary beds (Paskapoo sandstone and Miocene gravels) are present in the eastern part of the study area as uplands, but these sediments dominate for roughly the western two-thirds of the study area. The beds dip gently to the west and southwest, in the same direction that the land surface rises. Because of the structure, units generally thicken to the west. Generally, younger sedimentary rocks outcrop westward (Figure 3).

Quaternary stratigraphy and deposits

Single sites with a long Quaternary record are not known in the study area although glacial deposits occur almost everywhere, even on the highest points (Plate 3). Stalker (1973) attributes the attenuated Quaternary record to the fact that there are relatively few east-trending preglacial valley systems that would be good locations for deposition and preservation of Quaternary sediments. A few extensive deposits of buried gravel and local occurrences of till do exist in the preglacial valleys found in the area. The gravel is thought to be "preglacial" and therefore part of the Saskatchewan gravels and sands as defined by Stalker (1968). The mineralogy of these gravel deposits is similar to those found on top of the Hand and Wintering Hills. It is also similar to that of the modern Bow River, indicating that the ancestral river flowed more directly east than at present. The ancestral rivers farther south, in the Oldman basin, have red and green argillites, Crowsnest volcanics, sill-type intrusives, and purplish quartzites and sandstones (Stalker 1973). More northwesterly ancestral rivers (Red Deer and North Saskatchewan) have greater percentages of dolomite. Overall, there is a change in composition of the ancestral Bow gravels from west to east as limestone and dolomite percentages decrease. These clasts do not survive well in fluvial conditions. There is some conjecture concerning the origin of the buried gravel deposits. Rutherford (1937 cited in Stalker 1973) stated that:

> The relationship of the Saskatchewan gravels to the late Tertiary conglomerates and others of a similar type in Alberta, has not [been] established, but there is a possibility that these conglomerates contributed largely to the gravel phases of the Saskatchewan type.

Others (e.g. Dawson and McConnell 1895, and Coleman 1910, cited in Stalker 1973) proposed that much of the material represented outwash from a 'pre-Laurentide' Cordilleran ice sheet or a reworking of the ice sheet by water.

Some evidence of Laurentide glaciations older than Late Wisconsinan has been found in the study area. Stalker (1973) identified one older till, which he correlated to his Maunsell till (Stalker 1960), south of Drumheller in S 35 T 28 R 20 W4th. From borehole evidence he also stated that Labuma till may form the base of the fill in the preglacial Bow Valley (Stalker 1973).

The types and extent of surficial deposits have been mapped in detail by several authors (e.g. Stalker 1973 and Shetsen 1987). The diversity of surface deposits is so great that a visually complicated map is produced when they all appear on the same sheet. For this reason, large-scale sediment/process associations are difficult to recognize. A generalization of the surface deposits is presented in Plate 1 as a remedy. Mapped areas showing glaciolacustrine and glaciofluvial deposits include all areas that are either;

i. overlain by glaciolacustine/glaciofluvial sediments; such as glaciolacustrine mantling of stagnant ice deposits in the north-northwest portions of the study area or,
ii. underlain by glaciolacustine/glaciofluvial sediments; such as dunefields developed on top of glaciolacustrine sediments.

The true extent of glaciolacustrine and glaciofluvial systems is therefore much easier to ascertain from Plate 1 because of the visual simplification achieved.

Other generalized categories delimited in Plate 1 are:

> a. Areas with thin and discontinuous glacial deposits that may be indicative of areas which had, in the latter phases of glaciation, either actively eroding ice or stagnant ice that lacked a contribution of sediment from up-ice zones of the ice sheet. This category also includes hummocky topography, immediately northwest of the Hand Hills, which is bedrock-cored.
>
> b. A fairly restricted band of thick glacial deposits is located in the central portions of the study area.

On the basis of the great disparity in amounts of glacial deposits between zones a and b, it may be reasonable to assume that their glacial dynamics were different. If simple stagnation dominated thinly mantled areas in zone a (mapped by Stalker (1973) as ground moraine) then more active transportation and deposition processes explain better the presence of thick deposits in zone b. Stalker (1973) theorized that the thicker deposits were the result of active recessional ice.

Landscape evolution of the study area

The record derived from fluvial deposits indicates an extremely dynamic landscape for the latter part of the Cenozoic. Since the latest Miocene (~4.8 Ma), base levels of the Bow and Red Deer Rivers have lowered by approximately 330 m (1,000 ft). This lowering apparently took place before the first continental glaciation reached the area, as ancestral "preglacial" channels of the rivers are at about the same elevation as the modern, more southerly diverted rivers. If these ancestral channels are about 650 ka old (e.g. Stalker 1968), then downcutting occurred at a rate of approximately 20 cm per thousand years. The earliest stages of erosion caused the nearly total removal of sediment to form the modern plain, eroding around 190 m (~600 ft) of the total. The amount of material removed to form the modern central Alberta high plain is a staggering 190 million m^3/km^2. The last 140 m of the downcutting took place in discrete channels which were later filled with glacial materials. Whether the erosion occurred uniformly or in pulses is unknown. Since the gravels of the eastern Hand Hills and Wintering Hills are intermediate in elevation between the dated gravels on the highest part of the western Hand Hills and the buried "preglacial" channels, they should be of some intermediate age. A date from them might give some information on possible variations in the rate of downcutting.

Chapter 2: Literature Review

At first glance the sections of this chapter appear to address disparate themes. However, the literature and concepts reviewed are central to the analysis and interpretation of observations presented in later chapters.

1. Radiocarbon dating

Introduction

The radiocarbon method of dating was developed at the University of Chicago by W.F. Libby in the late 1940s. As with most other isotopic dating methods, radiocarbon dating relies on the spontaneous radioactive decay of an unstable atom to form a stable product of some type. Radio-isotopic dating can be considered as three groups, depending on (a) whether the amount of a radio-isotope is a fraction of a presumed initial level (e.g. radiocarbon) or the reciprocal accumulation of a stable daughter product (e.g. potassium-argon), (b) the degree of restoration to an equilibrium achieved by a chain of radioactive decay following some disturbance (e.g. uranium series dating), or (c) the measurement of the effect of some local radioactive process on the sampled materials compared to the value of the initial environmental conditions (e.g. fission track dating) (Bradley 1985). Radiocarbon is a good technique because datable organics are fairly ubiquitous in many forms, such as vegetation, shells, paleosols, and bone (Bradley1985).

Radiocarbon (^{14}C) dating has proven to be the most useful technique for studies of the late Quaternary. The half-life of radiocarbon (the time it takes for half the ^{14}C to decay) was initially calculated at about 5,568 years, which allows high resolution dating of younger samples to a maximum of about 40,000 years, depending on the sample (Bradley 1985). The radiocarbon half-life was later recalculated at 5,730, but to avoid confusion, the figure of 5,570 (the Libby half-life) is used by convention. The convention was maintained because the difference was not great enough to warrant republishing all the dates available at that time (Bradley1985).

Radioactive carbon is formed only by an indirect reaction of cosmic radiation from space with the Earth's upper atmosphere at an altitude greater than about 10,000 m. Neutrons are released by the collision of cosmic rays, primarily protons travelling at high velocities, with the nuclei of the atoms comprising the atmospheric gases. The interaction of these neutrons (n) with the nitrogen in the upper atmosphere produces radiocarbon. Cosmic rays are influenced by the Earth's magnetic field and are concentrated near the magnetic poles causing a similar concentration of neutrons and therefore ^{14}C. Atmospheric oxygen oxidizes the ^{14}C to form radioactive carbon dioxide ($^{14}CO_2$) which mixes with the ordinary CO_2 of the atmosphere. Plants usually absorb the mixed CO_2 from the air as a primary source of carbon for the process of photosynthesis, introducing it into the food chain. Upon death, no new ^{14}C is assimilated, and that which is present breaks down to nitrogen, with the release of a β particle (Bradley1985). It is not possible to predict when a particular ^{14}C atom will decay, but for a large sample of atoms, a certain number of disintegrations will occur over a certain length of time, on average. The statistical uncertainty introduced by calibration samples and background radiation is inherent in all ^{14}C samples. Dates are therefore expressed as a probability, i.e. the midpoint of a Poisson probability curve, together with its standard deviation, to define a known level of probability. For example, a date of 5,000 ±100 years B.P. indicates a 68 percent probability that the true age is between 4,900 and 5,100 years B.P. There is a 95 percent probability that the true age is between 4,800 and 5,200 years B.P. and a 99 percent probability that the true age is between 4,700 and 5,300 years B.P.

Causes of variability in radiocarbon dating

While it is tempting to accept every radiocarbon date at face value, there are grounds to believe that all dates are not equal. As well as the variability introduced by simple probability there are a number of initial assumptions and physical factors to consider.

a. Variations due to exchanges in carbon reservoirs

Continuous exchange of CO_2 between the two major radiocarbon reservoirs (the atmosphere and oceans) provides a supply of ^{14}C for living organisms. Assumptions that exchanges are constant, resulting in constant levels of atmospheric ^{14}C are, therefore, fundamental to radiocarbon dating. Some authors feel that this assumption is not valid, but is not a critical problem, in that its magnitude can be assessed, at least for most of the Holocene (Bradley 1985). Some possible causes of radiocarbon variability are listed in Table 3. Stuiver *et al.* (1991), however, investigated the influence of climatic, solar, oceanic and geomagnetic factors on variations in atmospheric $^{14}C/^{12}C$ ratios. They found that most of the variance in the Holocene atmospheric $^{14}C/^{12}C$ record can be attributed to the geomagnetic (millennium time scale) and solar (century time scale) influence on the flux of primary cosmic rays entering the atmosphere.

Table 3: Possible causes of radiocarbon fluctuations (from Damon *et al.* 1978).

I. Variations in the rate of radiocarbon production in the atmosphere
  (1) Variations in the cosmic-ray flux throughout the solar system
    (a) Cosmic-ray bursts from supernovae and other stellar phenomena
    (b) Interstellar modulation of the cosmic-ray flux
  (2) Modulation of the cosmic-ray flux by solar activity
  (3) Modulation of the cosmic-ray flux by changes in the geomagnetic field
  (4) Production by antimatter meteorite collisions with the Earth
  (5) Production by nuclear weapons testing and nuclear technology

II. Variations in the rate of exchange of radiocarbon between various geochemical reservoirs and changes in the relative carbon dioxide content of the reservoirs
  (1) Control of CO_2 solubility and dissolution as well as residence times by temperature variations
  (2) Effect of sea-level variations on oceanic circulation and capacity
  (3) Assimilation of CO_2 by the terrestrial biosphere in proportion to biomass and human activity
  (4) Dependence of CO_2 assimilation by the marine biosphere upon ocean temperature and salinity, availability of nutrients, upwelling of CO_2-rich deep water, and turbidity of the mixed layer of the ocean

III. Variations in the total amount of carbon dioxide in the atmosphere, biosphere, and hydrosphere.
  (1) Changes in the rate of introduction of CO_2 into the atmosphere by volcanism and other processes that result in CO_2 degassing of the lithosphere
  (2) The various sedimentary reservoirs serving as a sink of CO_2 and ^{14}C. Tendency for changes in the rate of sedimentation to cause changes in the total CO_2 content of the atmosphere
  (3) Combustion of fossil fuels by human industrial and domestic activity.

Invoking climate alone acting on oceanic circulation and/or global wind speed changes seems incorrect as the theorized changes are incompatible with proxy climate records. While the climate/ocean-related ^{14}C-redistribution between carbon reservoirs evidently played a minor role during the Holocene, it may have perturbed atmospheric $^{14}C/^{12}C$ ratios measurably during the late-glacial

Younger Dryas event. Stuiver *et al.* (1991) made first-order corrections to the radiocarbon time scale based on adjusted lake-sediment and tree-ring records for the Holocene ^{14}C record and from geomagnetically defined model ^{14}C histories for the late Pleistocene ^{14}C record (12,000-30,000 ^{14}C yr B.P.) (Table 4).

Table 4: Calendar Yr- Radiocarbon Yr age calibration derived from (1) the McElhinny/Senanayake Pre-Holocene dipole and (2) the Tauxe/Valet pre-Holocene dipole (from Stuiver *et al.* 1991).

^{14}C age	Cal age 1	Cal age 2	Avg cal age
28,000	30,000		
27,000	29,500		
26,000	28,500		
25,000	27,500		
24,000	26,600		
23,000	25,600		
22,000	24,600		
21,000	23,600		
20,000	22,500		
19,000	21,500	22,500	22,000[a]
18,000	20,400	21,500	21,000[a]
17,000	19,300	20,400	19,800[a]
16,000	18,200	19,300	18,700[a]
15,000	17,100	18,100	17,600[a]
14,000	16,000	16,900	16,500[a]
13,000	14,900	15,800	15,400[a]
12,000	13,700	14,600	14,200[a]

[a] Recommended calibration

The calibrated ages of Stuiver *et al.* (1991) are based on;

1. age anomalies found between ^{14}C and U/Th dates of coral, and
2. geomagnetic paleointensity derived from marine sediment.

In summary, while assumptions of past uniform ratios of $^{14}C/^{12}C$ in the atmosphere may be incorrect, study of the evidence of variation provided by proxy data and geomagnetic modelling can provide information with which to make corrections. While the corrections may be useful in defining an absolute chronology for late-Pleistocene events, it may be best to continue using the uncalibrated dates currently in the literature. This is done now by the use of the Libby radiocarbon half-life convention (5,570 yrs) in spite of its known inaccuracy of approximately 3 percent from the recalculated half life of 5,730. If the recalculated half-life were used, the current chronologies would only be ~7% different from the suggested calibration of Stuiver *et al.* (1991).

b. Variations due to datable material

The largest problem with datable organic material is the introduction of contaminants. They may be introduced at any or all of several stages in the lifetime of an organic deposit and the stage at which a contaminant affects a sample may be specific to the type of deposit. Contaminants may be assimilated while the organism is alive, during burial and diagenesis, collection and storage, or processing.

i. Contaminants introduced during the life of the organism and during burial.

Fractionation of carbon isotopes occurs when a plant takes up certain isotopes preferentially during photosynthesis. Most plants seem to fix ^{12}C more easily than ^{14}C during photosynthesis, but the degree of preference varies between species (Bradley 1985). An assessment of the fractionation effect can be made by measuring the ^{13}C content of a sample as the fractionation of ^{14}C is very close to twice that of ^{13}C. Measurement of ^{13}C present is relatively easy because it usually occurs in quantities great enough for a mass spectrometer to detect. Content of ^{13}C is generally expressed as a departure from a Cretaceous limestone standard, the Peedee belemnite, so that:

$$\delta^{14}C = 2\delta^{13}C = \frac{(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{PDB}}{(^{13}C/^{12}C)_{sample}} \times 10^{3}‰$$

A difference of 25‰ in $\delta^{13}C$ would appear to produce an age difference of ~400 years. The reference value adopted is -25‰, the reference value for wood. Comparison of dates is possible by the adoption of this reference although publications often do not indicate whether corrections have been made; this is a problem that can lead to misinterpretations (Bradley 1985).

Another problem which has been noted is the "hard water effect". This occurs when aquatic algae and vascular plants take up carbon from water containing bicarbonate derived from old inert sources, such as from old peat bogs or from limestone and other calcareous rocks (Bradley 1985). The water in these areas has a much lower $^{14}C/^{12}C$ ratio than the atmosphere, sometimes causing dates on the aquatic organics to differ in apparent age by several thousand years, in comparison to terrestrial organics. Some authors (e.g. Jackson 1979, Mott and Jackson 1982) have assumed that mosses from hardwater aquatic environments containing ^{14}C-deficient bicarbonate are reliable materials for radiocarbon dating. Experimental studies have shown that mosses are incapable of directly using bicarbonate (e.g. Glime and Vitt 1984, cited in MacDonald *et al.* 1987). They take up their carbon as dissolved carbon dioxide directly from the water. Postulating that the carbon dioxide in the water is atmospheric in origin, some workers (e.g. Jackson 1979) felt that the dates derived from the mosses were reliable. However, dates received from a six-metre lake core taken in the southwestern foothills of Alberta seem to throw into question the reliability of moss-derived dates (MacDonald *et al.* 1987). Although the dates derived from aquatic organics were internally consistent, they produced ^{14}C ages significantly older than terrestrial macrofossils found at similar levels. The age differences ranged from approximately 1,400 to 6,400 years but did not have a linear relationship. Modern bryophytes growing in the lake had less than 85 percent modern ^{14}C, giving dates of up to 1,640 ±60 yrs B.P. Moss from 5.35 m gave a date of 16,130 ±80 yrs B.P. whereas wood from 0.50 m deeper produced a date of 10,400 ±70 yrs B.P. The non-linear relationship indicates that the aquatic-organic dates cannot be calibrated. MacDonald *et al.* (1987) speculated that the incorporation of ^{14}C deficient carbon by the mosses can be facilitated by the processes that produce isotopic equilibria of carbon species in water. When the pH is lower than seven, the carbonate equilibrium reaction which generates ^{14}C-deficient CO_2 (#1) is favored making the ^{14}C-deficient CO_2 available for uptake by the bryophytes.

$$1.\ CO_2 + H_2O = H_2CO_3,\quad 2.\ H_2CO_3 = H^+ + HCO_3^-,\quad 3.\ HCO_3^- = H^+ + CO_3^{2-}$$

Also, if the pH of the bicarbonate-rich ground water is higher than that of the lake, CO_2 can be generated from the HCO_3^- in the ground water as it enters the lake (see #3) (MacDonald *et al.* 1987). Only the conditions of high lake pH and low groundwater pH would favor the production of bicarbonate (#2). The use of aquatic macrofossils (e.g. mollusc and gastropod shells) from hard water environments would also seem to be suspect. Contamination could occur during growth as the larger aquatic organisms would ingest the ^{14}C-deficient lacustrine vegetation and phytoplankton as food. No comparative studies are available for lacustrine shells, but marine shells are known to demonstrate reservoir effects of between 570 and 750 years, depending on location (Hjort 1973, Mangerud and Gulliksen 1975). The reservoir effect is most noticeable where there are several types of datable material present. At a site where charcoal, mollusc shells, *Lama guanicoe* (guanaco, a lama relative) bones, and *Arctocephalus australis* (sea lion) bones were present, the marine-derived material (*Arctocephalus australis* feeds on marine fish) consistently dated older than the terrestrial material (*Lama guanicoe* and charcoal) (Albero *et al.* 1986). All species which feed from an environment subject to the reservoir effect will, therefore, produce spuriously old dates no matter what trophic level they occupy. In a study from west-central Alberta, Mandryk (1990) accepted dates from samples of lacustrine aquatic macrofossils because they are in correct chronological order with a bulk-dated sample of organic mud (gyttja). This is in spite of the fact that the lake is located on carbonaceous bedrock and has ground water as its major source of water. MacDonald *et al.* (1987) demonstrated that, from a site to the south of Mandryk's, dates on contaminated material are internally consistent. Organic material tested would have no exemption from the hard water effect just because it is a macrofossil because it would still obtain its organic carbon from a contaminated source and would therefore be contaminated. Other aquatic sites in western Alberta have also produced dates in excess of 14,000 yrs B.P (White *et al.* 1979). Since then, it has been discovered that these sites were contaminated by organic matter of Cretaceous age during burial (White *et al.* 1985).

ii. Contaminants introduced during diagenesis

Throughout the early history of radiocarbon dating, bone dates were judged inaccurate when compared to charcoal and wood (Stafford *et al.* 1987). The inaccuracy occurs because, even though bone would seem to be an ideal material for ^{14}C dating (due to the fact that it contains twenty percent protein by weight), fossil bone can lose most of its original organic matter and frequently contains contaminants having different ^{14}C ages (Stafford *et al.* 1987). As well, different fractions from bone are known to be discordant with each other. The mineral portion is easily contaminated, so efforts were re-directed toward the organic fraction. The initial pretreatments performed on the bone samples were thought to be inadequate, so more bone-specific treatments were developed. Dates on organic fractions, left as HCl-insoluble residue, were used after treatment with NaOH. Extraction of bone protein (collagen) by decalcification using chelating agents was also tried (Stafford *et al.* 1987), leaving a "weak-acid insoluble residue" that was often contaminated with humates. The collagen is also unstable and will decay into amino acids which are more soluble than the collagen. These amino acids can be contaminated by foreign amino and humic acids (Beukens, pers. comm.). The major analytical problem is how to separate the collagen from all amino and humic acids. A second problem is the contamination by old carbonate. The use of either NaOH or conversion of collagen to gelatin, with subsequent gelatin extraction, were attempted as remedies to humic acid contamination. Recently, rigorous methods for isolating organic fractions (such as chromatographic extraction of total collagen-derived amino acids and the isolation of individual amino acids) have been accomplished (Klinken and Mook 1990). The most widely used and accepted method at present is the Longin method. This method involves;

> 1. the dissolution of the inorganic matrix of the bone in warm HCl,
> 2. washing the residue to remove carbonates and then all amino and humic acids (the stage where these two different components are removed is indicated by a change in pH)
> 3. to ensure the removal of all humic acids the collagen is dissolved in warm, acidified water, centrifuged,dried, and combusted.
>
> (from Beukens, pers. comm.)

The repeated washing results in the loss of collagen, but this is not a problem with good samples. Beukens (pers. comm.) cited the Lyon laboratory's analysis of their data base of "good" dates showing that 80% of all bone dates were acceptable to the submitters; while the acceptance of wood and charcoal dates was 60 percent, undifferentiated organics in soil 38%; and burned or calcined bone 27 percent. He elaborated, saying that the "reliability of the bone, wood, and charcoal dates are (sic) actually the same (no contamination) but bone gives better results, according to the submitters because it dates events directly, while wood and charcoal usually date events by association". Evin (1990, p. 78) states that,

> "Therefore 35,000 yr B.P. has to be considered the practical limit of the classical radiocarbon dating method. Older dates may be obtained by the radioactivity counting technique only from the cellulose of wood. Organic matter from unburnt bones may also give reliable results beyond 35,000 yr B.P. by the A.M.S. procedure"

The post-depositional contamination of shell is somewhat more difficult to determine. The shells of most molluscs are made of aragonite which may dissolve and be redeposited in the stable crystal form of calcite. During this process, exchange of carbon takes place and the sample is thereby contaminated (Bradley 1985). Chappell and Polach (1972,) noted that recrystallization can occur in two different modes; an open system which is susceptible to ^{14}C contamination, and a closed system which is internal and involves no contamination. The first process tends to be concentrated around the sample margins, and so a common strategy is to dissolve away the surface material of the sample with hydrochloric acid and to date the remaining material. Greater amounts of leaching may be required for old samples and even repeated leaching may not produce a reliable result. For very old samples (infinite aged), only 1 percent contamination by modern carbon will give an apparent age of 37,000 years (Bradley 1985). Unfortunately, the amount of contamination may vary between species, as some exhibit a "tight" shell matrix which may be resistant to post-depositional contamination (Barnosky *et al.* 1987). For these reasons, many investigators consider that dates of >25,000 years on shells are essentially infinite in age.

iii. Collection and storage

Several precautions can be taken to minimize contamination during collection and storage and should be strictly adhered to. These are especially important when microgram quantities are required for AMS dating. A common procedure for staff of the Quaternary Paleontology Department, at the Provincial Museum of Alberta, is to handle samples only with clean forceps. Once collected, samples should be air-dried as quickly as possible in order to avoid mildewing or fungus (Arnold pers. comm.). Sample containers should be sterile and not used more than once to avoid mixing or microorganism growth. Measures should be taken to prevent handling by unqualified staff. Sample labels should be kept on the outside of containers in case the sample is wet and the ink water-soluble.

iv. Contamination during processing

As dating techniques have been refined it has become possible to test for contamination during sample preparation and processing. Close attention to these details has recently allowed investigators to ascertain realistic limits for radiocarbon dates on uncontaminated material. Evin (1990) evaluated the different kinds of material used for ^{14}C dating, plus old (standard counting techniques) and new methods (enrichment method) of sample preparation, in order to estimate the reliability of the oldest of the published radiocarbon dates. He felt that since a natural radiocarbon content of under 2 percent of the modern level is present at 35,000 yr B.P., older samples are extremely sensitive to contamination. Beyond 35,000 yr B.P., even very good material will often give problems except when very selective pretreatment can be used. He suggested that the practical limit of the classical radiocarbon dating method be 35,000 yr B.P. The only material from which older dates may be obtained by the radioactivity counting technique is wood cellulose. Collagen from unburned bones may also give reliable results beyond 35,000 yr B.P. by the AMS procedure, but all other material must be discarded as unreliable. One of the problems in dating very old samples is that coal is used as a background material, in some laboratories, to establish an infinite age calibration. When CO_2 made from an infinite-aged material is introduced into a counter, it is assumed that all counts of radioactive disintegrations are from background radiation sources. Lowe (1989, p. 117) stated that "many ^{14}C dating laboratories have established that coal samples exhibit a finite ^{14}C age apparently caused by contamination of the specimens before any laboratory preparation is undertaken". He considered that fungal and microbial contamination was a possible cause and suggested that other materials (such as geologically-derived graphite) be used. Beukens (1989) also found that many "infinite" aged materials would produce finite dates. A date of 58,000 ±1,200 was obtained for cylinder CO_2 (made from natural gas), indicating intrinsic contamination during the graphitization stage at 0.001 percent. Wood fragments and calcites gave dates in the 52,000 - 53,000 yr B.P. range. Fossilized Redwood of Tertiary age, from Axel Heiberg Island, produced a spuriously young date of 49,500 ±680 yr B.P. It is apparent that many "old" materials exhibit low, but very real levels of contamination. Beukens (pers. comm.) concludes that sample processing contributes ≤ 0.15 pMC, which does not significantly affect the result for $\leq 30,000$ yr B.P. samples.

2. Taphonomy and Pleistocene biostratigraphy

i. Taphonomy

A new direction in the field of paleo-life sciences is the field of taphonomy. At one time, study of past life was dominated by paleontologists whose main interest was the collection, description, and display of specimens. They tended to assume that analysis of these specimens gave a reasonable approximation of the organism's life and evolutionary patterns (Behrensmeyer 1984). However, a great deal of the paleoenvironmental evidence associated with fossils is lost in the processes of:

1. Death - when a sector of a population experiences a higher or lower mortality.
2. Interment - ascertaining if a community is poorly represented in the fossil record due to its habitat (plains vs. swamps).
3. Fossilization - recognition that some species may preserve better in a particular environment, such as a robust animal in an area dominated by high energy fluvial systems.
4. Excavation - where sampling techniques such as using large screens would favour the recovery of large animal elements, biasing the paleoecologic sample.
5. Interpretation - biases could be introduced by a particular worker as each has his/her own area of expertise.

As fossils are paleoecological samples, processes at each of the stages will act to bias the sample. The goals of taphonomy are to understand the origins and to correct the biases of the natural paleoecological sample (Wolff 1981). It is not possible to study all aspects of a fossil's passage through time, but it is important to try to observe whatever additional information is present. The study of all aspects related to a fossil discovery is therefore taphonomic in nature as it offers the possibility of adding to the understanding of past processes.

Vertebrate burrow trace-fossils

Fossil vertebrate burrows are not widely reported in paleontological literature. This is in spite of the fact that a large proportion of living vertebrates, particularly mammals, excavate burrows (Voorhies 1975). Voorhies speculated that the dearth of information on vertebrate burrows may be due to:

1. Lack of detailed observations.
2. Tendency of burrowers to avoid areas of active sedimentation.
3. An evolutionary increase in the burrowing habit as a result of Cenozoic climatic change.

In a study of Pliocene rodent burrow casts (krotovinas) from Nebraska, Voorhies (1975) noted that the burrows had been infilled by a volcanic ash. The burrow casts were located in a sandy eolian deposit and the ash occurred as an overlying layer. The rodents did not penetrate the ash layer, so the burrows must have been open and active before the ash fell. An absolute age determination for the ash would therefore give a minimum age of the rodent occupation. Thorpe (1949) noted some burrow casts in Colorado. In this case, the fill material was the dark organic-stained soil occurring at or near the surface. The soil would have been in place while the burrow was open. In both instances, the relative age of the burrowing activities can be estimated. If the rodents penetrated the overlying unit, it must have been in place while the burrow was occupied. If the overlying unit was not penetrated by the rodents, then it was deposited after (or during) the death of the colony.

Study of the structure of living, occupied burrow systems may be helpful in reconstructing the incomplete systems of fossil burrow casts of related species. Burns *et al.* (1989) noted that the architecture of burrows of the white-tailed prairie dog (*Cynomys leucurus*) is poorly known. In excavations of active burrows in southern Montana, they noted several structures in the tunnels which they thought might function as "turning bays", "sleeping quarters", "hibernacula" and a "maternity area". Evidence indicating how horizontal burrows may migrate upwards was observed. In cross-section, the burrow floors were underlain by a series of crescent-shaped laminations. Burns *et al.* (1989) postulated that as the animals moved along the tunnels, they would inadvertently rub against the walls and ceiling, knocking material loose. The material would compact at the bottom of the burrow, causing the burrow to migrate progressively upward. Population densities of animals and burrow systems was found to be low, as well as the actual rate of digging new burrow tunnels. Burrows were found to depths of about 2.4 m below the burrow entrance. The entrance was located on a mound piled up by the prairie dogs, so that the actual maximum depth below surface was somewhat less (about 2 m).

ii. Pleistocene biostratigraphy

Fossil mammal remains dominate the Quaternary terrestrial paleontologic record, so the emphasis in paleontologic and biostratigraphic work has been directed towards them. Because they are almost completely restricted in occurrence to association with sediments, including tephra, and extrusive volcanic rocks, their study is governed by the principles of Superposition, Original Horizontality, and Original Continuity of Sedimentary Strata formulated in 1669 by Nicholas Steno (Woodburne 1987). Smith (1815, cited in Woodburne 1987) recognized that another fundamental concept for the study of fossil mammals is the Principle of Paleontological Correlation. This means that "Biologic remains contained in, or forming, strata are uniquely important in stratigraphic practice. . . they provide the means of defining and recognizing material units based on fossil content (biostratigraphic units)". These are comparable to the material lithostratigraphic units, defined, characterized, and recognized on the basis of lithologic content and are interpretive only in that species limits (i.e. identifying a species in time and space) require interpretation. Evolution is irreversible, making it possible to partition enclosing strata temporally, and thereby to recognize a given interval of time from place to place, and to propose a correlation on that basis. A biostratigraphic unit thereby becomes a chronostratigraphic unit (which is still interpretive as it is based on paleontologic data). Therefore, a direct link exists between biostratigraphic and chronostratigraphic units, although chronostratigraphic units can be based on any kind of time-significant information (Woodburne 1987).

Pleistocene biostratigraphy starts at the beginning of the Irvingtonian land mammal age (at about the Olduvai subchron), falling within a time span between 1.6 and 2.0 Ma (Lundelius *et al.* 1987). The beginning is partly characterized by a gradual extinction of several genera that did not survive into the Irvingtonian, an extinction that began somewhat before the end of the Blancan. The slow extinction event began at around the time of the Gauss chron (late Blancan, 2.47 Ma) These included *Dipoides, Ogmodontomys, Nebraskomys, Pliolemmus, Pliopotamys,* and *Pratilepus.* Several more genera disappeared at the start of the Irvingtonian (early Matuyama chron, 1.88 Ma). These include *Paenemarmota, Procastoroides, Prodipodomys, Pliophenacomys, Ophiomys, Mictomys, Hypolagus, Borophagus, Rhynchotherium, Equus (Dolichohippus),* and *Nannippus.* The youngest occurrence of *Borophagus* was from the Wellsch Valley (southern Saskatchewan) Local Fauna where it apparently persisted into the Olduvai subchron (Lundelius *et al.* 1987). The faunal transition was gradual as some genera disappeared before the Olduvai subchron, while characteristic Irvingtonian genera such as *Mammuthus, Euceratherium, Soergelia, Tetrameryx, Smilodon,* and *Lepus* began to appear in North American faunas. The Rancholabrean Mammal Age is named for the Rancho La Brea Local Fauna of California (Lundelius *et al.* 1987). The faunas are characterized by the presence of *Bison* and many recently extinct genera and/or species of larger mammals, such as *Smilodon fatalis, Panthera leo atrox, Canis dirus,* and *Mammuthus.* As well, many extant species of carnivores and rodents made their appearance at the start of the Rancholabrean. Several Eurasian immigrants to North America included *Oreamnos, Ovis, Ovibos, Alces,* and *Homo.* There is no good basis for an absolute chronology of the beginning (age estimates range from 0.2 to 0.55 Ma) or main duration of the Rancholabrean Mammal Age. However, its termination is fairly well dated as it falls in the range of radiocarbon dating. Divisions for most of the Rancholabrean have relied upon attempts to fit faunas into a four-fold glacial-interglacial framework tentatively correlated with that of Europe (Kurtén and Anderson 1980, Lundelius *et al.* 1987) on the basis of the paleoenvironmental interpretation of a given fauna. Glacial phases include; the Nebraskan (1.5 to 1.2 Ma), the Kansan (0.85 to 0.7 Ma), the Illinoian (0.6 to 0.3 Ma), and the Wisconsinan (0.1 to 0.01 Ma).

The practice of referring faunas to either a glacial or interglacial stage has become questionable in light of the idea by Graham and Semken (1976) that the climate on the Great Plains may have been more equable during certain glacial phases than during a typical interglacial. This would have resulted in local faunas that do not seem "arctic" in nature because of apparently incompatible or disharmonious elements. Also, short-term climatic fluctuations may go unrecognized or, if recognized, may be difficult to date (Lundelius *et al.* 1987).

The discovery of two tills below the type Nebraskan till has cast doubt on the four-fold glaciation hypothesis long in vogue for the North American Quaternary. A drill core revealed two tills underlying the classic Nebraskan till in the type region, Iowa. The tills are overlain by three volcanic ashes. The oldest ash named, simply, the ash at Afton Iowa, produced a fission-track date of 2.2 Ma (Easterbrook and Boellstorff 1982). Overlying the Afton ash are Pearlette "B" and Pearlette "S" which produced dates of 2.0 and 1.2 Ma, respectively. The Nebraskan till lies stratigraphically above these three ashes. Overlying the Nebraskan till are Pearlette "O" and Hartford ashes which are dated at about 0.6 to 0.7 Ma, respectively. Classic Kansan till overlies the two younger ashes. A Local Fauna commonly designated as late Kansan lies immediately below the 0.6 Ma ash and is therefore approximately Aftonian in age. The facts that the Nebraskan till does not represent the earliest North American continental glaciation, and the differentiation of at least seven tills within the type "Nebraskan-Kansan" sequence, demonstrate that these terms are meaningless in the classic area. The glacial age designations (if they mean anything at all) are obviously misaligned with respect to the till sequences and the terms "Nebraskan", "Aftonian", and "Kansan" have lost meaning as chronological units. Climatic criteria are therefore not a sound basis for chronostratigraphic or geochronologic unit divisions (Lundelius *et al.* 1987).

3. Glacial stratigraphy and ice-sheet reconstructions in central and southern Alberta and Saskatchewan

Few glaciated areas of Canada have been long studied with so little gain in consensus of findings as the western and southwestern zones of Alberta. This region is particularly interesting in the context of possible interaction between Cordilleran and Laurentide ice sheets. The relationships of deposits and landforms diagnostic of these interactions are invaluable in reconstructing absolute and relative chronologies and events in this region.

i. Quaternary stratigraphy of the southwest Continental glaciated regions

There have been numerous studies and interpretations of Quaternary stratigraphy dealing with the southwest parts of the province and adjacent Montana. Recent studies (Richmond and Fullerton pers. comm., Klassen 1989) reveal contrasting interpretations of the numbers, extents, and style of both the Continental and Cordilleran glaciations (Figure 5). This section will attempt to outline the two stratigraphies and rationale for each. It will treat them separately so reasoning and evidence for each can be in sequence. As centres of glacial dispersion for other than the Wisconsinan Continental glaciation are contentious, and the evidence for an Early Wisconsinan Laurentide glaciation are dubious, only the latest Continental glaciation is referred to as being of Laurentide provenance (e.g. Dredge and Thorleifson 1987).

Fullerton and Colton (1986) and Richmond and Fullerton (pers. comm.) find evidence of four pre-Illinoian Cordilleran and three Continental glaciations (Figure 5). Their oldest pre-Illinoian Continental glaciation is not represented

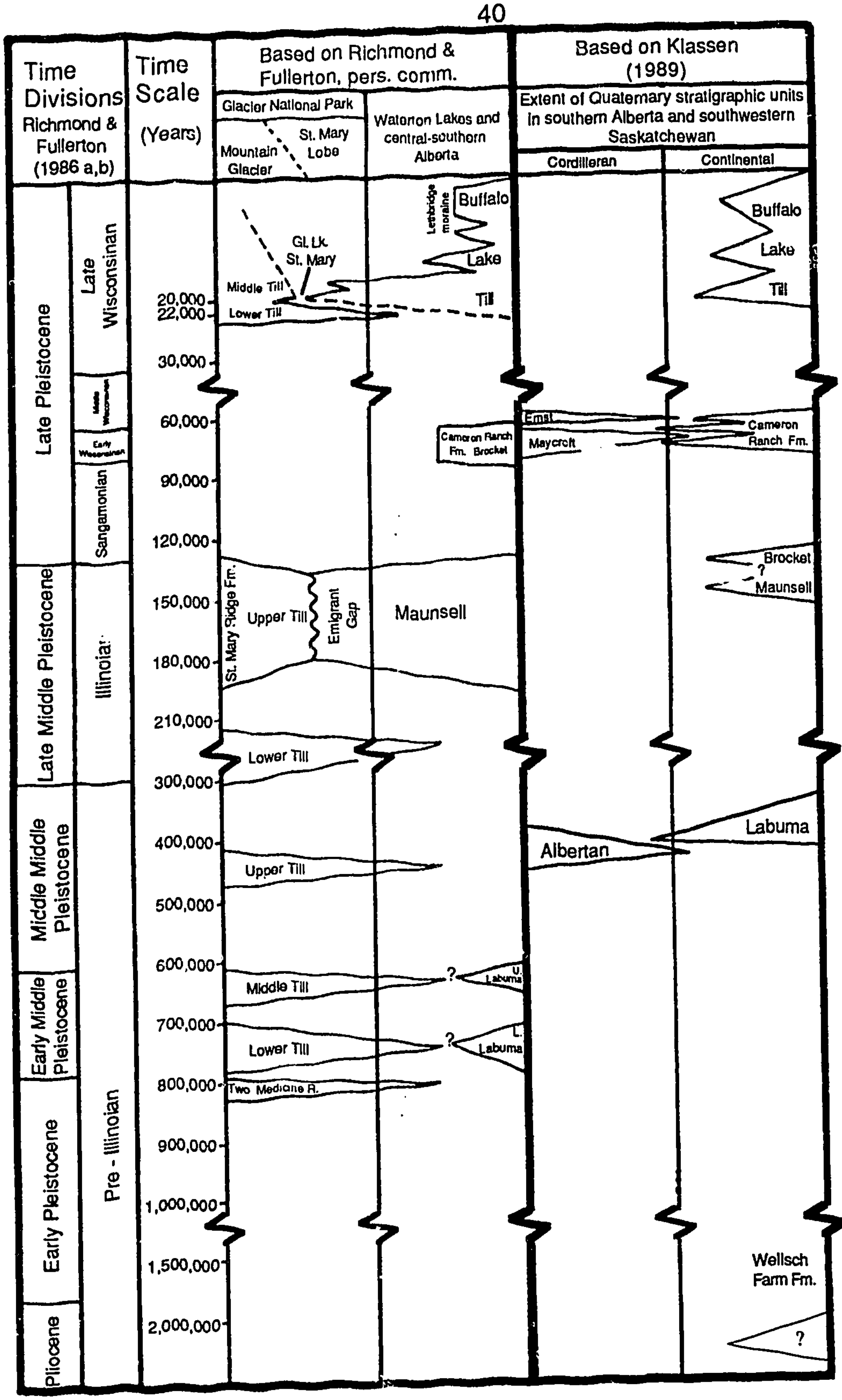


Figure 5: Two Pleistocene stratigraphic reconstructions for the southwest Continental, and southeast Cordilleran glaciated areas.

on Figure 5 as the till related to it is only found at sites to the east of their main study area (Richmond and Fullerton pers. comm.). They find the two Continental Labuma tills are distinguishable from older and younger tills on the basis of several physical properties, such as hardness and overconsolidation, intense staining, and strong jointing. However, the two Labuma tills are indistinguishable from each other on field criteria alone, except for their superposition, and alluvium between the tills. The Cordilleran tills are distinguished by the presence of intertill paleosols. Correlations of pre-Illinoian Continental and Cordilleran tills are only tentative in Fullerton and Colton's (1986 a,b) reconstruction. The Continental tills are dated on the basis of correlation of the younger two tills with till units to the east and north which underlie Pearlette "O" type ash, and Lava Creek "B" (Wascana Creek) ash, both dated at 610 ka B.P. The upper pre-Illinoian Cordilleran till has been dated, using an "Uranium trend" method, at 410 ka B.P. (Richmond and Fullerton pers. comm.).

Richmond and Fullerton (pers. comm.) distinguish the Maunsell Till by the presence of weathering zones and alluvium that overly and underly the till. It is approximately relative-dated by the presence of *Bison* fossils below correlated tills in central Montana. The first appearance of *Bison* in North America is tentatively dated at about the start of the Illinoian (Lundelius *et al.* 1987). The Maunsell till is therefore judged to represent an Illinoian glaciation. It is thought to represent the largest, most extensive Continental glaciation, and was synchronous with Cordilleran glaciation . According to Richmond and Fullerton (1986 a,b) this was the only known coalescence of the two ice masses in Montana (Figure 5).

After recently re-evaluating several lines of evidence Richmond and Fullerton (pers. comm.) now consider the Cameron Ranch Formation and Brocket Till as being equivalent Early Wisconsinan tills (Figure 5). These findings and the rationale behind them are as yet unpublished, so cannot be elaborated at present. There are apparently no equivalent Cordilleran Early Wisconsinan tills in Montana.

The Buffalo Lake Till is identified in Montana at several locations. Richmond and Fullerton (pers. comm.) correlate this till with Christiansen's (1972) Battleford Till and Stalker's (1969) "dark grey" till, both having underlying sediments which have yielded radiocarbon datable material. Finite and infinite ^{14}C dates from 21,000 to >34,000 yr B.P. have been produced from a number of sites. Although there is no evidence of coalescence of the Late Wisconsinan Laurentide and Cordilleran ice sheets in Montana, there is evidence of their close proximity. This is demonstrated by an "integrated succession of glacial lakes and drainage channels that are associated with the advances of the respective ice lobes" (Fullerton and Colton 1986, p.76). A date of 14,860 ±140 yr B.P. came from Glacial Lake St. Mary, a lake ponded between the Cordilleran and Laurentide ice masses showing the proximity of glacial ice until very late in the Pleistocene. The deposition of the Lethbridge Moraine would have been as a recessional feature according to this reconstruction sometime after about 14,000 yr B.P.

Klassen's (1989) report is based on papers written by Stalker. Stalker's analysis of stratigraphy is based on the several types of information from many sources, but strongly relies on vertebrate paleontology. Volcanic ashes are used to date various lithostratigraphic units. He also relies on paleomagnetism, but notes that only one Quaternary section has shown a paleomagnetic reversal, the rest being normal. The reversed section contains the oldest known Pleistocene sediments in southern Saskatchewan. These are three bedded units that underly four tills in the Wellsch Valley section (Stalker and Churcher 1972). A vertebrate fossil assemblage of Irvingtonian land mammal age was found in the middle unit of the three bedded units (Figure 5). The lowest bedded unit contains a pattern of paleomagnetic polarity which has been correlated with the Olduvai Normal-Polarity Subchron and on that basis has been estimated at ~1.7 to 1.8 Ma (Foster and Stalker 1976, Barendregt 1984). Deposition of the three subtill bedded units is thought to have taken a total of 10 to 20 thousand years. The presence of a substantial number of Shield stones within the bedded units, indicates that there was an earlier glaciation and that the bedded sediments are actually an interglacial deposit. An older till unit has not been found in the Wellsch Valley, but the missing unit could possibly relate to one of the lower tills of the Sutherland Group (Klassen 1989). Wide climatic fluctuations, somewhat like today's, were thought to be prevalent because the vertebrate assemblage from the central part of the unit contains both cold and warm faunal elements.

Nonglacial Middle Pleistocene sediments are identified at several sites in southern Saskatchewan and Alberta. Pearlette "O" ash (~610 ka B.P.) was interbedded with lake clay at a site in the Wascana Creek valley, Saskatchewan (Westgate *et al.* 1977). A younger fluvial unit containing an ash layer dated by fission track at 435 ka B.P. has been identified as a member of the Saskatchewan Gravels and Sands deposit at Medicine Hat, Alberta (Westgate *et al.* 1978). Ice sheets from the northeast had apparently not reached this area before 435 ka B.P. as the gravels and sands do not contain any Canadian Shield material. These gravels are dated as being mid-Kansan to Yarmouthian on the basis of vertebrate fauna. The onset of glacial conditions to the east and west of Medicine Hat is signified in the gravels by both the incorporation of mountain outwash into the upper part of these sands and gravels, and superposition of proglacial lake sediments.

Little evidence of the subsequent glaciation is available because its drift is rarely exposed (Stalker 1983). The earliest advance to reach the Medicine Hat area attained an elevation at its terminus of about 900 m in the southwestern Plains but failed to extend as far west as Lethbridge. No date is given for this glaciation.

The oldest glaciation at Medicine Hat produced till overlying the Saskatchewan Gravels and Sands. This is thought to be the Labuma till deposited by the Continental ice sheet during the "great glaciation", when both ice sheets purportedly reached their all-time limits. The unit of Saskatchewan Gravels and Sands underlying the Labuma till contains a fauna of possibly late Yarmouthian age, giving a minimum age for the till (Stalker 1976). This advance may represent the all-time glacial maximum of both the Continental and Cordilleran ice sheets, reaching elevations of 1,555 m in the southern foothills near the border with the United States and up to 1,680 m in the Porcupine Hills (Stalker 1959,1962). The Cordilleran Albertan till was deposited by a large piedmont lobe in the Waterton Lakes area. The presence of sands and silts between the Albertan and Labuma tills indicates that the Cordilleran ice had undergone substantial retreat before the Continental ice approached the mountains so that coalescence did not occur.

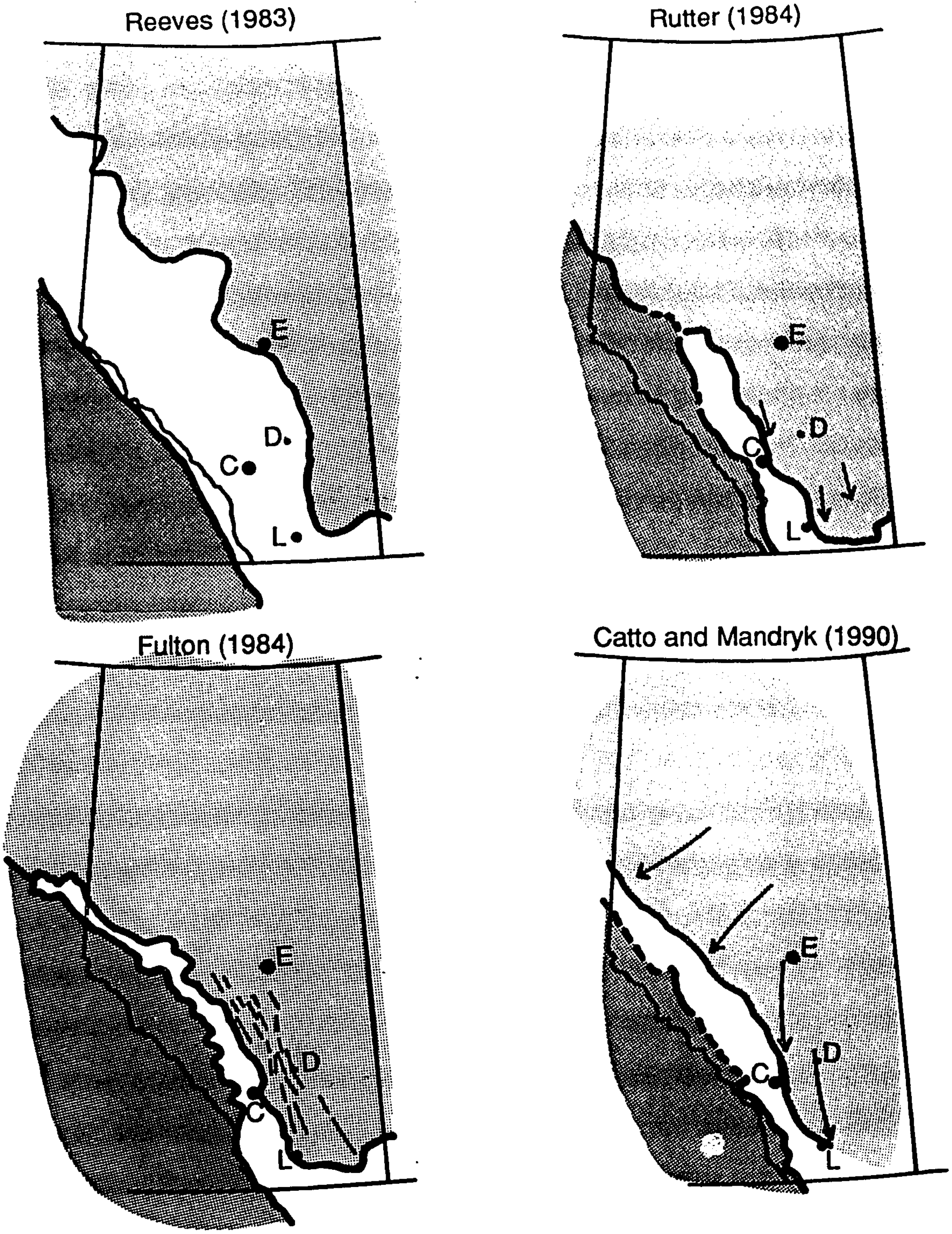
Little is known of the Brocket and Maunsell tills. They are thought to have been deposited in the latter part of the Middle Pleistocene (Figure 5). These tills are thought to represent one advance by Alley (1973) and two by Klassen (1989). No equivalent Cordilleran tills are known from this time in Klassen's (1989) reconstruction of stratigraphy (Figure 5). Stalker and Harrison (1977) viewed the next (Early Wisconsinan) glaciation as the only one to achieve coalescence between the Continental and Cordilleran ice sheets. According to this scheme, the Early Wisconsinan was the glaciation responsible for deflecting Cordilleran ice southeastward, subsequently depositing the "foothills erratics train", and leaving a pattern of associated streamlined landforms which indicate the flow direction of Cordilleran ice. Rutter (1984) tentatively designated the Buffalo Lake till as being Early Wisconsinan in age. Klassen (1989) assigned the Buffalo Lake till to the Late Wisconsinan. However, it remains that in spite of the impressive array of features attributed to the Early Wisconsinan glaciation, there are "no deposits inside or outside the limit of the last ice advance that can be proven to be Early Wisconsinan on the basis of unquestioned stratigraphic evidence or absolute dates" (Klassen 1989, p.155). The designation of the Cameron Ranch Formation Continental till and the Ernst and Maycroft Cordilleran till to the Early Wisconsinan is therefore only speculative (Figure 5).

Despite the facts that Late Wisconsinan glacial deposits make up the majority of surface materials in the Interior Plains, and that this glaciation occurred within the limits of radiocarbon dating, the extents and isochrons of the Late Wisconsinan ice sheets are matters of considerable debate. Klassen (1989) attributed the Buffalo Lake till to the Late Wisconsinan, and followed

Prest's (1969) proposal that the Lethbridge Moraine is the minimum position of the limit and that the maximum possible position of the limit lies in Montana. He based the case for this limit on two factors; that Late Wisconsinan tills apparently end there, and that surface nonglacial material from areas some distance beyond the Lethbridge Moraine are "older" than the age of the Late Wisconsinan maximum (Karlstrom1981,1986, Jackson 1983, Jackson and Pawson 1984). Stalker (1977) also supported the limit at the Lethbridge Moraine on the grounds that fresher-looking topography is found east of the moraine than to the west, and that there are apparent truncation markings and deep incision of major valleys beyond this limit. Fullerton and Colton (1986), however, found no difference in how "fresh" the topography looks on either side of the Lethbridge Moraine nor any difference in degree of valley incision. MacDonald *et al.* (1987) stated that Late Wisconsinan dates from west of the Lethbridge Moraine have been from contaminated samples, and this indicates that the western landscape is probably not significantly older than to the east.

ii. Late Wisconsinan ice limits and dynamics

Several authors have applied the available data towards reconstructions of Late Wisconsinan ice limits and their associated flow patterns and deposits (Figures 6 and 7). There are major differences of opinion over ice limits of both the Cordilleran and Laurentide ice sheets, particularly in the southwest. These are based on varying interpretations of stratigraphy and its relation to the ages of several key landscape features. Of particular interest are the ages of the foothills erratics train and associated till, and sets of northwest-southeast trending streamlined features formed by both the Laurentide and Cordilleran ice



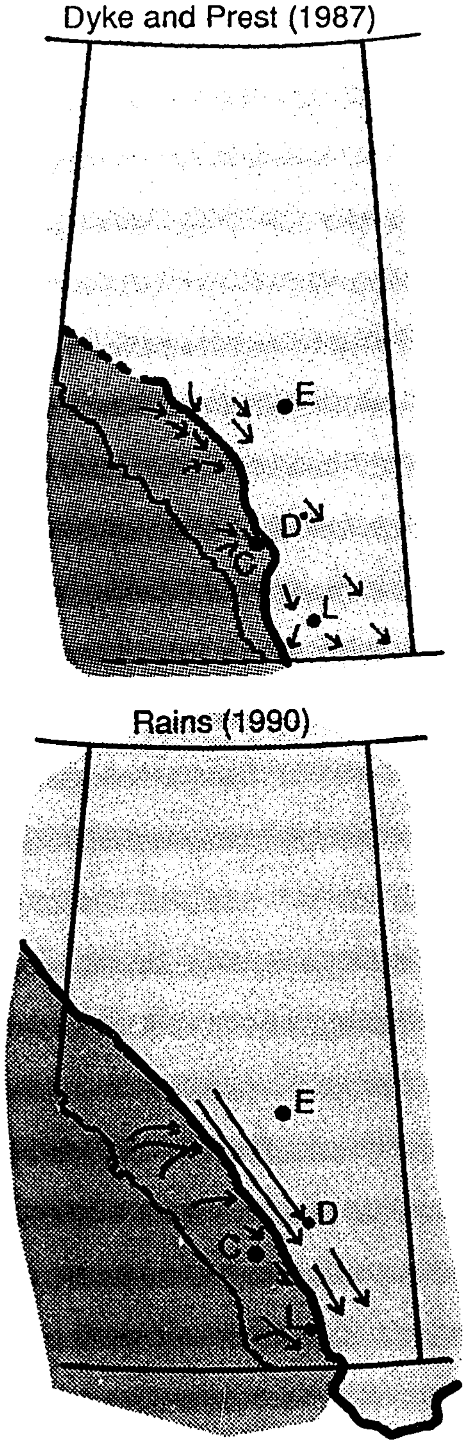
Reeves (1983)

Rutter (1984)

Fulton (1984)

Catto and Mandryk (1990)

Figure 6: A comparison of four reconstructions of Late Wisconsinan glaciation in Alberta in which the Laurentide and Cordilleran ice sheets either did not coalesce or only achieved partial coalescence. Light gray = Laurentide ice sheet, dark gray = Cordilleran ice sheet and nunataks, E = Edmonton, C = Calgary, D = Drumheller, L = Lethbridge.



Dyke and Prest (1987)

Rains (1990)

Figure 7: Comparison of two reconstructions of the Late Wisconsinan maximum glaciation in which almost complete coalescence of the Cordilleran and Laurentide ice sheets occurred. Light gray = Laurentide ice sheet, dark gray = Cordilleran ice sheet and nunataks, E = Edmonton, C = Calgary, D = Drumheller, L = Lethbridge.

sheets. These streamlined landforms run nearly parallel to the structural grain of the central and southern Alberta foothills. The foothills erratics train was originally thought to be the result of supraglacial rockfall loading of Athabasca valley ice in the Jasper area (e.g. Stalker 1985). The Gog quartzite blocks were then supposedly transported by a large, extensive tongue of ice out of the mountains and towards the southeast as the Cordilleran ice was deflected by Continental ice. Reeves (1983) felt that the Cordilleran ice did not extend eastward beyond the Continental Divide, and Laurentide ice did not go appreciably west of Edmonton at Late Wisconsinan maximum (Figure 6). He cited several Late Wisconsinan dates from lake cores taken from the southwestern foothills as evidence that ice did not coalesce at that time. No rationale is given to explain his placement of the glacial limits, but that reconstruction does not allow for coalescence at any time during the Late Wisconsinan. Reeves (1983) maintained that during the Late Wisconsinan maximum, an "ice-free corridor" persisted between the main unglaciated parts of Alaska and Yukon to areas south of the Laurentide ice sheet, thus allowing easy southern access for flora and fauna.

Rutter (1984) chose the Lethbridge Moraine as the Late Wisconsinan Laurentide limit, citing relative freshness of topography and the Late Wisconsinan lake-core dates from the foothills. His reconstruction shows non-coalescence for the whole southwest to as far north as the Hinton area, Alberta (Figure 6). During the Late Wisconsinan maximum, ice flow along the southwestern margin of the Laurentide ice sheet was from northwest to southeast, as indicated by numerous streamlined features on the ground (Plate 1). Rutter (1984) maintained that Cordilleran ice extended only to near the foothills, terminating as minor piedmont lobes. If that interpretation was correct then the northwest-southeast trending streamlined features, formed by Cordilleran ice farther east, must be older than Late Wisconsinan. Rutter (1984) also referred to the relatively narrow opening, in his reconstruction, as "the ice-free corridor".

Fulton (1984) roughly agreed with Rutter (1984) on the distribution and flow directions of Late Wisconsinan Laurentide ice. His non-glaciated "corridor" is, however, [illegible] different than Rutter's in being relatively narrow and long. He [illegible] Cordilleran ice to be more extensive in the south, and less extensive [illegible] Flow at maximum was interpreted as almost parallel to the terminus of the Laurentide ice sheet from west of Edmonton to south of Lethbridge, a distance of over 500 km (Figure 6).

Catto and Mandryk (1990) agree with Reeves (1984) that no coalescence of the ice sheets occurred during the Late Wisconsinan. Their Laurentide ice limits, however, more closely agree with those of Fulton (1984) and Rutter (1984) who showed some coalescence. The reconstructions of Catto and Mandryk (1990) show flow directions at glacial maximum to be markedly different than those proposed by Fulton and Rutter. Rather than flowing from northwest to southeast, paralleling the Laurentide terminus (as proposed by the previous two authors), a somewhat radial flow pattern was envisaged from assumed dispersal centres to the northeast. The interpreted direction of Laurentide flow turned towards the south-southeast near its proposed western and southern limit (Figure 6). All of the Laurentide termini postulated by the previously noted authors occur at nearly the same elevation, about 975 to 1,005 m (3,200 to 3,300 ft) asl following at least that length of the foothills from the Edson area (west of Edmonton) to south of Lethbridge.

Dyke and Prest (1987) accepted evidence for Cordilleran coalescence along the western edge of the Laurentide ice sheet during the Late Wisconsinan maximum (Figure 7). That reconstruction shows a predominantly northwest-southeast flow direction for the near-marginal southwestern Laurentide ice sheet, beginning as far north as directly west of Edmonton. This flow direction was thought to have been the result of coalescence with, and deflection by, a large piedmont ice lobe issuing from the Athabasca Valley. Their Late Wisconsinan Laurentide terminus lay far to the south in Montana, consistent with the stratigraphic reconstructions and rationale of Fullerton and Colton (1986).

Rains (1990) and Rains *et al.* (1990) favoured nearly complete coalescence and ice flow patterns very similar to those of Dyke and Prest (1987). However, there is some divergence in opinion as to the relative extents of separate mountain valley glacier systems. These authors argue that the Athabasca Valley piedmont was only one of several Cordilleran lobes responsible for the southeast deflection of Laurentide ice west and southwest of Edmonton. Major basins, such as the North Saskatchewan and Bow, south of the Athabasca valley, produced discrete piedmont lobes that coalesced with, and helped deflect, the Laurentide ice sheet. Smaller piedmonts from such valleys as the Brazeau, Red Deer, Oldman and Waterton, were probably of minor importance in that respect. The almost continuous pattern of southeast trending streamlined features formed by mountain-based ice and/or subglacial meltwater (Rains *et al.* 1990) may have been the generally near-synchronous product of discrete valley lobes about the time of maximum Late Wisconsinan glaciation (Figure 7).

iii. Reconstructions of ice-sheet profiles

Mathews (1974) noted that surface slopes of ice lobes can be estimated from the gradients of their ice limits, contemporaneous recessional moraines, or lateral melt-water channels. Approximations of profiles can be fitted to a parabola with the formula;

$$h = Ax^{1/2}$$

in which h is the height above the terminus, x is the distance upstream of the terminus, and A is a coefficient that varies from glacier to glacier. For example, the value for the coefficient A is calculated for segments of the Antarctic and west-central Greenland ice sheets at 4.7 $m^{1/2}$ (Figure 8).

Several ice-sheet lobes of Laurentide origin exhibit values of only 0.3 - 1.0 $m^{1/2}$. These low values indicate a basal shear stress of only about 0.07 to 0.22 bar. Profiles were derived from matching the outermost deposits of Continental ice sheets with the highest glacial deposits on any of several nunataks in northern Montana and southern Alberta, producing A values from 0.67 to 1.0 $m^{1/2}$ (Figure 8).

More generalized Laurentide ice sheet profiles in Alberta, depicted with large vertical exaggeration, were estimated by Rains (1990). These allow very conservative approximations of the ice sheet thicknesses at the Late Wisconsinan maximum, and during several phases of subsequent deglaciation.

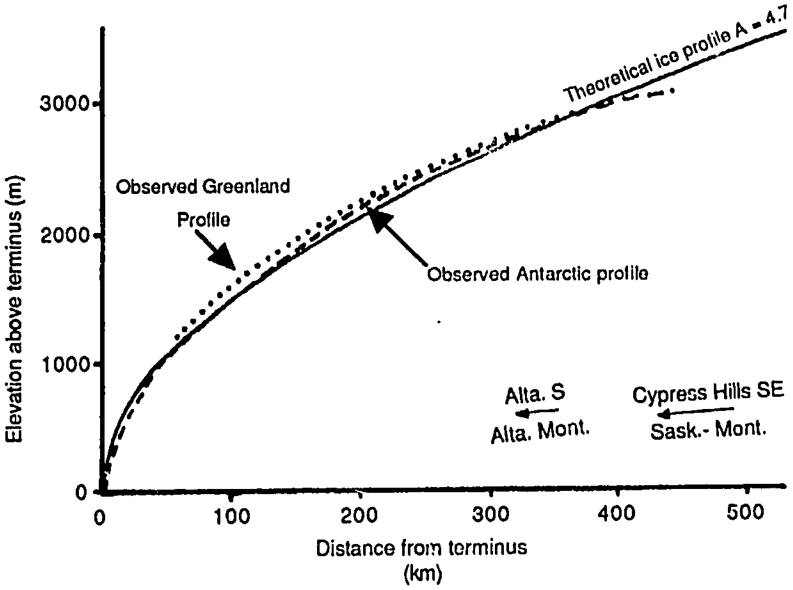


Figure 8: Height of present or former ice surfaces at various distances up-stream from the termini. Based on Mathews (1974)

4. Laurentide processes, landforms and sediments

Introduction

When evaluating landforms and deposits left by past glaciations, the use of models is essential. Although actualistic studies may be a reliable method of relating landforms to glacial processes, the range of observations that can be made is extremely small. This is because most processes occur in subglacial positions that are inaccessible, and because modern analogues of past events may not be attainable. For example, the present Antarctic ice sheet cannot be used as a surrogate of the Laurentide.

Shaw (1988, p.1) discussed the use of models and the way they can be applied. A broad-brush approach to glacial modeling "involves painting the general succession expected of a cycle of glacial advance and retreat". This would raise the expectation that proglacial sediments be succeeded by subglacial sediments which, in turn, would be succeeded by supraglacial and finally proglacial sediments. But due to erosional or nondepositional phases, the probability of all events being preserved is low. Even in extreme cases, such as near the former margins of the Laurentide ice sheet where, the processes of deposition are supposed to have been dominant, there are large areas which contain virtually no glacigenic sediment. Thus, the modeling approach may also be found wanting as it fails to provide details on sediments in particular associations, such as the subglacial association. An example of the subglacial association is that although drumlins have been recognized as subglacial landforms, the possibility of predicting the associated sediment on the basis of form alone is low.

Shaw (1988) felt that a bridge was needed between process/properties studies and the notion of environmental successions with the advance and retreat of the ice sheets. A partial solution to the problem has been provided by the concept of sediment/landform associations. There are some severe limitations to this approach as it is not yet possible to place some associations into particular environments (Shaw 1988). This approach causes theory to lead observation as models are based on fictitious or imaginary sequences representing sediments the way they ought to be rather than the way they actually are.

There is a suggestion that empirical models may be useful. Shaw (1988, p. 3) cautions that the rather restricted observational base for glacigenic sediments means that empirical models must "be preliminary and seen as guiding the way rather than presenting a *fait accompli.*" Models should then serve as maps - guiding exploration, with each discovery improving the quality of the map or extending it (Dott 1988). The models should then be built on observations, the interpretation of which is always somewhat speculative. As many of the processes in glaciation are not usually observable, there always has to be imaginative inference used for interpretations. The validity of these models can only be tested against observations of the landform/sediment associations that they were invented to explain.

Landform zonation schemes based on mapped landforms and deposits for the inner parts of former ice domes of the Laurentide ice sheet have been devised by Aylsworth and Shilts (1989) and Bouchard (1989), among others. The zones reflect interpretations of the former glaciological and glacial hydrological conditions. Although the two models differ slightly, they show sufficient similarity to suggest a general model for the inner parts of ice domes when applied to a retreating ice mass around or on the Canadian Shield (Shaw 1988).

Zone 1 (outermost)

This zone is characterized by either no or few glaciofluvial deposits and the presence of unpatterned thick drift (Shilts *et al.* 1987, Bouchard 1989, cited in Shaw 1988). The landforms are typically till plains and chaotic low till hummocks with an absence of eskers and Rogen moraines (Shaw 1988).

Zone 2

Well developed Rogen moraines and drumlins, occurring in distinct fields oriented parallel to the ice flow, are found in this zone. Dense networks of large eskers are also prominent features in this zone. A transition between zones 1 and 2 has been identified by Bouchard (1989), and is typified by mainly longitudinal forms such as drumlins and flutings (Shaw 1988).

Zone 3

This zone is dominated by an intricate dendritic pattern of eskers with drumlin fields and widely dispersed fields of Rogen moraines. Less frequent Rogen moraines, and decreasing size and spacing of eskers, occur in zone 3 compared to zone 2. Tunnel valleys aligned with or containing eskers are prominent features, and drumlins in this zone may be either depositional or erosional (Shaw *et al.* 1989). Broad areas of kettled outwash commonly lie directly adjacent to and on the same bedrock as drumlin fields. Large and complex moraines, with abundant glaciofluvial sediments, are produced in this zone by the coalescence of ice-contact fans or fan deltas. Short esker segments also occur in the outer fringe region of zone 3 (Shaw 1988).

Zone 4 (innermost)

Areas of little postglacial sedimentation coupled with extensive bedrock outcrops characterize this zone. However, areas of exposed bedrock or thin drift also occur within zones 2 and 3 in places between drumlins and in areas of bedrock fluting, and alongside eskers (Shaw 1988).

It is then necessary to study the sedimentary record of each of the zones, and, when done, to attempt a unified explanatory model for the sediments and landforms. Since no direct observation is available on the subglacial processes that produced these, understanding must come from interpretation of the sediments and landforms themselves. Unfortunately, the origin of individual landform types is poorly understood, so that inharmonious hypotheses exist for spatially related landforms. Shaw (1988) noted that Rogen moraines have been attributed to englacial folding in compressive flow zones, while drumlins have been speculatively assigned to subglacial meltwater effects. Hummocky moraine has been attributed to both supraglacial and subglacial processes. These landforms have been found as an apparent continuum in places and occasionally have the added complication of superimposed subglacial flutings.

Drumlinised and large-scale oriented complexes

Although the origins of many types of drumlins are enigmatic, there are some cases where drumlins can be demonstrated to include pre-existing sediment or bedrock. These drumlins discount theories of formation which include pervasive subglacial tectonics, because the material they are made of is undeformed. The drumlins are likely the result of erosion and are residuals with surrounding material having been eroded away. The numerous shapes of drumlins have not been adequately explained, but large-scale streamlined features have shown a similarity to erosional forms produced by turbulent flows (Sharpe 1987). Such drumlins also occur in close association with tunnel valleys and eskers, providing evidence consistent with formation of some drumlins by subglacial meltwater sheet floods (Shaw and Kvill 1984, Shaw *et al.* 1989).

Hummocky moraine

The close association of hummocky moraine with drumlins has been noted in the Prairies of western Canada (Gravenor and Kupsch 1959, cited in Shaw 1988). Shaw (1988) also noted that several authors have observed similarities between the diamictons of hummocky moraine and basal till. Some (e.g. Hoppe 1952, cited in Shaw 1988) have argued that the material in many hummocks is actually basal till squeezed into subglacial cavities by the ice overburden pressure. Evidence from fabrics and the details of hummocky relief from Hoppe's site tend to support this view. Hoppe (1952) also provided observations from modern glaciers to demonstrate the plausibility of the mechanism. Stalker (e.g. 1973) also argued for subglacial formation of hummocks by ice pressing. Some (e.g. Clayton and Moran 1974) contended that hummocks are the result of redistribution of surface debris as the glacier down-wastes. Since both processes have been demonstrated, it remains for field studies to provide evidence as to which actually occurred at any given locality. The choice must be based on the geomorphic and sedimentologic characteristics of the forms themselves.

Shaw (1988) noted that the major difficulty with the ice-pressed hypothesis is the lack of a mechanism that would produce regularly spaced cavities of similar size which could, in turn, produce the hummocks. He theorized that if the hummocks represent infilling by ice-pressing of large inverted scallops produced on the underside of a floating ice sheet, then they are related directly to some types of drumlins and Rogen moraines formed by subglacial meltwater. The meltwater would deposit some sediment, but more importantly, it would erode giant scallops into the overlying ice. The hummocks could then form by ice pressing down on the sediment as the water support drains away. Moraine plateaux may represent broad areas of ice roof collapse which resulted in ice-walled lakes. This might explain the common observations of lacustrine sediment on moraine plateaux. Shaw (1988) felt that the main factor favoring a meltwater hypothesis for hummocky moraine is its ability to integrate hummocks, drumlins, and Rogen moraine, as part of a landform/process continuum . He maintained that "fitting together" gives the hypothesis an aesthetic attraction that should encourage further work in this direction.

Glaciotectonism

The visual appearance and structure of glaciotectonic features are related to the settings in which they occur. Escarpment settings are often offered by erosional remnants or the slopes of broad preglacial river valleys that faced the direction of glacial flow (Tsui *et al.* 1989). Fabric as derived from the trends of ice-thrust ridges and fold axes, and the strikes of the preglacial bedrock topography and ice-deformed beds, tend to lie perpendicular to the direction of glacial advance. Other glaciotectonic settings are found on flat, featureless plains (Tsui *et al.* 1989). Attitudes of fabric elements such as the trend of ice-thrust ridges and associated source depressions and the strike of the preglacial bedrock surface also tend to lie perpendicular to the glacial flow direction. The dip direction of deformed beds tends to be parallel to the ice-flow direction (Tsui *et al.* 1989). Fenton (1987) found three types of visibly glaciotectonially altered terrain in the Sand River area, Alberta. These were: (1) hill-hole pairs, (2) hills with a fault-bounded depression, and (3) rubble terrain. All three terrain types are easily identified on air photographs or topographic maps. Fenton and Pawlowicz (1991) have shown that surface and downhole geophysical techniques can detect "hidden" deformed material, primarily in poorly consolidated Cretaceous to Teriary sandstone, mudstone and coa.

Theories for the formation and settings of glaciotectonic features are also subject to controversy. Tsui *et al.* (1989) postulated that ice-thrust features in all glaciotectonic settings tend to form near local topographic troughs in front of an ice sheet where water bodies were impounded. The features would form when meltwater would collect in front of the ice sheet, decaying the permafrost. The ponded water would increase pore-water pressure, thus decreasing the resistance or "passive earth pressure" against ice thrusting (Tsui *et al.* 1989, p. 1317). Bluemle and Clayton (1984) also found that thrusting only occurs where glacial hydrological conditions permit. Shaw (1988), however, noted that theories of thrusting requiring reduced material strength from high pore-water pressure are refuted by the active thrusting within deeply permafrozen ground. Babcock *et al.* (1977) noted fractured quartzite clasts in sorted units caused by glacial thrusting. Although pore-water pressure is invoked in the explanation of the phenomenon, it may be questionable that such intense and localized pressures are indicative of the soft-sediment, low resistance deformation visualized by Tsui *et al.* (1989). As an alternative to the soft-sediment deformation glaciotectonism, Shaw (1988) theorized that where glaciotectonic structures occur in conjunction with drumlins and flutings, increased stress occurred on grounded areas to the side and ahead of zones of decoupling from the glacier bed. These stress concentrations would likely have been very short-lived since they would have enhanced ice flow by deformation and caused a flattening of the ice profile.

Exposed bedrock zones

Large, previously glaciated areas with virtually no surficial sediment have been reported from a number of locations, including a broad area north of Elk Island National Park, east of Edmonton and the area immediately north of Georgian Bay, Ontario (Shaw 1988). A variety of erosional marks of several scales (from millimetres to several kilometres) are observed in these areas, depending on the hardness of the bedrock. The marks themselves are somewhat unusual in that they do not show cross-cutting relationships, have sharply defined rims, and do not have striations related to their formation. These features would not be expected if they were produced glacially, but the form and sharp rims are common to erosional marks produced by turbulent flows (Shaw and Kvill 1984, Sharpe 1987, Shaw *et al.* 1989). Because erosional drumins and flutings merge with areas of bedrock bearing glaciofluvial erosion marks this also supports the idea that all features may have been formed by subglacial meltwater (Shaw 1988).

Eskers and tunnel valleys

These are important features originating from subglacial drainage. They are often found together, the eskers winding across the floors of tunnel valleys, indicating subglacial formation for both features. Eskers radiate outwards from ice accumulation areas and often occur in broad fans which terminate in broad end-moraines (Shaw 1988). Some authors argue that tunnel valleys are formed by catastrophic discharges of subglacially stored meltwater (Boyd *et al.* 1988, cited in Shaw 1988). Tunnel valleys form anastomosing systems which can be vast and are often in close proximity to drumlins, secondary valleys and areas of exposed bedrock. Eskers would have formed somewhat later under more "normal" tunnel discharges.

5. Periglacial landforms and sediments

The study of characteristic periglacial landforms and sediments may be useful in interpreting past conditions. Periglacial phenomena in the stratigraphic record are unlike evidence of temperate continental glaciation in that they can be studied more accurately using modern analogues. It is a process that can, in some instances, be tested in laboratories or gauged in the field. Unfortunately, it is sometimes difficult to identify features caused by periglacial processes as they can closely resemble landforms/sediments caused by other processes. It is therefore very important to be aware of the mechanics and appearance of periglacial phenomena in order to make correct identifications.

Ice wedges

Knowledge of the processes and environments of ice wedge formation is necessary to understand properly the significance of the presence of fossil ice wedges (also known as ice wedge pseudomorphs). Analysis of the present conditions of formation provides analogues for past processes. Detailed investigation of pseudomorphs may help to define the times at which processes and conditions favourable for their growth occurred.

Active ice wedges

Ice wedges are vertically foliated and characteristically wedge-shaped bodies of massive ground ice. Development is best in fine-grained soil with high ice content and little primary bedding structure. They are the most widely distributed and easily recognized type of underground ice (Mackay 1972). Ice wedges are currently considered to be a form of ground-ice macrostructure. As such they are ice veins occurring in the ground; Soviet researchers use the term *Idyanye zhyly* (ice veins) (Jahn 1975). Ice wedges were first described by M. F. Adams (1815) and A.T. von Middendorff (1862) in Siberia. They were described by Figurin (1823) and other Soviet travellers (cited in Embleton and King 1975).

Leffingwell's explorations (1915, cited in Brierly 1988) proved helpful in interpretation of the wedge-like structures. Scientific study of ice wedges over a period of about eight years allowed him to develop his "contraction theory" on their origin. He reported that cracking is often audible. His ideas concerning ice wedge formation are controversial, but are generally accepted today. The contraction theory has been substantiated more recently and is based upon the linear coefficient of thermal expansion and contraction for different materials. Ice is the primary material considered since it makes up the bulk of permafrost in the upper 10 m of fine-grained sediments in many places (Black 1976, Mackay 1972). Ice has a linear coefficient of about $50 \times 10^{-6}/°C$ (Lachenbruch 1960, 1962). This would cause a block of ice 10 m long to shrink by 5 mm in length with a drop of 10° C. The contraction indicated in Leffingwell's theory results in a crack which may or may not penetrate the permafrost. Mackay (1972) established that open cracks usually develop in frozen ground in February and March on Garry Island. The cracks vary in width on the surface from a few mm to 2 cm. Crack depths are frequently greater than 1 m. On Spitzbergen, frostcracks only 2 to 3 mm wide are found each year (Jahn 1975). If the crack does not penetrate the permafrost then no permanent structure will remain after seasonal thawing. Lachenbruch (1960, 1962) proposed the following sequence of events for ice wedge formation.

1. Initially a crack develops during the winter.
2. The following spring, runoff from the melting snow drains into the crack. When the permafrost layer is encountered this meltwater is refrozen. A vertical ice vein within the permafrost develops.
3. The subsequent winter, thermal tension reopens the crack. The ice vein is a zone of weakness since the linear coefficient of thermal expansion of the ice in the vein is different from the frozen material around it.
4. The next spring more runoff water freezes within the crack, so the ice vein or wedge grows annually or seasonally.
5. In each freeze-thaw cycle an ice wedge grows in width by 5 to 20 mm, at the top of the feature. The rate of width growth decreases with depth .

Initial crack development originates near the top of the permafrost and then propagates both upward to the ground surface and downward into the subjacent ice wedge (Mackay 1984). The addition of material perennially to the ground poses space problems. When the permafrost warms in the summer it expands and forces the excess material to the surface. The encasing sediments flow and shear, usually next to the wedge, to form double-raised rims at the surface on either side of the wedge and cause dipped or deformed bedding in the subsurface (Jahn 1975, Black 1976). Wedges may widen to many metres, but 5 to 6 m appears to be the maximum. The majority are probably no more than 1 to 1.5 m wide near the surface and extend into the ground to a maximum of 3 to 4 m (French 1983). The limiting factor on size seems to be the angle of the wedge - permafrost contact which relates to the shear strength of the material. At about 45°, flowage of excess material takes place completely in the wedge and no further widening takes place (Black 1976). The primary crack relieves the thermal tension in a direction perpendicular to the crack, but not parallel to the crack. A random crack will tend to propagate towards the primary crack, with a near-orthogonal intersection being the result (Lachenbruch 1962).

In areas where measurements of ice wedge growth were taken, average annual growth has been used to infer age. For example, Black (1952) reported an annual growth of 0.5 to 1.0 mm in northern Alaska. Wedges 1 m in width were therefore considered to be about 1000 years old. Most wedges in Antarctica are thought to be less than 5,000 years old (Black 1973). Mackay (1984), however, carried out repeated observations on ice wedge cracking on Garry Island. Maximum annual growth over a six-year period was approximately 2 mm, but most wedges grew less than 1 mm. The low growth rate occurred because only about 40 per cent of the wedges cracked each year. Wedges which cracked in any given year were more likely to crack in subsequent years, recurring within 5 to 10 cm of the previous year's crack. Few cracks were continuous for more than 3 to 4 m laterally. Growth rates of ice wedges at Illisarvik were highly variable, site-specific, and time-dependent so that no average growth rate could be given except to say that maximum growth rates may reach or exceed 2.5 cm/year (Mackay 1988). Another complication is the growth of vegetation which may act to trap snow and change the thermal properties of an area, thereby eliminating cracking. A 10 year old ice wedge may therefore be the same size as a slowly growing 1000 year old wedge (Mackay 1988). Ages of periglacial activity may be estimated where datable organics are located either above, below, or within a wedge or pseudomorph. Thermoluminescence has also been employed to date the sediments containing fossil wedges or pseudomorphs directly (French and Godzik 1988).

Active ice wedges are today restricted to areas with a mean annual temperature of between -5 and -8 C° (Berg 1969, Péwé 1973). Péwé (1963) found that the climatic conditions necessary for formation involve a mean annual temperature of no warmer than -6C°. Some Soviet researchers (Baulin *et al.* 1967, cited in Jahn 1975) found that a mean temperature of only -2 C° will produce frost cracks necessary for ice wedges to form. Whether the permafrost is needed to form the wedges depends on local factors. Other studies (e.g. Romanovskij 1973, cited in Black 1976) show that extensive studies in Siberia indicate ground temperatures of only -2 to -4°C will generate ice wedges in "dusty sandy" and sandy-clayey deposits of alluvial origin. More typical environments where ice wedges are found are in the Arctic coastal lowlands and the Yukon River lowlands of Alaska, in particular where ice wedges are formed in the 'muck formation'. The climate is characterized by intense winter cold and a large temperature range (for example, Galena, with a mean January temperature of -24 C°, an annual absolute minimum of -53 C° and absolute maximum of 32 C°) (Embleton and King 1975). A rapid temperature drop in the upper 5 to 10 m of permafrost is thought to be necessary for ice wedge formation by some (e.g. Black 1976). Moisture content, which is largely dependent on texture, is a critical factor in the contraction process. To initiate a crack in ice-cemented frozen gravel requires a 10 C° drop in temperature over the period of a day (Black 1983). In saturated fine-grained sediments, a temperature drop of 4 to 8 C° can induce the formation of a crack. A sudden change of only 4 C° was sufficient to initiate contraction cracks in supersaturated permafrost at Barrow where winter changes of more that 20 C° were measured by a probe imbedded in the ground. Gradients of 10 C°/cm were recorded both horizontally and vertically depending on differences in exposure, snow cover, etc. (Black 1976). Noting that average annual air temperature and ground surface temperatures can differ by 1 to 6 C°, Black (1976) concluded that no simple relationship exists with mean annual air temperature except that the colder temperatures regionally promote more contraction cracking.

Ice wedges are like other forms of ground ice in that they can be either epigenetic or syngenetic. Epigenetic wedges have consistent, typically wedge-like shaped smooth walls reaching right up to the soil surface. Syngenetic forms appear to be made up of interconnected wedges, one on top of the other

(Shumskii 1952, cited in Jahn 1975). They may grow laterally where valley a floor is not stable. Age of the sediments and wedges can be inferred from the wedge relationship to the sediments being deposited or deformed.

Ice wedge casts

Based on the nature of the infilling material, ice wedge casts are divided into two principal groups, each associated with a different paleoenvionment. Infilling material may be either primary or secondary (Jahn 1975). Although water is the primary infilling material for secondary fill wedges, it is not preserved after the wedge degrades. Wedges become extinct for several reasons. In modern wedge systems, snow, water or gelifluction debris may bury the wedge and insulate the ground from large changes of temperature, or, adjacent wedges may develop to relieve the overall stresses (Embleton and King 1975). The net effect is that wedges become extinct when winter stresses at the top of the crack cease to exceed the strength of the wedge ice. Climatic change is responsible for the extinction of the ice wedges which have left fossil ice wedge casts beyond their present distribution. Ice wedge casts are the best indicator of former permafrost and a rigorous periglacial environment (Péwé 1973).

Primary non-ice filled wedges

These are usually referred to as sand wedges, but may include a much broader category of structures than its actual wording conveys (Jahn 1975). Black (1969) considers the main feature of sand wedge sediment to be its vertical foliation with each vertical sand bed being the remnant of a small frostcrack. Jahn (1975) states that foliations are not the most important structural feature of such wedges. Foliation may occur in secondary filled wedge casts and cannot therefore be considered diagnostic of sand wedges. Bowl-like bedding structures in overlying sediments are considered by Jahn (1975) to be characteristic of fossil wedges with primary non-ice fill. This results from wind-transported sand being deposited into a comparatively wide crack. Another feature considered to be diagnostic of sand wedges is upward warping of beds adjacent to the wedge. The warping shows that the effect of lateral growth of the wedge has been preserved because the non-ice fill supporting the wedge walls prevents any structural changes taking place during ice degradation. Upwarped bedding is occasionally preserved in secondary fill wedges when they are filled with fine-textured materials (Jahn 1975). He identified some sand wedges from areas not considered to be polar deserts. However, the sand wedges are best formed in very cold areas of low snow accumulation and/or with high degrees of deflation, typical of polar desert settings in parts of Antarctica and, to a lesser degree, the Arctic.

Secondary fill wedges

This is the group sometimes described as "classical ice wedges" but are more properly referred to as pseudomorphs. They originate as a wedge-like ice form which can be formed either syngenetically or epigenetically. Pseudomorphs of epigenetic ice wedges are most common in Pleistocene deposits. They are preserved because preferential melting of ice occurs along the ice wedge boundary, and voids appear along this boundary. The voids are subsequently filled with sediments from runoff water derived from melting snow and surface permafrost deterioration. As thawing continues, ice is completely replaced by sediments derived from runoff and slumping processes (Péwé

1969, Washburn 1973, Jahn 1975, Walters 1978). Near the end of the wedge degradation, the surface material becomes supersaturated because of the water perched above the permafrost table. Since most silts and sands slump and flow readily when wet, wedges in these materials are often not preserved. Ice wedges thawing in angular gravel should therefore be more commonly preserved (Black 1976). The main feature of the pseudomorph is the lining apparently caused by water running down the walls. The lining is characterized by orientated grain fabrics parallel to the wall of the pseudomorph (Jahn 1975). The middle part of the cast is formed by the slumping of secondary material during permafrost degradation. The fabric of the slumped material may be concave "resembling stacked dishes" (Mears 1981, cited in Brierly 1988). Post-depositional alteration of the stacked fabric may occur after initial deposition (Walters 1978). These wedges often feature a regular shape, broad on top, rapidly narrowing with depth.

A number of processes may form features similar to "true" ice wedge casts. They may be the result of glacial thrusting, solidification, disturbances through landslides and soil tonguing due to desiccation (Yehle 1954). Some criteria for recognizing ice wedge casts are listed below, from Black (1976). He noted that an almost infinite variety of situations exist in nature, so that details cannot be provided. The criteria are meant as guidelines and cannot be used as inflexible rules for identifications.

Table 5: Criteria for identifying ice wedge casts (from Black 1976)

---

1. Supporting evidence of permafrost, such as a permafrost table (as recorded by change in fabric of the soil and by secondary deposits). Biological indicators such as tundra plants or animals can be misleading and suggestive at best, especially following deglaciation.
2. Type of host that will be supersaturated in normal permafrost conditions where winter ground temperatures are not extremely cold.
3. Evidence to suggest little snow cover or thin active layer, and cloudy, wet, cool summers.
4. Multiple wedges forming polygons whose diameters and configurations are consistent with space filling requirements and supposed coefficients of thermal expansion of the host.
5. Pressure effects from widening wedges should be preserved locally adjacent to some wedges in a group. Upturned strata and realigned clasts are typical.
6. Slump fabrics should show stratification arcuate downward across wedges in contrast to the vertical fabric of primary sand wedges.

A size proportion criterion may be an additional diagnostic feature (Berg 1969). The width to height ratio suggested must be 1:3. Active and fossil ice wedges are commonly associated with patterned ground (e.g. Lachenbruch 1962). The pattern cells may vary from 30 to 100 metres across (Washburn 1956, Péwé 1973). Once the various criteria have been applied, a reasonably confident identification can be made. If the cast can be put into a stratigraphic context, combined with other paleoenvironmental information for a site, then it will reflect previous climatic regime(s). A problem arises in identifying each occurrence of fossil ice wedges. Since a number of processes can form wedge-shaped structures each must be critically evaluated in order to make the correct interpretation. A number of pseudomorphs were examined by Black

(1976, 1983). Diverse forms were noted in pseudomorphs which he deemed to be correctly identified, even where the exact process of formation was unknown. He also examined some sites where features previously identified as pseudomorphs were reevaluated as products of desiccation or thawing.

Although ice wedges may typify as much as 25 percent of the tundra surface in some areas (French 1983), very few quantified or experimental data on ice wedges exist. A number of authors postulate conditions necessary to form and maintain active ice wedges, but sparse site-specific data are given. The presumed mechanics of formation are described in broad terms with few observations to support them. Dating wedges by size is dubious, especially in subarctic locations where vegetation and snow accumulations may affect subsurface thermal regimes. Because of the wide variation of ice wedge pseudomorphs, and structures which look like them, the criteria used to identify pseudomorphs are, at best, only suggestive and not proof of their identity.

Involutions

Periglacial involutions may also resemble features formed by non-periglacial processes. When periglacial processes are determined to be the formative agent, the feature is called a periglacial involution. These are commonly found in association with ice-wedge casts and have been described as aimless deformation, distribution and interpenetration of beds produced by frost action (Washburn 1973). French (1983) felt that although there is a common acceptance of cryostatic pressure as the basic cause, the particular mechanism of formation is not clearly understood. Several authors have suggested possible processes of formation summarized below;

Author	Suggested mechanism
Sharp (1942)	differential expansion of silts and clays by ice segregation may result in their injection into adjacent unfrozen sediments
Hopkins and Sigafoos (1954)	differential lateral freezing rates caused by insulating vegetation mats at the surface cause a lateral pressure in the direction of the mat
Washburn (1956)	the downward freezing plane squeezes and contorts unfrozen sediments trapped above the permafrost table
Kostyaev (1969)	moisture controlled density differences which result in a gravity controlled readjustment with an upward movement of finer, less dense sediment, and a downward movement of coarser, denser sediment.

(Extracted from French,1983)

Non-periglacial involutions may be formed by processes such as ice shoving or glacial thrusting, volume change due to the presence of swelling clays, differential loading, mass movement, and tectonic deformation (Schaefer 1949). Washburn (1973), therefore, suggests that the identification of past periglacial environments based on the presence of involutions must be used with extreme caution.

Frost Sorting

The differential movement of sediments according to particle size has been reported by numerous workers (Brierly 1988). Two mechanisms have been proposed for this process; frost push, and frost pull. In frost push, it is thought that the greater thermal transmissivity of the larger particles will permit faster penetration of the cold front through the particle than through the surrounding matrix. Segregation ice would form around the particle as pore water is drawn towards the cold zone. The segregation ice could then heave the large particle or stone. The stone would be prevented from returning to its original position during melting by fine particles seeping into the space formed by the melting ice (Washburn 1973).

The mechanism envisaged in the frost pull hypothesis involves stones being moved upwards during the period of frost penetration from the surface. The descending freezing front would form a void above the particle by frost heave. The clast attaches to the surrounding matrix as the freezing front descends past it. Since the clast is not frozen to the matrix below, it detaches and is free to heave with the overlying matrix. The stone is prevented from returning to its original position by particles falling into the void formed during heave. Corte (1963) reported that laboratory experiments show fine particles (<74 mm) migrate downwards before an advancing frost plane while coarser particles will move upwards in the same way as stones. Lateral and vertical sorting are therefore dependent on the orientation of the freezing front relative to the particles of the unfrozen medium. Other laboratory experiments tend to support the frost pull hypothesis (Washburn 1973).

6. Selected slope processes in southern Alberta

In a study of landslide distributions on the plains of southern Alberta, Beaty (1972) discovered that of more than 100 slump-type landslides, 75 percent were on slopes facing north, northeast, or northwest. Since most of the slopes examined were in river valleys, landslides from random processes should have produced slumps at all cutbanks. Since this is conspicuously not the case, Beaty (1972) postulated that prevailing winds (especially chinooks) are the controlling factor. Strong winter winds would affect slopes by distributing snow unequally across the prairie surface, with large drifts building on the leeward slopes. The strongest winds are from the southwest, allowing major accumulations on the north-facing slopes. Slopes with large snowdrifts tend to have more moisture which would act to enhance several types of mass movement. The distributions of landslides would then appear to be controlled, to a large degree, by wind processes as wind affects moisture availability.

Beaty (1975) noted that the north and northwest slopes of the Cypress Hills in southeastern Alberta are extremely precipitous. The steepness of many segments of the northern margin is directly attributable to widespread slumping. He suggested that the erosion which caused the initial oversteepening of the hill was caused by meltwater channels along its northern and western margins.

Chapter 3: Site Descriptions and Interpretations

The aim of this thesis is to analyze the Quaternary stratigraphy of the Hand Hills using the fossils and trace fossils (burrow casts) of the Middle Wisconsinan prairie dog (*Cynomys churcherii*) as stratigraphic markers (Table 6). Hence, descriptions of sediments are limited to those features which will help to characterize, identify, and correlate sedimentary units.

Table 6: Accelerator radiocarbon dates from Hand Hills area prairie dog (*Cynomys churcherii*) bone collagen.

Date (yrs BP)	Sample No.	Site	% Collagen
22,200 ±320	RIDDL- 681	Winter	not available
29,610 ±220	TO- 1304	Winter	4.4
33,650 ±340	TO- 1142	Winter	3.8
23,000 ±150	TO- 1305	Heaton	2.9
25,980 ±180	TO- 1307	Courtney W.	1.9
33,650 ±340	TO- 871	Courtney W.	0.9
28,000 ±250	TO- 872	Schowalter	1.0
17,060 ±180	TO- 1143	Seward	0.2*

*This sample had the lowest collagen content of any sample processed at IsoTrace.

As part of the stratigraphic reconstructions, some post-depositional structures found in the sediments can be dated, relatively, to both the time of sediment deposition and the prairie dog occupation. It is then possible to interpret the stratigraphy of the area, relating several different types of features.

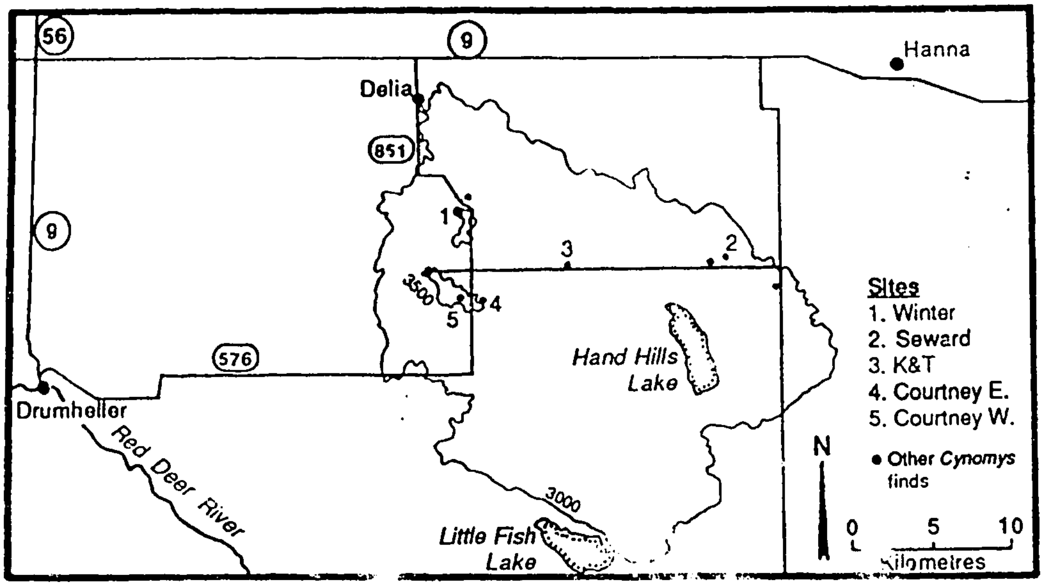
Sites that produced the largest quantities of datable remains often had incomplete or questionable stratigraphic sequences, or were lacking post-depositional structures in the sedimentary units. As stratigraphic reconstructions of the area form the main purpose of this study, the emphasis is placed on sites where these sequences and structures were evident, so not all fossil-producing sites are reported in detail here. For example, several specimens were found at the Heaton and Schowalter sites, located in the Wintering Hills about 20 km south of the Hand Hills. Dates were obtained on bone for the purpose of correlation with the Hand Hills population. However, the stratigraphies of both Wintering Hills sites were not as complete as those of the Hand Hills sites, and so are not included here.

Winter site

Introduction

The Winter site (Figure 9) is located in a gravel pit on the high plain of the western member of the Hand Hills, 28 km northeast of Drumheller, at about 1,090 m (3,576 ft) asl. It is situated at 5[illegible].4'N, 112°20'W, or SE 1/4 S16 T30 R17 W4 on the NTS map [illegible]P/9 (Craigmyle). The main excavation site (now covered during reclamation) was about 70 metres directly west of a large television tower operated by CFCN of Calgary, on property leased by Mr. Douglas Winter then of Youngstown, Alberta.

This site was discovered in 1983 by staff from the Tyrrell Museum of Palaeontology, Drumheller who were looking for Tertiary fossils in the Hand Hills gravel. They noticed in the south wall of the pit a sand lens that had been heavily excavated by burrowing vertebrates. They concluded that bones of the animal responsible for the burrowing were likely of the prairie dog reported by Storer (1972) as *Cynomys ludovicianus* (the black-tailed prairie dog) from other sites in the Hand Hills. A latex impression of the wall was taken, and the site



Based on Burns and Young (1988)

Figure 9: Location of the study sites in the Hand Hills. The Hand Hills are delineated by the 3,000 ft (915 m) contour.

abandoned. A cast made from the latex impression is currently on display in the Quaternary gallery of the Tyrrell Museum, Drumheller, Alberta.

In 1984 limited excavation of the site was undertaken by Dr. James Burns, Curator of Quaternary Paleontology at the Provincial Museum of Alberta, Edmonton (Burns and Young 1988). Excavation consisted of digging a notch in the general area of the activities of the previous year. Only a single burrow system was discovered, but it yielded enough bones to encourage further investigation at the site.

A crew of three accompanied Dr. Burns to the Hand Hills in late May of 1985 to excavate as many burrow systems as possible during the field season. The site was first sectioned off in a 5-metre grid. The overburden was removed partly by hand and partly with heavy machinery being used near the site by gravel pit operators. The burrow casts were then carefully exhumed in layers using trowels (Plate 4). The site was later mapped on a three-dimensional coordinate system. Survey points were recorded on top of a burrow cast wherever a change in altitude, direction, dimension, or a branching was noted. Burrow casts were then measured for width and depth directly below each surveyed point. Sketches of the site were drawn as work progressed and photographs were taken to aid later, more detailed drawings. During the 1985 field season, a latex impression was taken of some excavated burrows for future display. After a burrow system was mapped, the materials were broken down and wet-sieved. Forceps were used to pick the bones out of the sieves in order to minimize contamination of the bones, allowing their use for accelerator mass spectrometry (AMS) radiocarbon dating. The bones were then placed in glass vials where they dried before the lids were secured. Drying was thought to be necessary in order to minimize bacterial or fungal activity which could be another source of bone contamination.

A crew returned to the Winter site in 1986 to collect more fossils. The author assumed surveying responsibilities, and undertook also to map and describe any major stratigraphic features. Field procedures were essentially the same as for the previous year, with some modifications. Bones were occasionally collected using only dry sieving in order to reduce further possible contamination. Dry sieving was extremely time-consuming so that it was only done for limited periods. Surveying and mapping were also more time-consuming as the burrow systems became more numerous and thicker on the western side of the site (Plate 4). The relative density of burrow casts was thought to be related to the length of occupancy of the site (Burns and McGillivray 1989). The increased volume of burrow fill yielded a proportional increase in retrieved bones. The 1986 field season produced nearly a three-fold increase of total specimens retrieved. In all, over three thousand specimens (representing at least 10 species) were collected over three field seasons (Table 7). Over the three seasons, an area of 75 m^2 was excavated to an average depth of 1.5 m. Most importantly, from a paleontological perspective, a number of prairie dog skulls were recovered. Morphological features allowed Dr. Burns to conclude that the prairie dogs were a white-tailed variety. Statistics on several skull size parameters indicated that the Hand Hills prairie dogs were significantly larger than the largest extant prairie dogs (black-tailed prairie dogs, *C. ludovicianus*). Modern white-tailed prairie dogs (*Cynomys leucurus*) are smaller than the black-tailed. The Hand Hills prairie dogs were therefore designated as a new species, *Cynomys churcherii*,

Plate 4: Excavation at the Winter site during the 1986 season. Points were surveyed when a burrow cast changed direction, thickness , or intersected another cast. Burrow casts increased in number and thickness to the west of the site.

(hereafter referred to as *C. churcherii*) on the basis of size (Burns and McGillivray 1989).

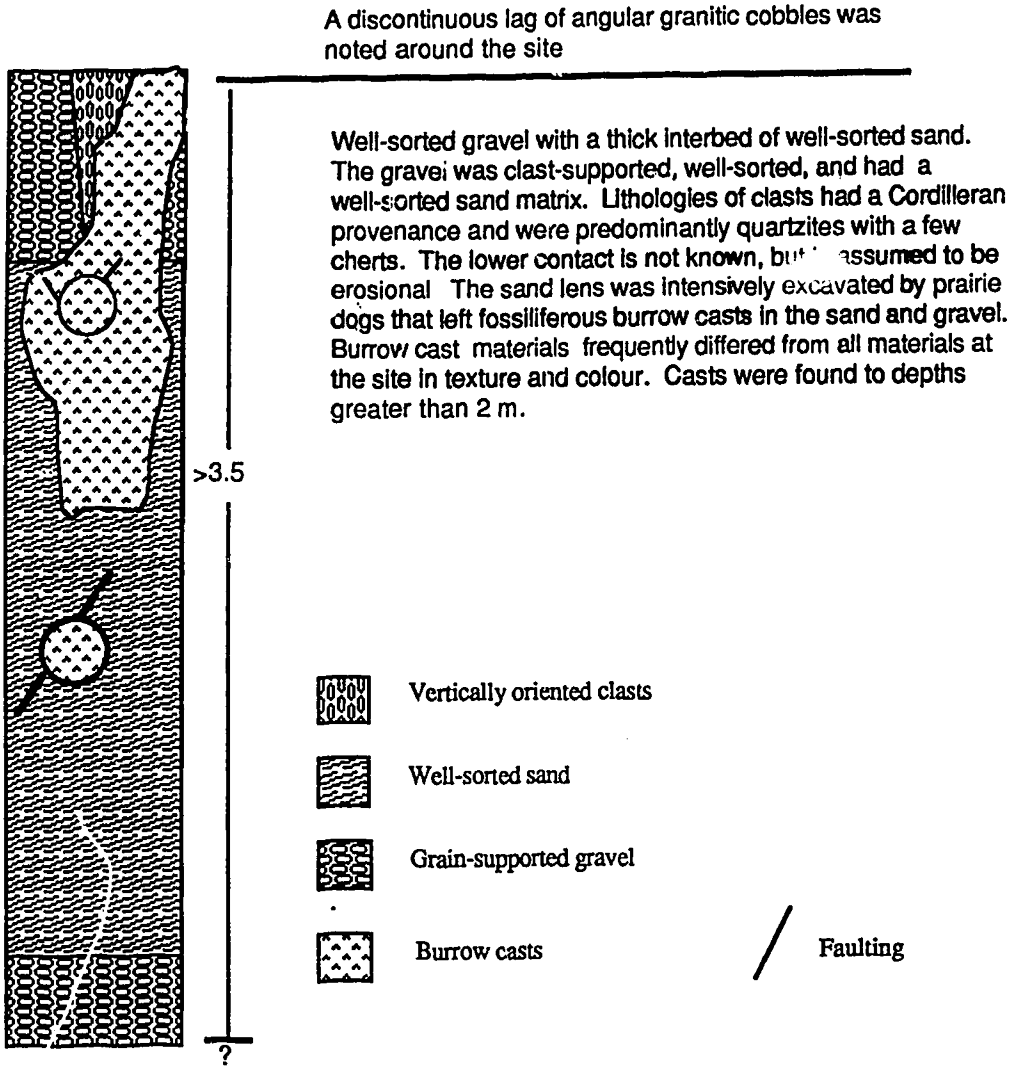
Table 7: Vertebrate species from the burrow casts of the Winter Site, a late Middle Wisconsinan prairie dog colony. From Burns and Young (1988)

Lagomorpha
Lepus cf. *L. townsendii* (cf. White-tailed Jackrabbit)
Rodentia
Peromyscus maniculatus (Deer mouse)
Lemmiscus curtatus (Sagebrush Vole)
Thomomys talpoides (Northern Pocket Gopher)
Spermophilus richardsonii (Richardson's Ground Squirrel)
S. tridecemlineatus (Thirteen-lined Ground Squirrel)
Cynomys churcherii
Aves
2 unidentified species
Amphibia
?Salamander sp.

Site descriptions

The Winter site consisted of interbedded, moderately thick units of well-sorted gravel and sand (Figure 10). A thick sand lens (>2 m) was conformably over- and underlain by well-sorted, grain-supported gravel. Interfingering contacts between the gravel and sand units were common (Plate 5). Generally, the contact between the sand and upper gravel unit was planar over much of the site, but undulated in the southwest sector. Clasts in both gravel units were of uniformly Cordilleran provenance, being primarily quartzites (>90 percent) and cherts. Shield clasts occurred only as a discontinuous lag on the surface around the Winter site and were poorly rounded and commonly equant-shaped. Cordilleran gravel clasts were well-rounded and were usually somewhat blade- or disc-shaped (Zingg 1935). Sizes of clasts varied from pebble to cobble (long

Figure 10: General stratigraphy of the Winter site.



A discontinuous lag of angular granitic cobbles was noted around the site

Well-sorted gravel with a thick interbed of well-sorted sand. The gravel was clast-supported, well-sorted, and had a well-sorted sand matrix. Lithologies of clasts had a Cordilleran provenance and were predominantly quartzites with a few cherts. The lower contact is not known, but is assumed to be erosional The sand lens was intensively excavated by prairie dogs that left fossiliferous burrow casts in the sand and gravel. Burrow cast materials frequently differed from all materials at the site in texture and colour. Casts were found to depths greater than 2 m.

axis to about 20 cm). The gravel units often appeared massive due to thick bedding and generally uniform texture (Rust and Koster 1978). Locally, planar cross-bedded, pebble-sized gravel occurred, but exposures of these were limited. Surface encrustations of secondary carbonates on the bottoms of clasts were common. The interclast matrix was well-sorted sand (Figure 11). The sand lens was comprised primarily of well-sorted sand, with thin (up to approximately 20 cm) lenses of fine silt occurring in the lower metre of the unit. Locally, the upper gravel unit displayed near-vertical long axial orientations (Plate 5) to depths below the upper sand-gravel contact (Figure 10). The near-vertically oriented clasts formed wedge-shapes that crosscut all bedding structures in the gravel and sand. Normal faulting was common in the sand lens. Pieces of well-mineralized, unidentifiable bone scraps from a large vertebrate were found in the gravel.

Burrow casts were primarily located in the sand lens (Plate 4) and were found to depths greater than 2 m below the surface. They were only rarely noted in the gravel because most of the gravel was initially removed quickly in order to get at the underlying, densely burrowed sand unit. Prairie dog burrow casts crosscut all sand bedding, faulting, and deformational structures. In the only location where burrow casts were observed going through the overlying gravel unit, the clasts in the gravel were vertically oriented (Plate 6). The cast fills consisted of at least two types of materials. A small proportion of the burrow casts consisted of nearly pure sand fills which were only distinguishable from the surrounding sand when their contents of bone and pebbles were discovered (Plate 7). Many of the fill materials consisted of a massive matrix-supported, relatively silt-rich diamicton, with clasts comprising from 0 to only

Figure 11: Grain-size distribution of sediment from the thick sand unit and the gravel unit's interclast matrix at the Winter site.

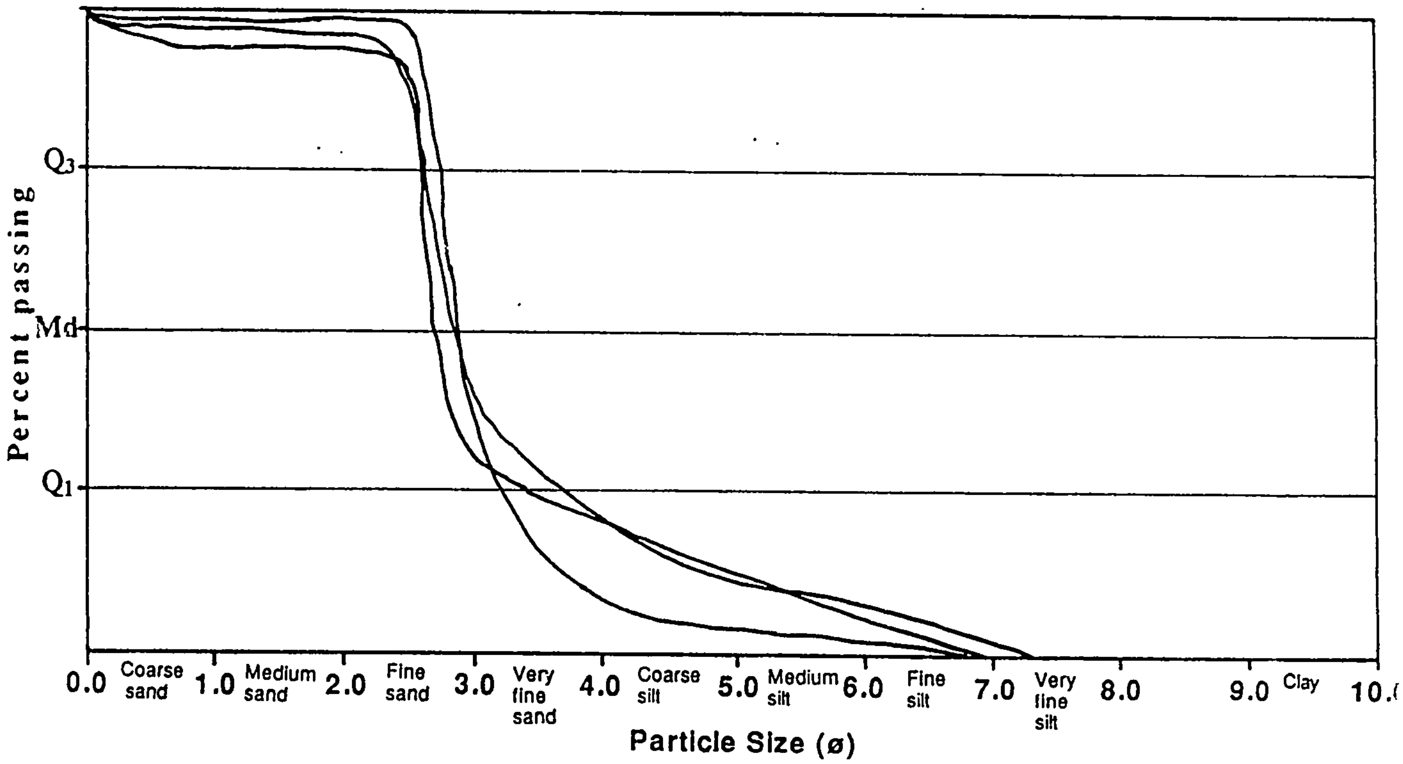


Plate 5: The contact between the sand and gravel units was gradational and/or interfingered. Left of the trowel is one of several wedge-shaped zones of vertically oriented clasts and massive sand observed at the site.

Plate 6, a and b: The only burrow cast found intruding the gravel unit. The burrow cast crosscut the zone of vertically oriented clasts.

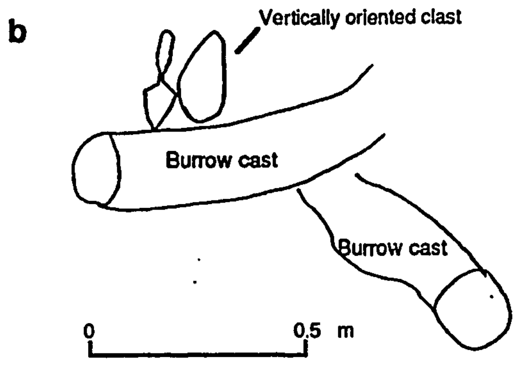
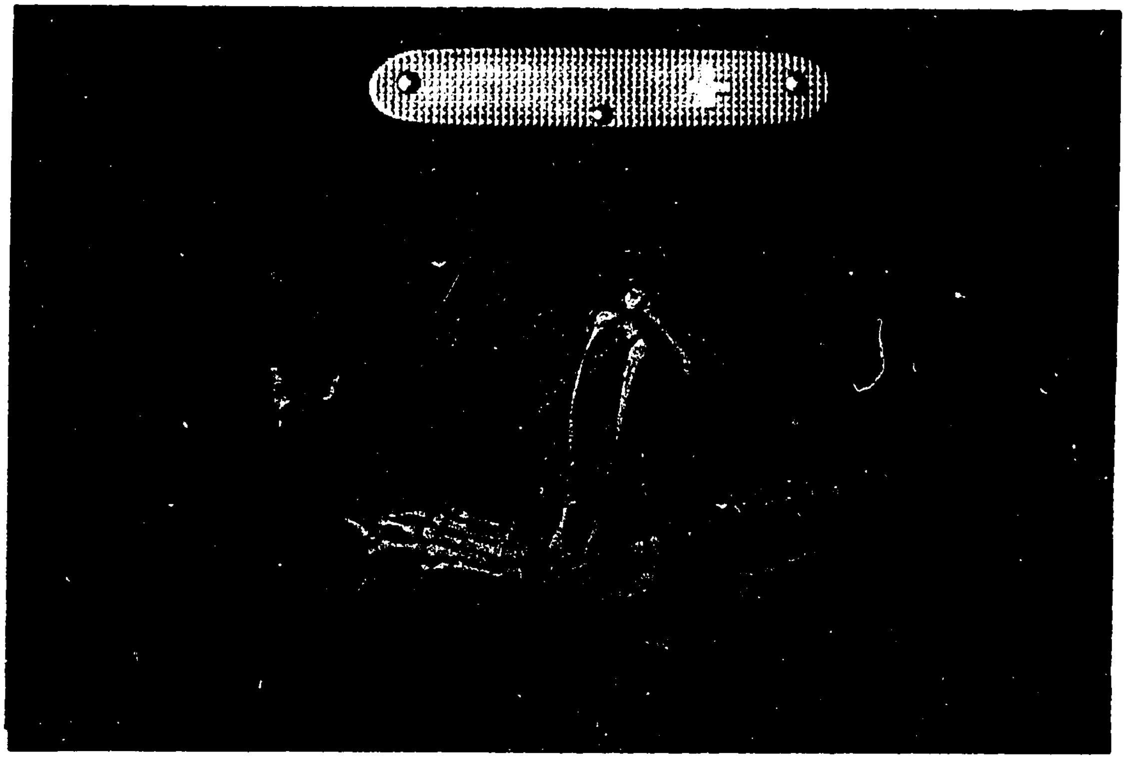
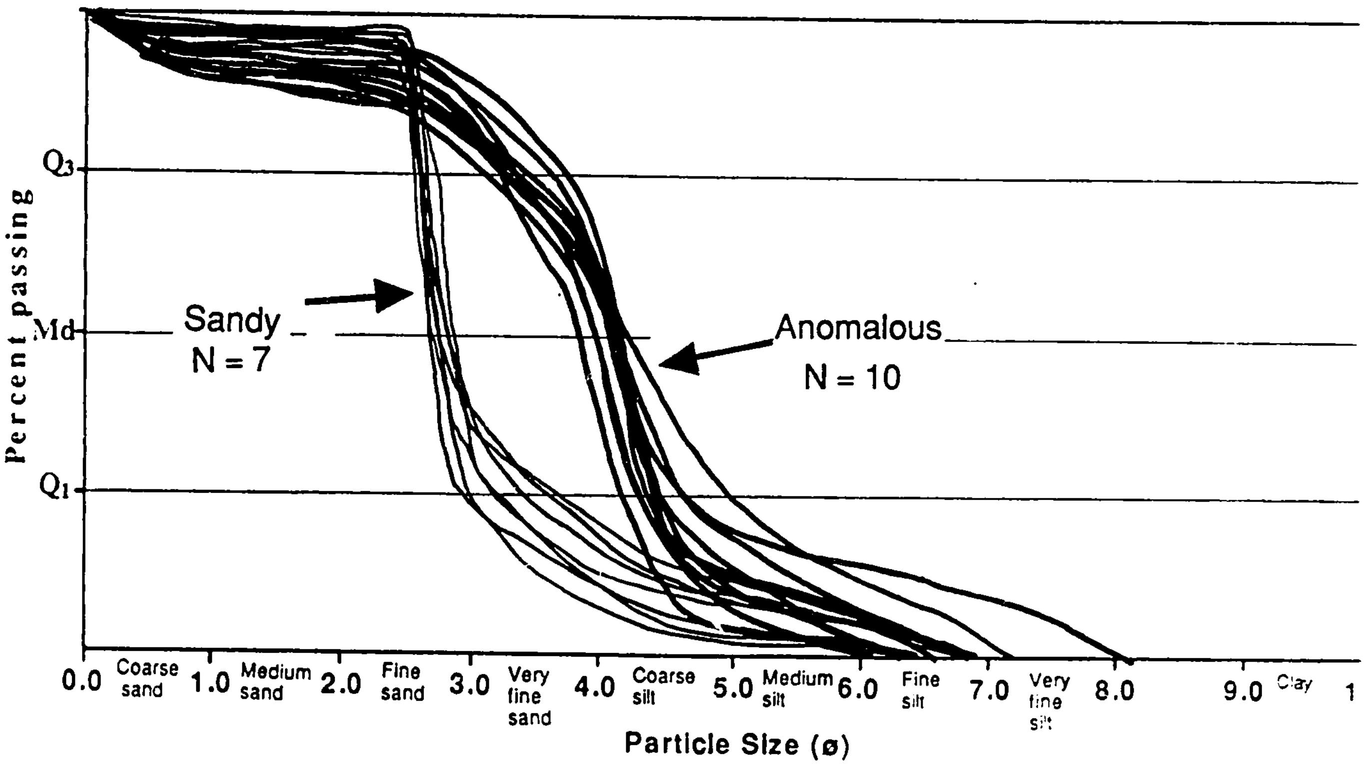


Plate 7: The burrow casts contained fills which varied in composition. Some fills were identical in colour and texture to the surrounding sand and were only located when pebbles or bone were encountered during excavation. (Photo by J. Burns)



about 20 percent of fill volume (Shvetsov (1954) volume estimates). Many of these casts overlaid crescent-shaped beds (Plate 8). The rest of the fill materials appeared to be intermediate in colour and texture. The diamicton type of cast matrix varied from sandy light-coloured (Munsell 5Y 8/3, pale yellow) materials that were practically indistinguishable from the surrounding sand, to darker (Munsell 5Y 5/2, grayish olive), relatively silt-rich fills. There was no material similar to the silt-rich grayish olive fills found at the Winter site; this type of fill material was "anomalous" as the source of material for these fills was unknown. Grain-size analysis was used to demonstrate the differences between some burrow cast fill materials (Figure 12). It also helped to demonstrate the similarity of the "sandy" cast fill and the encasing unit. Dry sieving without deflocculation or hydrometry was thought to be adequate as the majority of sediment at the Winter site fell within the size range that could be tested using sieves alone. A comparison of grain-size distributions was done on selected "sandy" burrow casts that were similar in appearance to the surrounding sand, and "anomalous" fills that were unlike any material at the Winter site (Figure 12). The "sandy" fills were very well-sorted, with the grain size of the majority of material being between 2.75 and 3.0 ø. "Anomalous" fills were not so well-sorted, with the majority of material between 3.0 and 4.5 ø. The Q1 value of the "sandy" fill was between about 3.0 and 3.6 ø, while the Q1 values of the "anomalous" fills varied from about 4.2 to 5.0 ø. The Md value of the "sandy" fill was between about 2.8 and 3.0 ø, while the Md values of the "anomalous" fills varied between about 3.9 and 4.4 ø. The Q3 value of the "sandy" fill was between about 2.7 and 2.9 ø, while the Q3 values of the "anomalous" fills varied between about 3.2 and 3.9 ø.

Figure 12: Grain-size distrubutions of burrow-cast fill material from the Winter site.



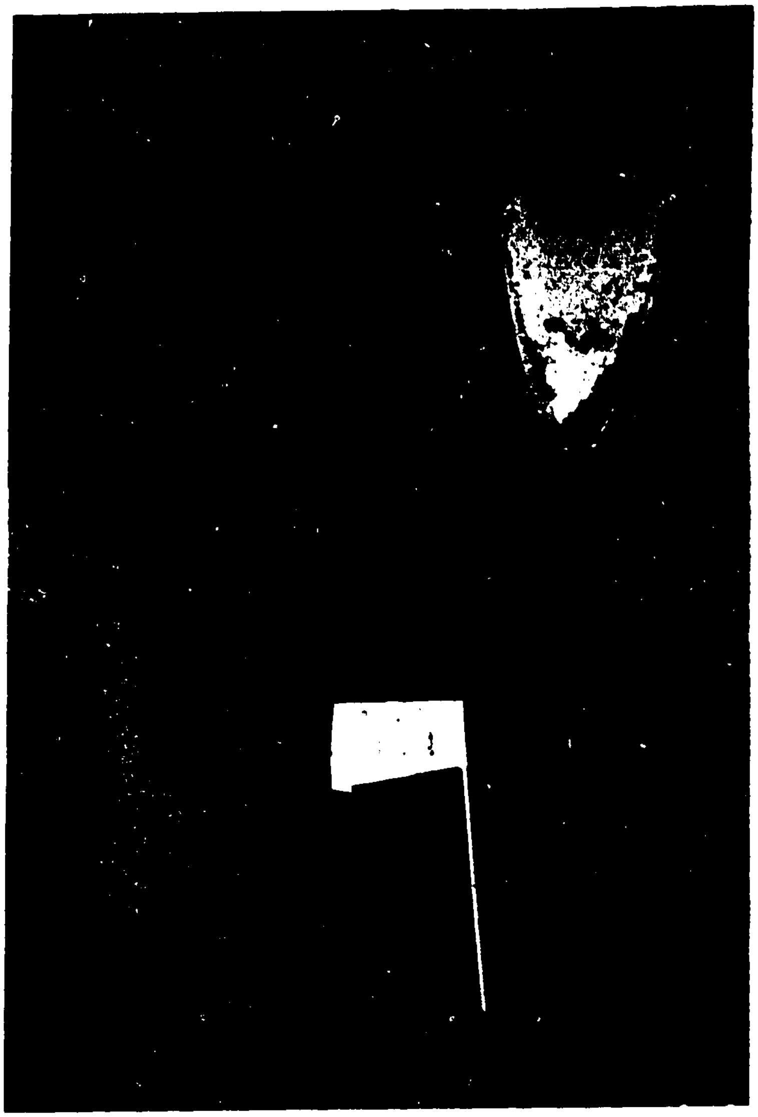


Plate 8: Some of the cast fill material was relatively rich in silt and did not resemble material in the surrounding or overlying units. The dark burrow cast is underlain by crescent-shaped beds, indicating that it was partially infilled by material sloughing off the walls and roof.

Instances of bedding within the fills were extremely rare as only two short (30 cm) sections, found in the very lowest reaches of the site, displayed laminations. Many casts had tubular shapes, averaging about 14 cm in diameter, but casts could be as much as 80 cm in vertical thickness but were wider than they were thick and were oblong in cross-sectional shape. Clasts found within the burrow casts were somewhat smaller than the overlying gravel (to a maximum of about 10 cm) but were identical to the gravel in lithological, roundness, and shape parameters. Although hundreds of clasts were inspected, none of Canadian Shield provenance was found in the burrow casts.

Summary and interpretation - the Winter site

The gravel and sand units found at the Winter site are judged to be part of the Tertiary-age Hand Hills conglomerate found elsewhere in the area (Russell 1958, Storer 1976, Burns and Young 1988) on the basis of lithology and stratigraphic position. Clasts of Canadian Shield origin on the surface show that the Hand Hills were submerged by Continental glaciation originating to the northeast some time after the deposition of the gravel. The only demonstrable Quaternary deposits at the Winter site were the Shield clasts that existed as a discontinuous surface lag so the stratigraphy was incomplete. Wedge-shaped structures in the gravel and sand contained vertically oriented clasts and massive sand and were likely ice-wedge pseudomorphs on the basis of their diagnostic "rock lining." Lack of Shield clasts in the ice-wedge pseudomorphs may indicate that the periglacial conditions ceased before glacial deposition of the Shield clasts and could relate to a "preglacial" cold-warm cycle. The burrow casts represent the Middle Wisconsinan burrowing into the older Tertiary sediments by the extinct prairie dog *C. churcherii* (Table 6). A long occupation at the Winter site is indicated by both the number of burrow casts found, and radiocarbon dates received. Radiocarbon dates indicate occupation of the site for at <u>least</u> 11,000 yrs. Long occupancy favours concepts of a major ice retreat during the Middle Wisconsinan. Burrow-cast density (both numbers and thickness of burrow casts) increases to the west-northwest of the site, possibly indicating that the gravel was thinner and easier to penetrate in that direction when the site was inhabited. Burrow casts crosscut ice-wedge pseudomorphs, indicating that intense periglacial conditions had subsided before the Middle Wisconsinan. Areas where clasts were oriented vertically may have been preferred for excavation as the clasts may have been more easily moved than the overlapping horizontal clasts. Maximum burrow depths at the Winter site are very similar to those found in modern white-tailed prairie dog (*C. leucurus*) colonies. This strongly suggests that Laurentide glacial erosion at the Winter site was probably minimal. However, the presence of an "anomalous" cast-fill material shows that a unit of material that overlaid the gravel when the colony was active was removed from the site before excavations of the site began. This missing sediment provided the parent material for the "anomalous" cast fills that were deposited in the burrows. The process of deposition was likely by slumping and mass movement, as the cast fill materials were usually lacking in bedding structures. If the burrow cast materials were a sample of overlying sediments, as demonstrated elsewhere (Thorpe 1949, Voorhies 1975), then the stratigraphy may be partially reconstructed using the fill material as a "proxy" for the missing sediments. The fill material would have inherited some of the characteristics of the parent material, such as texture and lithology. The origin of the parent material cannot be ascertained directly from evidence at the Winter site as primary bedding structures (if any) of the parent material would have been altered by mass transport during deposition. However, the lack of Shield clasts in the burrow cast fill material indicates that there were none at the surface at the Winter site when the colony was active, or later when it was being infilled after the colony was extirpated during the onset of Late Wisconsinan glaciation. Tests for the presence of smaller calibre particles of Canadian Shield provenance were not done as they could have been transported to the top of the Hills by wind, just as they were over the Del Bonita uplands (Brierly 1988). This suggests that the Shield clasts were deposited during the Late Wisconsinan and that the Laurentide was the only Continental glaciation that achieved thicknesses sufficient to submerge the Hand Hills.

Seward site

Introduction

The Seward site (Figure 9) is located on the eastern member of the Hand Hills approximately 25 km southwest of Hanna at an elevation of about 975 m (3,200 ft) asl . It can be found on the NTS mapsheet 82 P/9 (Craigmyle) at 51°32' 20" N, 112°5'30" W or SE$^{1}/_{4}$ S6 T30 R15 W4th. The property is owned by Mr. Al Seward of Calgary.

The Seward site was first located by Dr. Burns of the Provincial Museum of Alberta, Edmonton, in 1985, and briefly investigated during the following summer. Dr. Burns made the first discovery at that site of the mid Wisconsinan prairie dog *C. churcherii* in 1986, thereby extending its known range. Enough bones were collected from two separate locations at the Seward site to process an AMS radiocarbon date from each. No detailed mapping of the site was undertaken at that time as the purpose of the visit was to survey pits for fossils of the prairie dog. However, it was decided in 1988 to map the deposits at the Seward site in hopes of finding evidence that might place the prairie dogs in stratigraphic context. Two sections were logged in detail that year, and two others briefly examined . The sections were connected and nearly continuous. They were oriented roughly 90° to each other, providing a three-dimensional view of the sediments and sedimentary features (Figure 13).

This site contained a number of unique features and relationships which were not as well demonstrated at any other site. With the permission of Alberta Environment and Mr. Seward we have sought to preserve key areas of the gravel pit. The whole pit could not be preserved, but sections with the most important characteristics have been set aside. Because of the large variety of features, each section will be described and interpreted separately in order to simplify analysis. Following that is a summary and interpretation for the Seward site as a whole.

Site descriptions

Four sections were logged at the Seward site (Figure 12). Four lithological units were observed at the site, but sections 1 and 2 contained only the lower two units because the upper two had been removed when the pit was

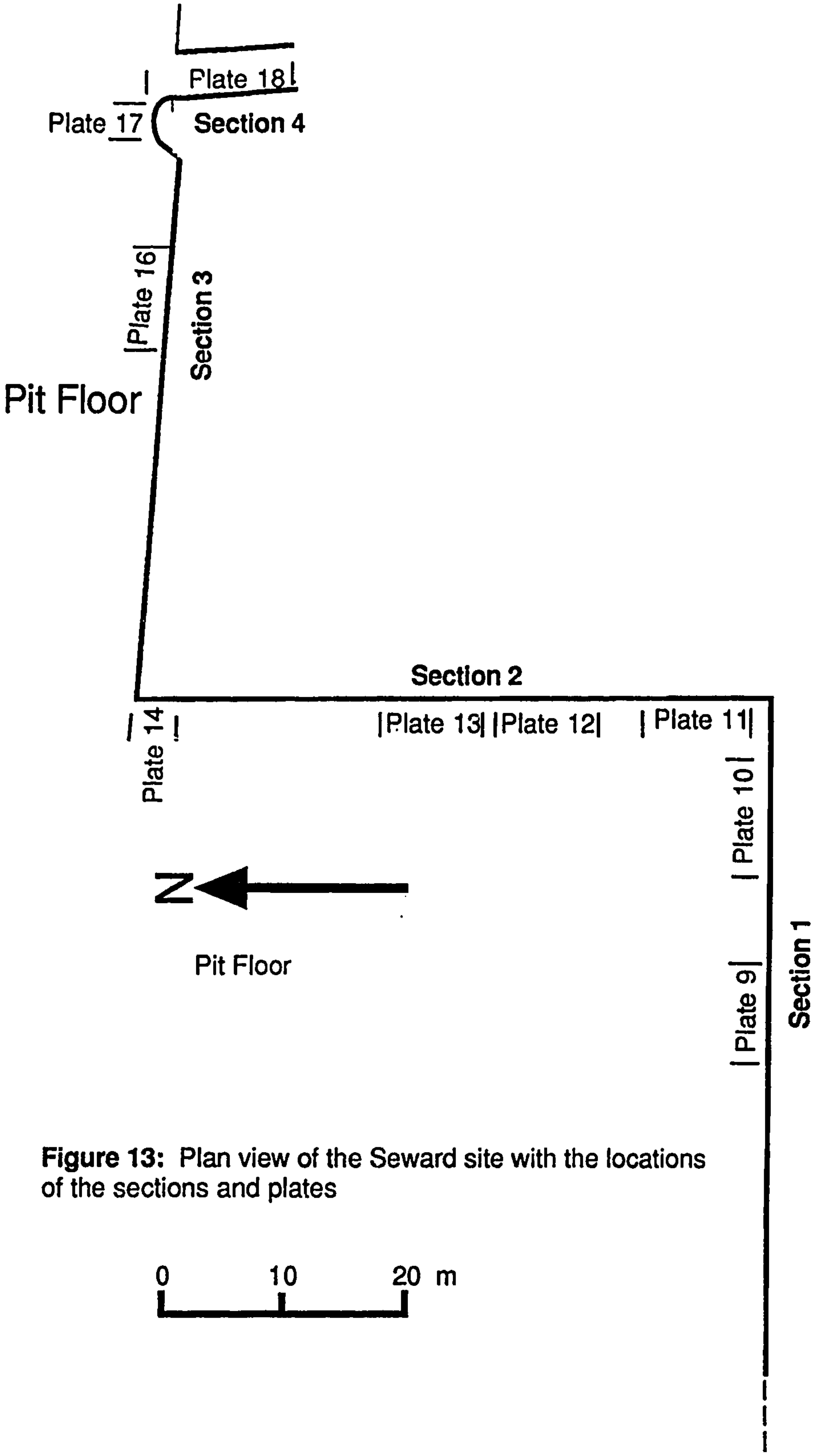


Figure 13: Plan view of the Seward site with the locations of the sections and plates

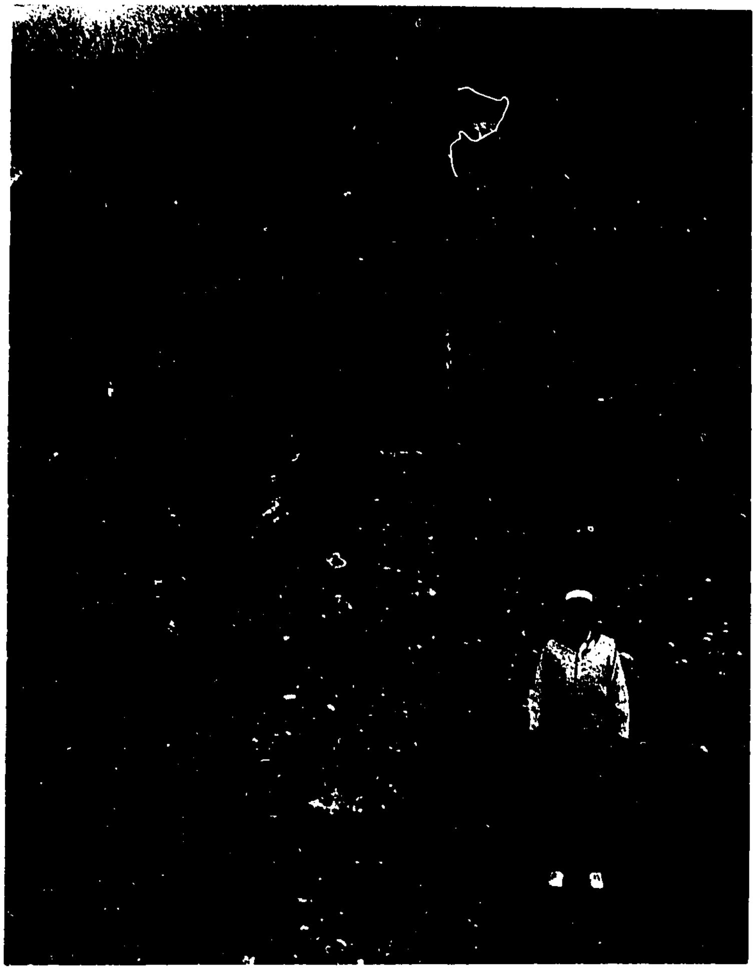
opened. Several types of post-depositional deformation structures, some previously observed at the Winter site, were common in the sediments.

Section 1

This section was the largest and best exposed of the four. It was oriented east-west, with the pit wall facing north, and was connected at its east end to the south end of section 2 (Figure 13). The section was approximately 100 m long, with some walls nearly 10 m high. In spite of its being the largest exposure, it had the least number of lithological units at the Seward site.

Unit I: Interbedded gravel and sand,

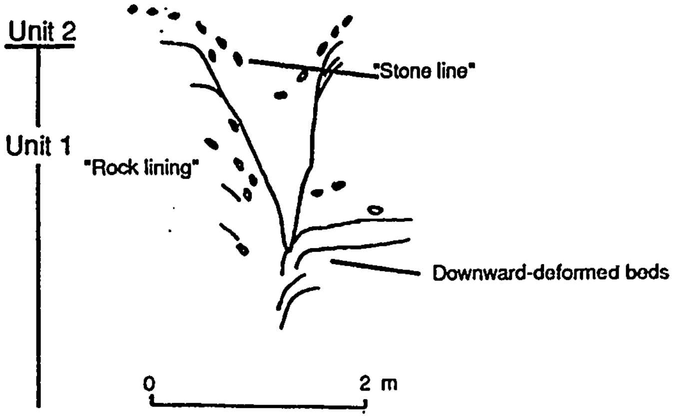
This was the basal unit exposed at the Seward site. It was comprised of planar bedded gravel (Plate 9) which contained lenses of laminated sand and silt. The gravel was clast-supported, was well-rounded, and tended to be somewhat blade- or disc-shaped. Lithologies were primarily quartzite (> 90 percent), and chert (~8 percent), with the occasional indurated sandstone. In some areas the gravel appeared massive due to thick bedding and generally uniform texture. Clasts were generally near-horizontally bedded, except locally, where a number were near-vertically oriented in a wedge shape. The interclast matrix was primarily sand. The silt and sand lenses achieved a maximum thickness of about 1.3 m (Plate 10). Gravel stringers, often only one clast thick, occurred in many of the sand and silt lenses. Many of the beds were deformed randomly, not exhibiting any pattern or structure. Locally, the contact between one of the silty lenses and gravel was interfingered (Plate 10). A wedge-shaped structure was also observed in the largest silt lens.



a

Plate 9, a and b: A large ice-wedge pseudomorph in Unit 1. The down-turned bedding of adjacent strata, and "rock lining" of the wedge are diagnostic features of pseudomorphs. The pseudomorph was filled by Unit 2 which contains a stone line.

b



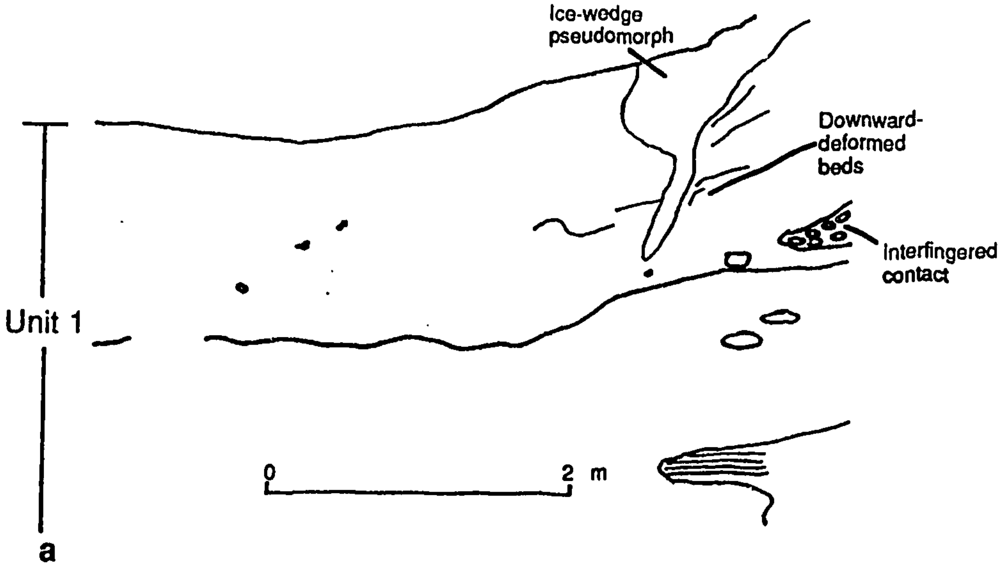


Plate 10, a and b: Interbedded silt and gravel. Thin beds of gravel were found within the large silt lens. Bedding of the silt was convoluted, except near the pseudomorph, where it was deformed downward.

b

Unit 2: Silty diamicton,

This unit was thin and discontinuous in section 1. It was only visible in depressions above the wedge-shaped pseudomorphs (Plate 9). The diamict matrix exhibited fine bedding that was concave downward. A thin bed of gravel-sized clasts was also concave, approximately parallel to the walls of the wedge-shaped feature (Plate 9). Clasts in the silty diamict were almost uniformly quartzitic and it was grayish olive (Munsell 5Y 5/2) in colour. There were no Shield clasts found in the silty diamict.

Interpretation - section 1

On the basis of stratigraphic position and lithology, the thick gravel beds are correlated with those of the Hand Hills conglomerate found elsewhere in the area. The wedge-shaped structures at the top of both the gravel and silt were likely ice-wedge pseudomorphs, based on two features: a gravel "lining" (gravel alignment parallel to the wedge walls), and dish-shaped structures in the overlying sediments. Both were likely formed as material slumped into the ice wedge during melt-out. The silt lens with the thin gravel stringers in Plate 10 was interbedded with the adjacent gravel and therefore was deposited contemporaneously with the gravel. The deposition of the silty lens likely occurred in a low-energy fluvial or overbank environment that was subject to somewhat large, short-lived seasonal or periodic fluctuations in flow. The diamict found in the slump structure of the ice-wedge pseudomorph in the gravel was likely originally an overbank deposit, with the stone line representing a flood event. Deformation of the bedding in the silt deposit (Plate

10) may have been caused by dewatering of the sediments after initial deposition, and/or lateral pressure exerted later by the growing ice wedge on the saturated/frozen sediments.

Section 2

This section is connected to section 1, so the units could be easily correlated. Orientation is roughly normal to section 1, as it runs north-south (Figure 13). The top metre of the unit was removed during the excavation of the pit. The section was about 50 m long and was well exposed because this area of the pit had been recently excavated. Exposures nearly 3.5 m high were found in the southern half of the section and were nearly 4.5 m high at the northern end.

Unit I: Interbedded gravel and sand,

Composition of the gravel and sand was identical to section 1. The lower metre of the gravel was quite resistant and was moderately cemented by carbonates. The nature of the upper contact is unknown in the southern half of the section because it was removed during quarry operations (Plate 11, and Figure 14). The unit consisted of interbedded sand, gravel, silt, and clay. Most of the gravel was grain-supported, but matrix-support was dominant locally in the upper half of the unit. Burrow casts containing prairie dog bones were common in the southern part of the section (Plate 11), becoming more numerous in the middle areas (Plates 12 and 13). The burrow casts crosscut planar-bedded gravel, but were more numerous in vertically oriented gravel and lenses of finer material (Figure 14). The cast fills were very similar to those

Plate 11: The south end of section 2, Seward site. Upper units were likely removed as overburden. Because of the stripping, only Unit 1 was present. The lower half of Unit 1 was dominated by clast-supported gravel, while the upper half was comprised of interbedded gravel, sand, and silt. Locally, prairie dog (*C. churcherii*) burrow casts were present (Figure 14).

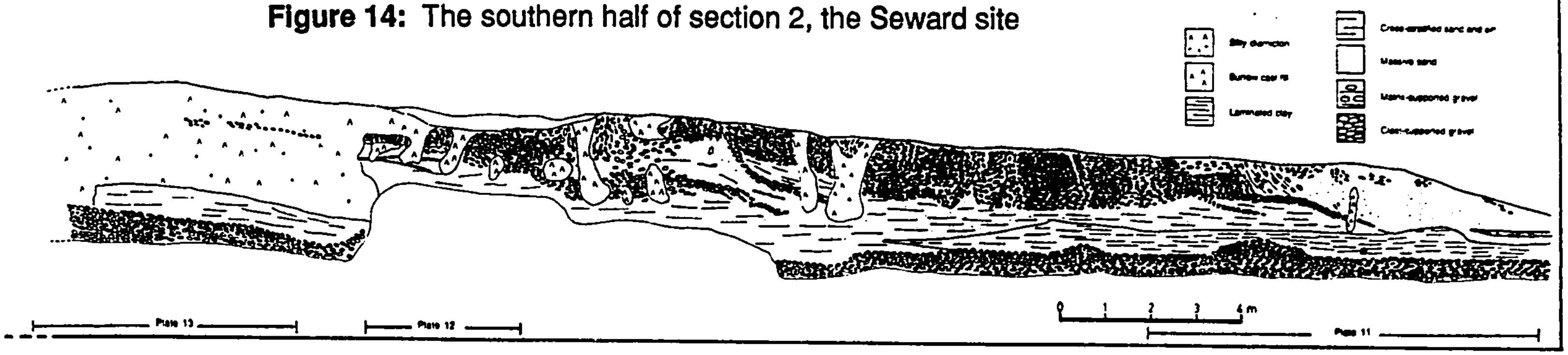


Figure 14: The southern half of section 2, the Seward site

Plate 12: Near the middle of section 2 (Figure 14). The composition of the upper part of unit 1 changed to be more dominated by fine-grained material. Burrow casts became common, both in the finer material, and in the gravel. The transition to Unit 2 occurred at the upper left (north) end of Figure 13, but the contact was graded and not distinct. The gravel bed in the left, upper part of the plate eventually pinched out to the north, in the area covered by Plate 13.

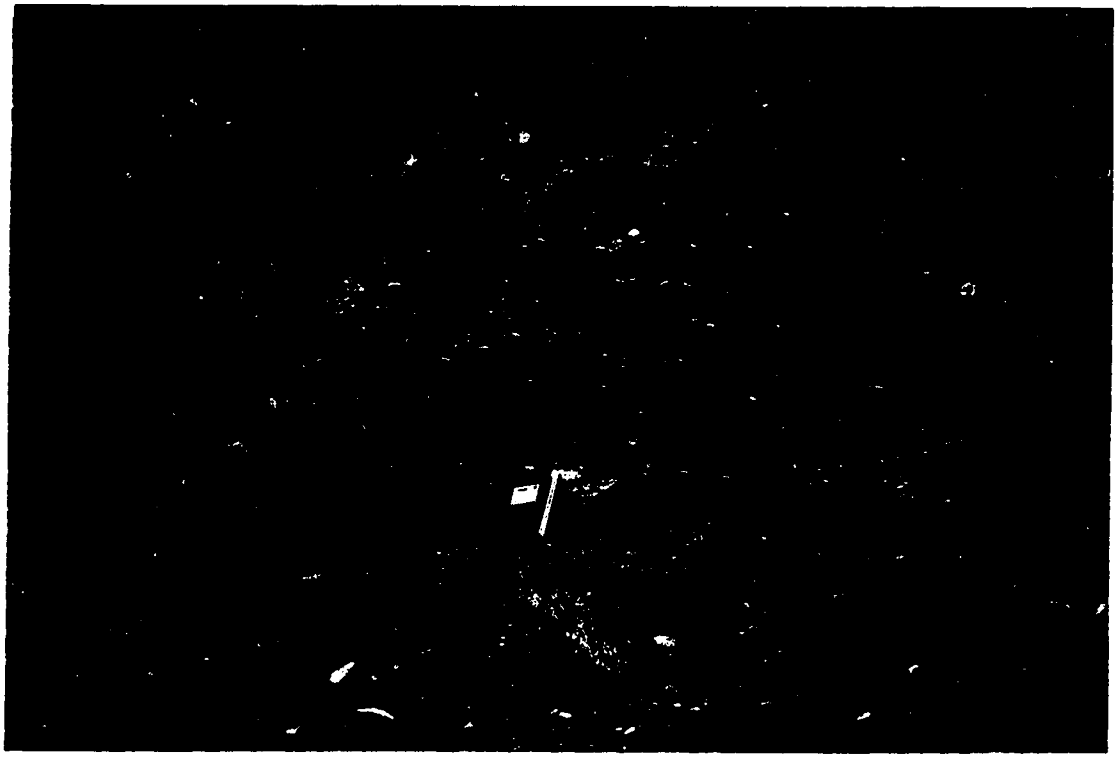
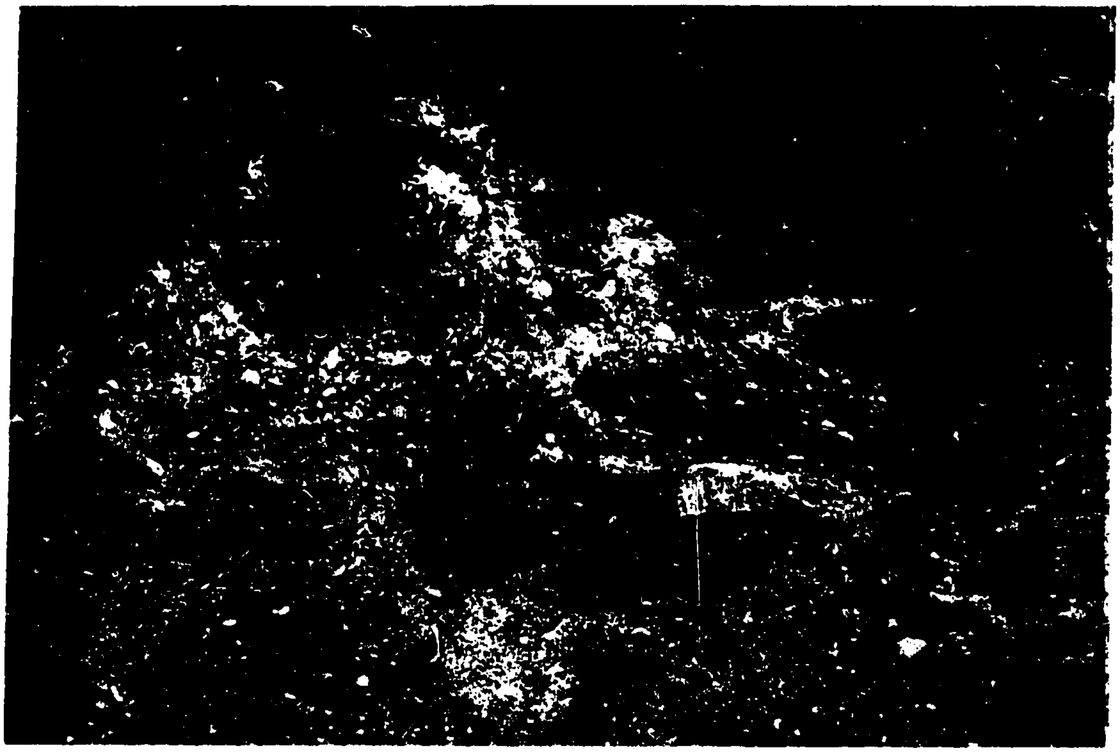


Plate 13: The middle of section 2 (Figure 14). The gravel bed thinned and eventually pinched out in the middle of the plate, at the transition between Units 1 and 2. Lower in the section, the contact between the two units was abrupt and vertical. The laminated silt beds overlying the gravel were truncated at the contact between the two units.

at the Winter site in that the matrix was compact, and generally grayish olive (Munsell 5Y 5/2) in colour. However, gravel clasts constituted more of the fill material volume at the Seward site (to about 50 per cent), especially in casts located in gravel lenses. Burrow casts were found to about 3 m depth. They contained clasts which were identical in lithology to the encasing unit, and contained no clasts of Shield provenance. Several diagnostic prairie dog bones (*C. churcherii*) were recovered from burrow casts in this unit.

Unit 2: Silty diamicton,

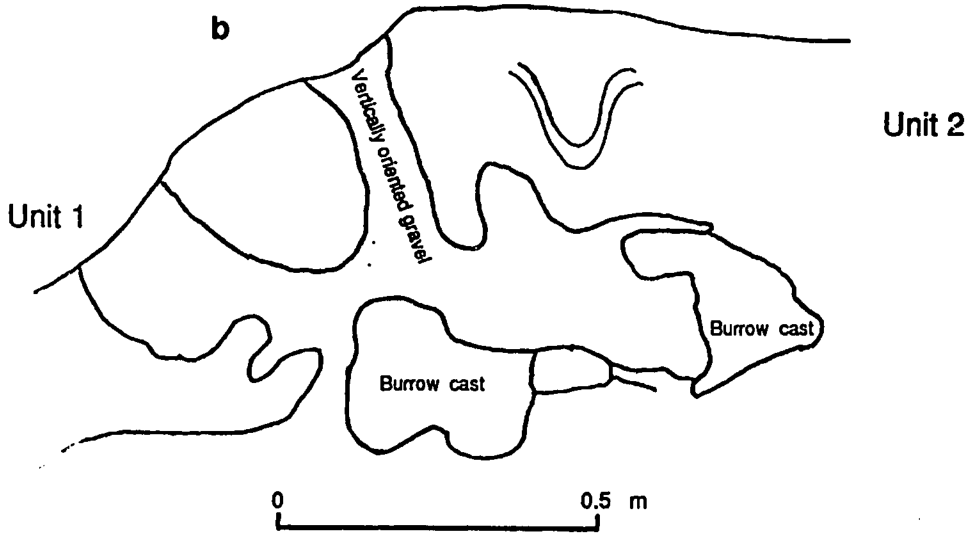
This unit was only found in the northern half of the section. The contact with Unit 1 was near-vertical in the middle of the section, and planar in the northern half of the section (Figure 14). Lower in the unit, the vertical contact in the centre of the section was abrupt and sharp where a silt lens made contact at approximately 3.5 m below surface (Plate 13, Figure 14). Approximately 1.5 m above that, the contact was gradational, as the gravel bed was interbedded with the silty diamict. The gravel bed became discontinuous, and eventually pinched out to the north into the silty diamict (Plates 12 and 13, Figure 14). Nearer to the surface, the contact between the silty diamict and material identified as burrow cast fill was indistinguishable. The contact with the underlying gravel was abrupt and planar. The unit was primarily massive throughout the bottom two-thirds, but had dish-shaped structures locally in the upper third at the north end of the section (Plate 14). It was grayish olive (Munsell 5Y 5/2) in colour. At the north end, the base of the dish-shaped or involution structures included underlying gravel unit (Plate 14). Burrow casts truncated the gravel and not the dish-shaped structures. Clast composition of



a

Plate 14, a and b: The north end of section 2, the Seward site. Burrow casts crosscut involution structures, both in the gravel, and in the silty diamict.

b



the silty diamict was similar to the other two sections in being almost purely quartzitic. There were no Shield clasts found in this unit. A number of identifiable prairie dog (*C. churcherii*) bone elements were recovered from this unit, but no burrow casts were detected.

Interpretation - section 2

A review of several relationships in the sediment is necessary to interpret this section. In the southern half of the section, the upper third of Unit 1 became increasingly dominated by silty and sandy beds from south to north (Figure 14). Also, increasing bioturbation of the unit by prairie dogs occurred to the north. Near the middle part of the section, the burrow cast fills were indiscernable in colour or apparent texture from the silty diamict in the northern half of the section. Bones and burrow casts of the extinct prairie dog, *C. churcherii*, were found in the gravel, whereas only prairie dog bones were found in the silty diamict. The contact between the silty diamict and the lower clay beds in the middle part of the section (Plate 13) was an abrupt vertical truncation of the clay beds. Abrupt vertical contacts were also observed where burrow casts intruded into gravel beds in the middle part of the section (Plate 12). The gravel bed in the middle part of the section (Plate 12) became discontinuous and pinched out to the north, and was interbedded with the silty diamict (Plate 13). It was therefore deposited contemporaneously with the parent material of the silty diamicton. The silty diamict was at about the same elevation and stratigraphic position as the silty overbank deposit found in section 1. Originally, the silty diamict was likely deposited in an overbank or low-energy fluvial environment with fluctuations in flow that laid down a number of gravel stringers. The upper regions of the overbank deposit were later cryoturbated (Figure 15), mixing the clasts into the enclosing silty sediments. Subsequently, the unit was bioturbated by the burrowing activities of the extinct prairie dog, *C. churcherii*. The deep-burrowing rodents truncated the horizontal beds in the middle part of the section, causing the vertical contact between the gravel and diamict units. Burrow casts were not detectable in Unit 2 because the unit was composed of material almost uniformly mixed by cryoturbation and bioturbation. The burrow cast fill was likely an overbank deposit, cryo- and bioturbated into a diamicton, and later removed during opening of the pit.

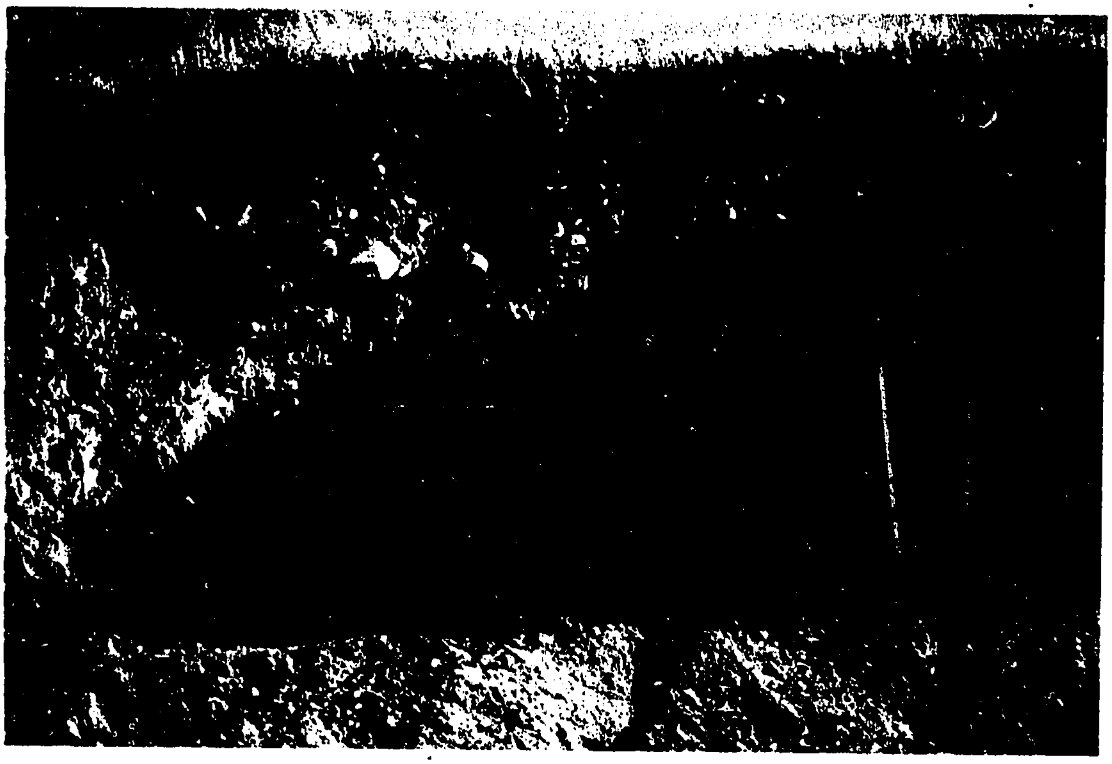
Section 3

This section was oriented roughly 90° to section 2 and trended approximately east-west (Figure 13). The western half of the section had collapsed so that the section was not directly connected to section 2. However, the lower two units could be correlated (Plate 15). The section was somewhat smaller than section 2, both vertically and horizontally, as it was only had a maximum height of about 3.5 m and was about 26 m long.

Unit I: Interbedded gravel and sand,

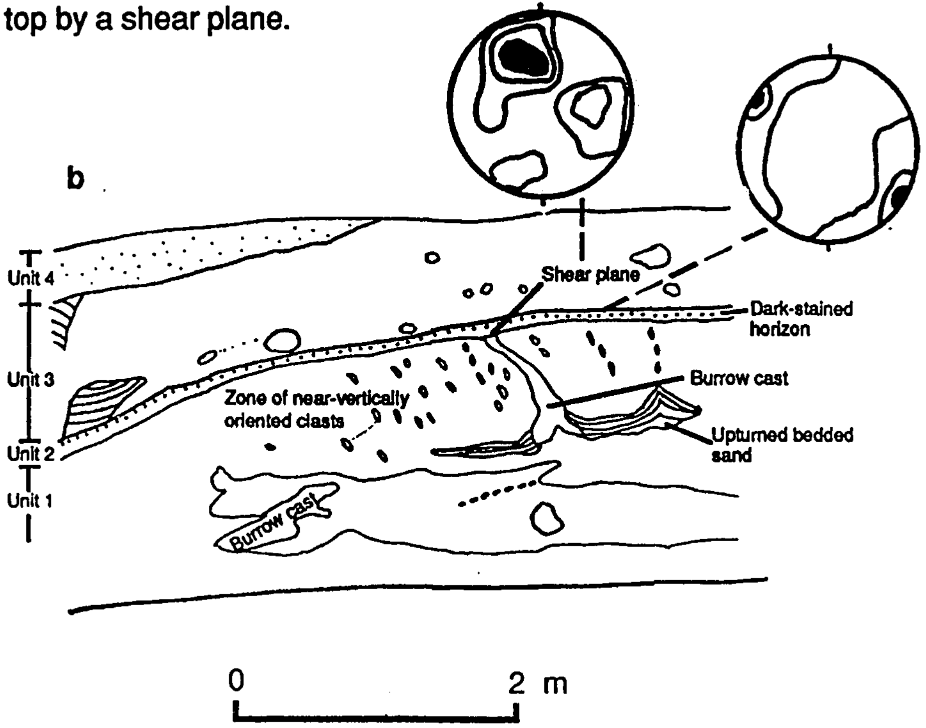
This unit is equivalent to Unit 1 described in section 1. The upper contact was unconformable and abrupt, dipping to the east by 1.5 m over its length. It varied in thickness from about 2.5 m at the west end of the section to about 1 m at the east end. The composition of the gravel varied from being clast-supported in the western third to being predominantly matrix-supported in the eastern third. The middle third was somewhat intermediate in composition

Plate 15: Southeast view with section 2 to the right, and section 3 to the left. Units could be correlated between the two sections on the basis of elevation.



a

Plate 16, a and b: The middle third of section 3. Burrow casts crosscut areas of near-vertically oriented clasts. The cast in the middle of the plate is truncated at the top by a shear plane.



(Plate 16). The interclast matrix was medium sand in zones of clast-supported gravel, and a fine-grained sand or silt in zones of matrix-support. Near-vertically oriented clasts were dominant in the upper metre of the unit for about the middle third of the section (Plate 16). In that area, burrow casts were found in association with the vertically oriented clasts, either directly below them in an underlying, undeformed sand lens, or crosscutting the vertical gravels. In one case, a cast was traced up to the top of the unit, but it was truncated by a shear plane at the contact between units 1 and 2. At the eastern end of the section soft sediment deformation structures (ball and pillow) were noted near the upper contact (Plate 17). They were asymmetrical as the tops were attenuated to the south. Two deformed vertical burrow casts were observed near the upper contact, in the zone of soft-sediment deformation structures (Plate 17). The burrow casts crosscut bedding structures in the lower, undeformed zone of the unit, but were deformed equally and in the same direction as the sand beds near the upper contact. In the lower, undeformed zone of the unit the burrow casts were tube-shaped and about 14 cm in diameter, but higher in the section they were attenuated to about 2 cm thick and 18 cm wide near the upper contact. Thin, beds of sand in the shear zone separated the burrow cast from the overlying unit so that contact with it was not made. The burrow cast fill was compact, with clasts comprising only about 10 to 20 percent of the volume. The cast fill matrix was grayish olive (Munsell 5Y 5/2). Clasts found in the burrow cast were primarily quartzitic, and none was of Canadian Shield provenance.

a

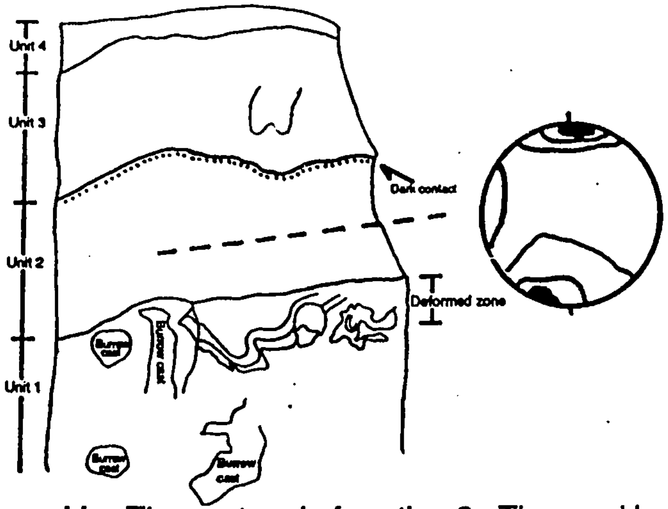
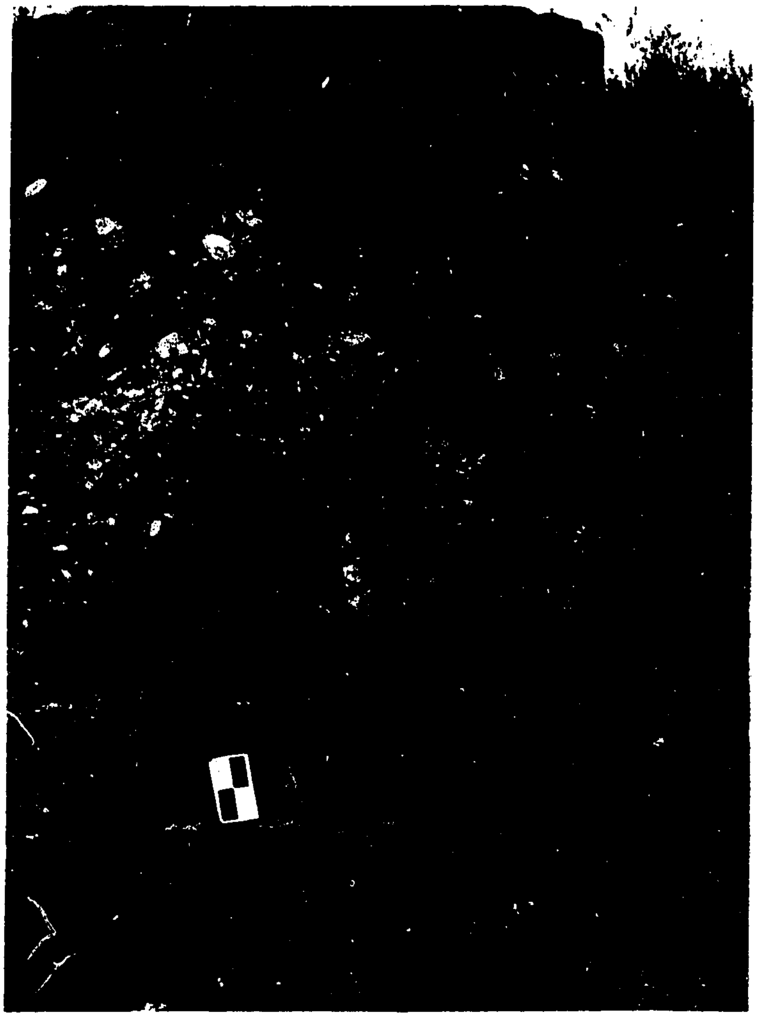


Plate 17, a and b: The east end of section 3. The sand lens in Unit 1 contained numerous prairie dog burrow casts. A soft-sediment deformation zone existed near the upper contact in Unit 1 where both the sand beds and burrow casts were deformed.

b



Unit 2: Silty diamicton,

This unit was in the same stratigraphic position as Unit 2 in section 2 and had many similar characteristics. It was a matrix-supported silty diamict that was grayish olive (Munsell 5Y 5/2) in colour. The lower contact was unconformable, apparently truncating sedimentary structures and burrow casts in the underlying unit (Plate 17). The upper contact was abrupt and dipped to the east at a low angle. Unit 2 was thicker to the east (to about 1.3 m) than the west (about 15 cm) so that the unit was approximately wedge-shaped. The unit varied in colour, being grayish olive (Munsell 5Y 5/2) for all but the upper 3 cm that were stained dark (dark olive 5Y 4/4). The staining was uniform over the upper contact of the unit. Fabrics from this unit plotted on a Schmidt Equal Area projection show a strong orientation of the first eigenvalue, (E1=75) in a north-south direction (306°), with a gentle dip angle (6°) (Plate 16). Prairie dog bones were found in this unit at 2 m west of the eastern end of the section, but burrow casts could not be detected. At that location, the fabric showed a north-south (6°) long-axis orientation that was fairly strong (E1=78) with a low dip angle (5°) (Plate 17).

Unit 3: Interbedded sand, gravel, and diamict,

This unit was comprised of poorly-sorted, planar crossbedded, interbedded coarse sand, pebbles, cobbles, boulders, and diamicton balls. Sand beds at the eastern end of the section were draped over a diamict ball. In the middle of the section, sand beds were overlain by diamict (Plate 16). A 3 m wide and 30 cm thick area of undeformed planar bedded sand was located between the two zones of diamict. The sand had a dull yellowish orange (Munsell 10YR 6/3) colour. The diamict was massive and blocky, had a dull yellowish brown (Munsell 10YR 4/3) colour, and had a bottom contact that was sharp and erosional (Plate 17). Boulders of Canadian Shield granite and schist were commonly found in this unit, both in the diamict and interbedded in the sand. A fabric from the middle of the diamict at 12 m west of the eastern end produced a mean northwest-southeast lineation vector of 338°, a high dip angle of 40°, but was not strongly oriented (E1=58) (Plate 17).

Unit 4: Massive sandy unit,

This unit was discontinuous and pinched out to the west. Its maximum thickness was nearly 50 cm at the eastern end of the section. The unit was massive and displayed conchoidal fracture. The bottom contact undulated, while the surface remained nearly planar and dipped to the east at about 15°. The upper 15 cm of the unit was organic-stained brownish black (Munsell 7.5 YR 2/2). Underlying sediments were also stained, but to lesser degrees. Colour near the base of the unit was dull yellow orange (Munsell 10YR 6/3).

Interpretation - section 3

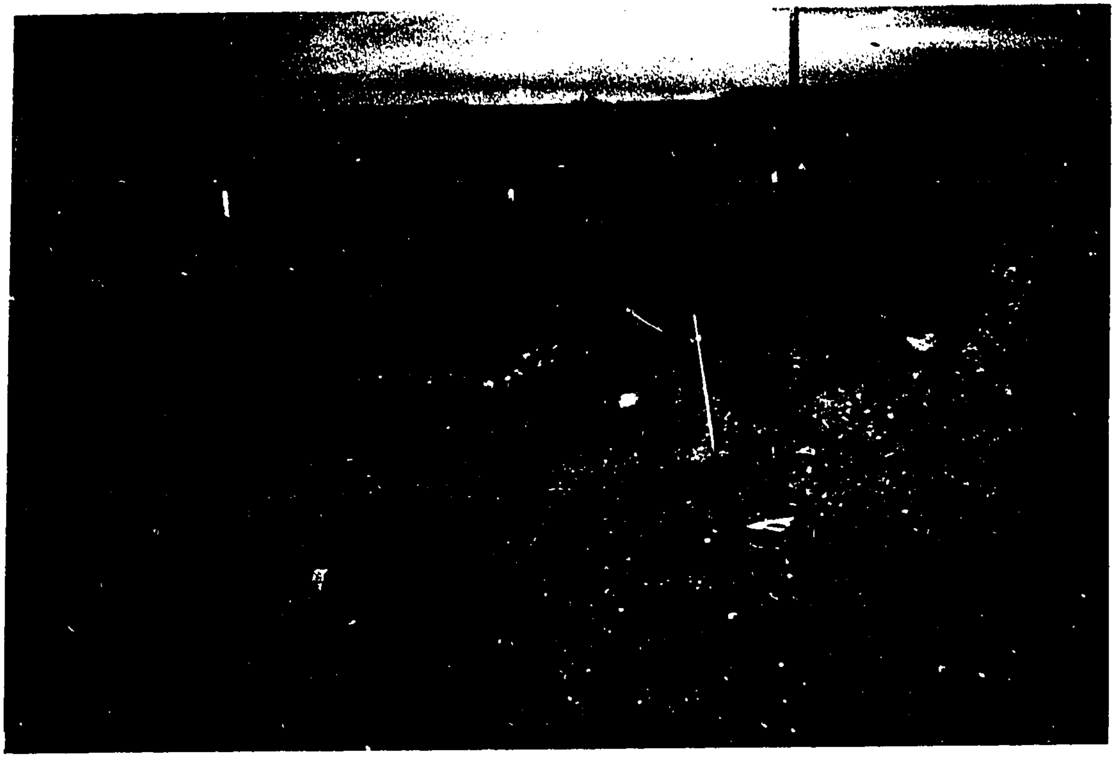
Unit 1 is another outcrop of the Miocene-age gravel. Near-vertical orientation of clasts in the middle of the section likely occurred as a result of periglacial activity at the same time as the periglacial activity observed in sections 1 and 2. Zones with vertically oriented clasts were likely favoured by prairie dogs as tunneling would have been easier therein than in adjacent, zones of horizontally bedded clasts. Evidence of burrowing activity increased towards the eastern end of the section where the sediments were finer-grained. Intense burrowing of the upper, finer-grained sediments resulted in the formation of the overlying silty diamict (as demonstrated in section 2). Clasts in Unit 2 and sediments and burrow casts in Unit 1 were deformed to the southeast, likely by glacial thrusting in a saturated environment. The same thrusting event caused the truncation of burrow casts along a shear plane at the base of Unit 2. Thrusting of Unit 2 likely caused even greater turbation of the unit. Interbedded sorted sand, gravel, and diamict in Unit 3 gives further evidence for the occurrence of a saturated subglacial environment. The massive sandy deposit on top of the outcrop was likely eolian in origin, and its organic staining was due to the formation of the Ah horizon of a dark brown Chernozemic soil. Eluviation of organic colloids from the Ah layer that illuviated at the top of Unit 2 is likely the cause of dark staining at that location. The finer texture of Unit 2 caused perching of the colloids on that surface, so that organics became concentrated there.

Section 4

Section 4 was oriented nearly north-south (Figure 13). It was a short (8.7 m) section, but contained all four lithologic units (Plate 18). The section was cut along the road down into the pit, so is thicker at its north end. Additional evidence for some processes observed in section 3 were present in section 4.

Unit I: Interbedded gravel and sand

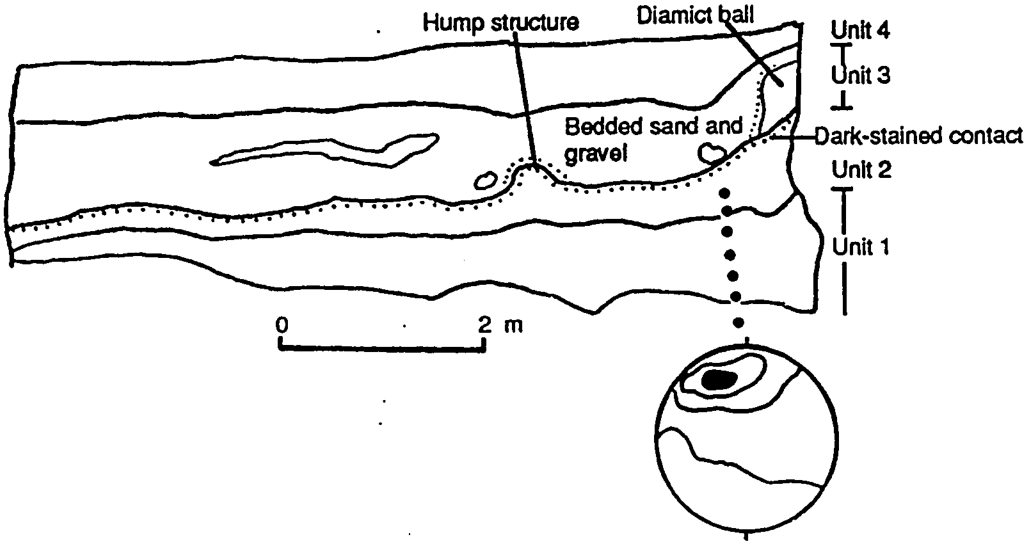
This unit was connected to and continuous with Unit 1, section 3. Numerous prairie dog burrow casts, some containing bones, were located in



a

Plate 18, a and b: Section 4 at the Seward site. The right (north) side of the figure is connected to the east end of section 3. Unit 2 is thin south of the hump structure, but thicker to the north of it. The bedded sand and gravel in Unit 3 is draped over both the hump structure and a diamict ball at the north end of the section.

b



the sand lenses at the top of the unit (Plate 18). Cast fills varied from silty-clay (grayish olive 5Y 5/2) to sandy (pale yellow 5Y 8/3). Clasts comprised only about 10 percent of fill volume, and were identical in lithology and shape to the underlying gravel. Asymmetrical soft-sediment deformation structures (ball and pillow) were present in the sand throughout the northern third of the section. The tops of the ball and pillow structures were attenuated to the south. The upper contact was planar, but dipped slightly (~15°) to the south. No soft sediment deformation structures were found in the southern 5 m of the unit, south of the hump-shaped structure in Unit 2, in the middle of the section. Burrow casts containing Richardson's ground squirrel (*Spermophilus richardsonii*) bones were present here and in other area sites. They had smaller diameters and fills that were looser, uncompacted, and darker than the prairie dog burrow casts and contained Canadian Shield granite and schist clasts. Bones found in these cast fills were stained reddish-brown and, along with the casts, were judged to be Holocene intrusives.

Two AMS radiocarbon dates were obtained on bone retrieved from burrow casts in the sandy, undeformed part of this unit. One (TO-1143) produced a date of 17,060 ±180 yrs B.P. This had the lowest collagen content of any bone sample processed at IsoTrace. The second sample, TO-1306, contained insufficient collagen to produce a date.

Unit 2: Silty diamicton

This unit was continuous with Unit 2 in section 3. The upper contact of this unit was planar and dipped to the south except at 3 m south of the north end of the section (Plate 18). There, the section thickened about 35 cm within the short space of about 1 to 1.5 m, producing a "hump-shaped structure." Fabrics taken in the unit produced strong first eigenvalues (E1=63) relating to mean lineation vectors from the northwest to southeast (344°) and a moderately low dip angle (24°) (Plate 18). Prairie dog bones were found at about 3.5 m south of the north end of the section, but burrow casts could not be detected. Burrow casts containing Richardson's ground squirrel (*S. richardsonii*) bones were noted at the south end of the section and could be traced into the overlying unit. The ground squirrel burrow casts had a smaller diameter than the prairie dogs , while the fill material was poorly compacted and contained clasts of Shield provenance. The unit changed colour and structure near the upper contact, becoming darker (Munsell 5Y 3/2, olive black) and blockier. The dark portion of the unit was heavily intruded by rootlets from surface vegetation. A bulk ^{14}C date on the dark-stained horizon produced a date of 9,170 ±150 yrs B.P. (AECV 631C). The organic material was only pretreated with HCl due to its low organic content.

Unit 3: Interbedded sand, gravel, and diamict

The majority of volume in this unit was comprised of tabular cross-bedded sand and gravel (Plate 18). Beds were draped over a large soft clast of diamict at the north end of the section giving the beds a high angle there. Sorting was poor, with large variations in grain size in a small area. Clasts were frequently angular. The bedded sand had a fairly constant dip of about 30° toward the southeast. The bottom contact of the unit was abrupt, with the beds in the unit conforming to the hump at the top of Unit 2, in the middle of the section. Small diameter burrow casts containing Richardson's ground squirrel (*S. richardsonii*) bones were observed.

Unit 4: Massive sandy unit

This unit was hard, dense, massive, and very resistant, showing "conchoidal fracture". Clasts were very rare, being concentrated in a line near the surface. Of these Canadian Shield granitic clasts were common. The lower contact was planar. Colour varied with depth, the upper 15 cm being organic-stained brownish black (Munsell 7.5 YR 2/2) and dull yellow orange (Munsell 10YR 6/3) near the base.

Interpretation - section 4

The units were equivalent to those in section 3. Unit 2 was thin in the southern half of the section, but thicker to the north of the hump (Plate 18). Soft-sediment deformation structures in unit 1 only occurred north of the hump. Cast-fill material closely resembled the overlying diamict in colour and texture, indicating that the diamict was the parent material for the fills. After burrow abandonment, material from Unit 2 slumped into the burrow, preserving the burrow structure as a cast. The original result would have been a cast that was continuous through the two units, but the casts were truncated at the top of Unit 1. Several features may help to explain why the casts were not continuous. First, clast alignments in the silty diamict show a strong orientation to the south-southeast. The hump structure in section 4, soft-sediment deformation structures and truncated burrow casts, and pebble alignment in sections 3 and 4 suggest ice-thrusting to the southeast under saturated conditions. The Middle

Wisconsinan prairie dog burrow casts were therefore truncated by ice-thrusting of the overlying silty diamicton. Later, saturated glaciofluvial sediments and soft-sediment clasts (diamict balls) were deposited in an englacial or supraglacial position and subsequently let down on top of Unit 2, with the bedded sands draping both the microtopography caused by the ice-thrusting and diamicton ball inclusions. Unit 4 was deposited after deglaciation, likely by eolian processes. Formation of the topsoil occurred sometime <u>after</u> the deposition of the eolian unit as there are no buried soil horizons in the section. Organic colloids were translocated down to the top of Unit 2 where they were perched and absorbed into the sediment, resulting in staining. Rootlets from surface vegetation heavily intruded the dark-stained layer at the top of Unit 2 in order to tap the organics. The date on the soil, 9,170 ±150 yrs B.P. (AECV 631C), may reflect the age of the oldest soil humic acids in the overlying soil, but likely would be too young for that as the pretreatment did not include the second step, washing with NaOH, which eliminates the younger organic contaminants, such as rootlet exudates. Tunneling throughout the section by Richardson's ground squirrels was accomplished after formation of the topsoil as the cast fills contain portions of the dark-stained organic Ah horizon.

Bones of the prairie dogs recovered from the Seward site were extremely poor in collagen. Other samples had from about 5 to 22 times the collagen content of the dated sample at the Seward site (Table 6). Low collagen contents can be a problem as the third washing dating pretreatment, the step that removes insoluble humic acids, is reduced. This means that humic acids may not be completely removed during processing, resulting in a "bad" date. The dark-stained layer at the top of Unit 2 demonstrates that there were free humic colloids being translocated downwards and deposited at the Seward site. Likely, some of these Holocene humic acids contaminated the collagen-poor prairie dog bone, resulting in a date that is too young.

Summary and interpretation- the Seward site

The fluvial environment during the deposition of the Hand Hills gravel was extremely variable in time and space. Locally, water flowing at fluctuating velocities deposited thin interbeds of moderately large clasts and fine-textured sediments. These sediments were later reworked by intense periglacial activity. The periglacial conditions were so extreme that they caused the formation of ice wedges deep into sorted gravel deposits. Sediments deposited in low-energy subaqueous environments subject to periodic flooding were cryoturbated, forming a diamicton. This diamicton acted as the parent material for many of the burrow cast fills. The finer sediments were a favoured habitat for the deep-digging Middle Wisconsinan prairie dogs. Prairie dogs had at least 11,000 yrs to mix the finer sediments, to even greater depths and extents than the periglacial activity, thereby increasing the extent(s) of Unit 2. Unit 2 would have been the parent material for many burrow fills as the burrows were abandoned during and at the end of the colony's life. Presence of burrow casts to depths of 3 m indicates that, at least locally, not much glacial erosion took place during the Late Wisconsinan. Therefore, the stratigraphy in the Seward site is probably not missing any post-Miocene to pre-Late Wisconsinan sediments, as they were probably not deposited. This is also based on the assumption that if there were older glacial deposits at the site, that were subsequently eroded, evidence of them in the form of Canadian Shield clasts would have been preserved in the burrow cast material, just as the Holocene ground squirrel burrow casts in section 4 contain Shield clasts. The Pleistocene prairie dogs were much more active excavators than the ground squirrels, turning large sections of fluvial material into a bioturbated diamicton. The diamicton should contain elements of the material present at the surface during the Middle Wisconsinan. Therefore, Late Wisconsinan glaciation was very likely the only glaciation to submerge the Hand Hills.

The prairie dog colony was extirpated by climatic change during the Late Wisconsinan glaciation, some time after about 22,000 yrs B.P. Evidence of intense periglacial conditions during either the Middle Wisconsinan or onset of the Late Wisconsinan at the Seward site was not detected. The flow direction of the Laurentide ice sheet, at the time the Hand Hills were submerged, was from north-northwest to south-southeast. Flow direction was indicated by asymmetrical ball and pillow structures, attenuated burrow casts, microtopography in ice-thrust sediments, and fabrics from thrusted silty diamict. Saturated basal conditions were dominant during thrusting. Glacial flow over the top of the Hills indicates that the ice sheet was thick and topographically unconstrained.

Unit 3 was deposited by stagnant ice. Englacial blocks of diamict and beds of poorly-sorted, bedded sand and gravel were let down over both pre-existing microtopography, and each other, producing contacts that were non-erosional. Conditions favouring eolian erosion and deposition existed some time after deglaciation, producing Unit 4. Soil later formed on the stabilized eolian deposits, and some of the humic fraction was translocated downward and deposited within both the sediment and fossils below.

K & T site

Introduction

This site is located on the northeast corner of the western member of the Hand Hills at about 1,020 m (3,350 ft) asl (Figure 9). It is about 7.5 km east-southeast of the Winter site, in S6 T30 R16 W4th, or at 51°32'10" N latitude and 112°14'10" west longitude on the NTS mapsheet 82 P/9. The pit was being operated by K&T Trucking of Hanna, Alberta, and has been active almost continuously since 1984. It was visited briefly by Dr. Burns and me during the late summer of 1986. Remains of prairie dogs were located in 1987 by D.B. Schowalter, but their stratigraphic context was unclear. Extensive logging of the sediments started late in 1988, and continued intermittently as new exposures were excavated, until 1990. Four sections were examined allowing a three-dimensional view of some sediments (Figure 15). The pit is still active so that none of the features noted will be preserved indefinitely.

Site descriptions

Four sections in three walls of the pit were logged between 1988 and 1990 (Figure 15). The walls were nearly continuous, making correlation of units straightforward. Four lithologic units were observed at the site, but the stratigraphy was complicated by several post-depositional processes. The four units were: bedded gravel and sand, matrix-supported diamict with vertically oriented Cordilleran clasts, matrix-supported diamict with near-horizontal clasts that may include clasts of Canadian Shield provenance, and poorly-sorted

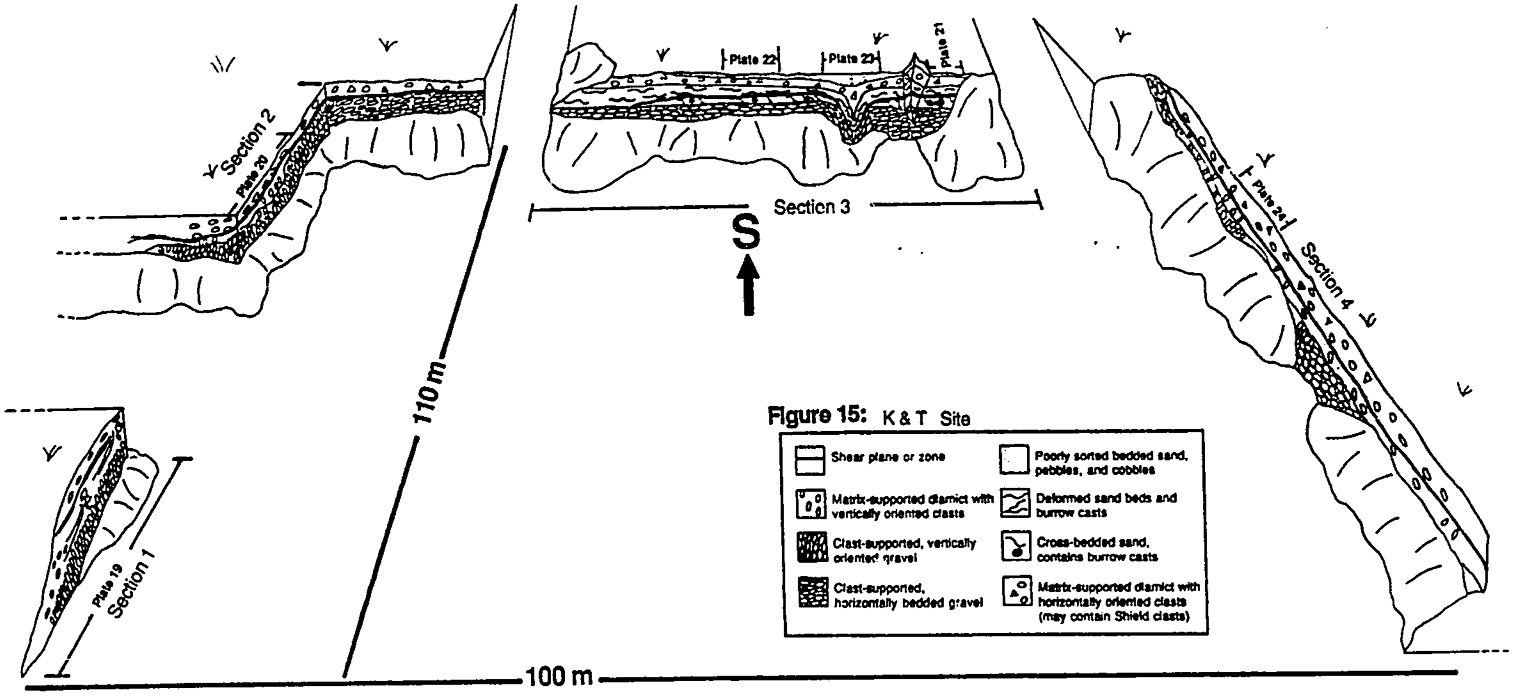


Figure 15: K & T Site

interbedded sand and cobbles. The second matrix-supported diamicton was probably a reworked portion of the first, so they are described together under the general heading of silty diamicton. The large number of fabrics taken at this site makes discussion of eigenvectors, and mean lineation and dip directions in the descriptions unmanageable, so they will be included in the plates only.

Sections 1 and 2

These sections were situated along the east wall of the main pit, and ran almost directly north-south (Figure 15). The middle third of the wall was removed during eastward expansion of the pit and was not logged. The character of the section changed so greatly between the northern (1) and southern (2) thirds that it is best to describe them separately. Only two of the four main lithologic units found at the site were located in sections 1 and 2, possibly because the upper two were removed when the pit was opened. Canadian Shield clasts were common on the surface, but could not be found within any units in sections 1 and 2. Also, no fossils or trace fossils of prairie dogs were found in sections 1 or 2.

Section 1

This section was at the northeast corner of the site (Figure 15). It was visited during a field trip of the Society of Vertebrate Paleontologists in 1988, but was eliminated during pit expansion in 1989.

Unit 1: Clast-supported gravel,

Only a thin exposure of gravel was found at this section (Plate 19). Clasts were primarily Cordilleran quartzites (>90 percent) and cherts. They were rounded to sub-rounded and primarily blade- or disc-shaped. The largest clasts had long axes up to about 20 cm, but averaged about 15 cm. The interclast matrix was a well-sorted medium sand. Clast orientation varied locally from sub-horizontal at the north part of the section, to near-vertical to the south.

Unit 2: Silty diamicton

This unit was comprised of several blocks of grayish olive (Munsell 5Y 5/2) diamicton that were overlain or underlain by shear zones (Plate 19). Two soft clasts of sorted sand were observed in the section, each at the end of a shear zone. Shear zones changed direction from planar, dipping to the north, to near-vertical in areas closer to the soft-clasts (Plate 19). The soft clasts were attenuated or rolled up in the up-dip direction of the shear zone. The larger of the two (~40 cm), at the south end of the section, was rounded in profile and contained several small flame structures in the higher, northern side of the soft clast (Plate 19). The smaller soft clast was in the middle of the section, had the northern end detached/attenuated and stacked over its south end (Plate 19).

The shear planes were very distinctive due to dark organic staining. Fabrics from the shear zones show a very strong orientation from northwest to southeast. The uppermost shear zone (about 40 cm below the surface) contained a thick dark band of organic material (Plate 19). The black (Munsell

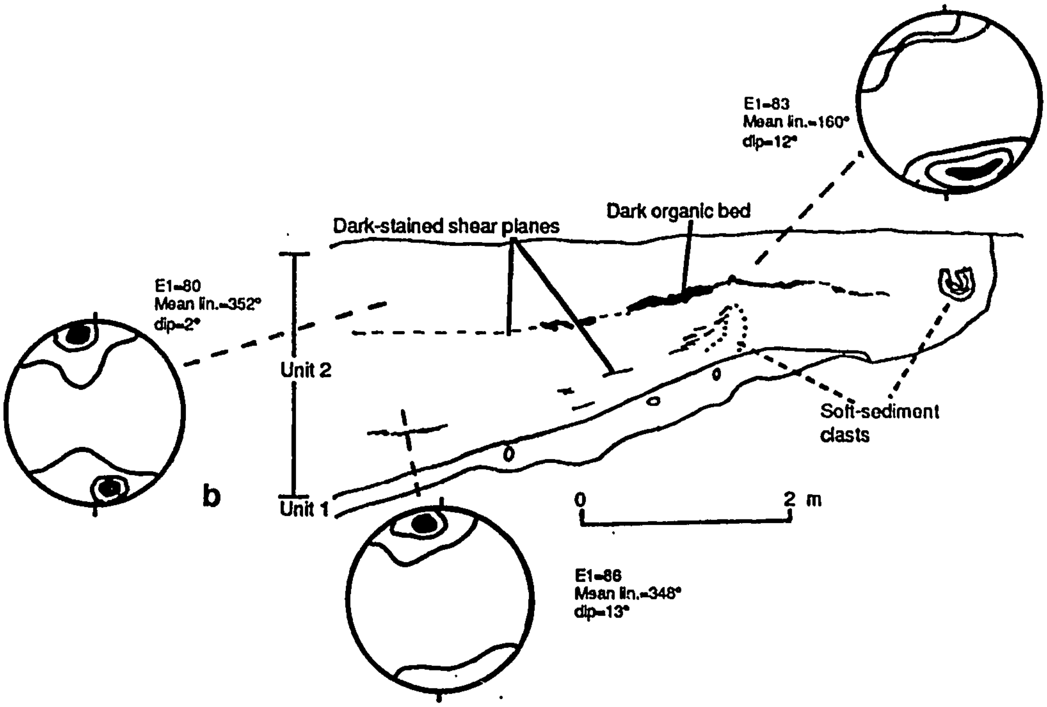
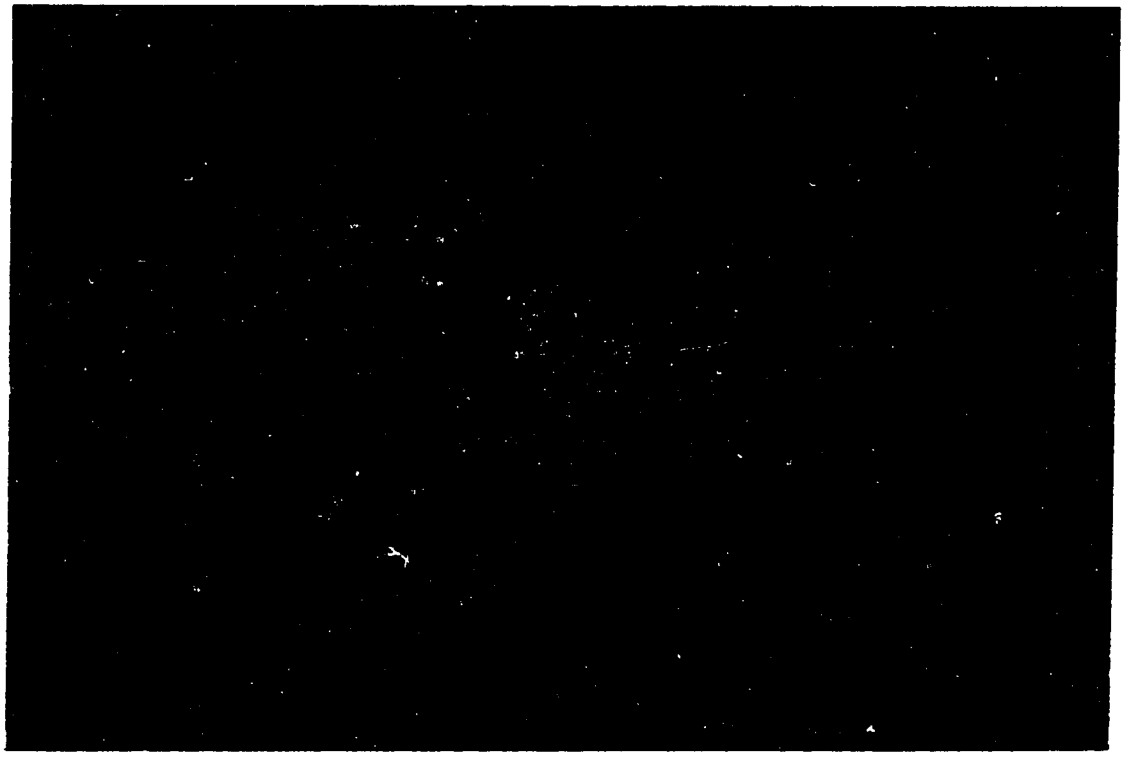


Plate 19, a and b: Section 1, the northeast corner of the K&T site. There were multiple dark-coloured shear planes throughout Unit 2. A bed of organics of indeterminate origin was found approximately 50 cm below the surface, along a shear plane.

a



7.5YR 2/2) organic material dried into friable granules, and could be easily broken up into a fine powder. It was extremely heavily intruded by rootlets from surface vegetation (see pp. 128-129 for discussion).

Section 2

Unit 1: Clast-supported gravel,

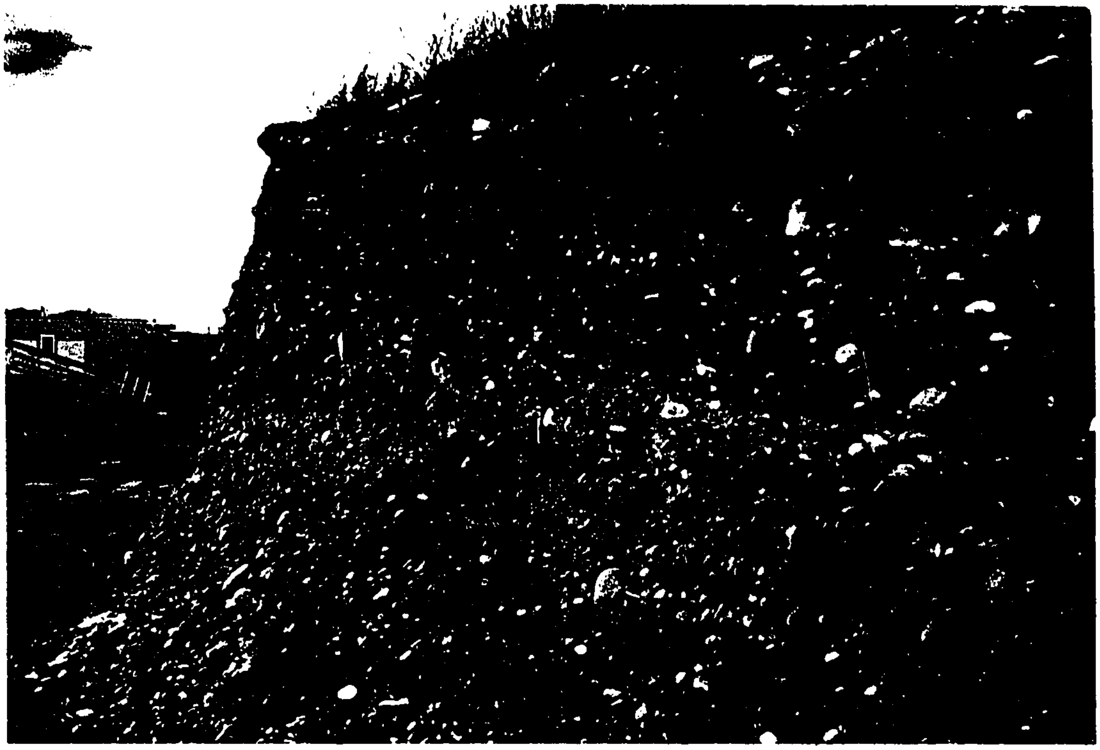
This unit is laterally continuous with, and of identical composition to, Unit 1 in section 1, directly to the south. The units were also similar in that they were both not well-exposed. Where the gravel was visible, it had an almost uniform near-vertical orientation (Plate 20).

Unit 2: Silty diamicton

This unit was divided into a lower and upper zone. Both zones had similar textures, were matrix-supported and had the same proportion of clasts (~15 percent of volume) to matrix. The clasts were primarily Cordilleran quartzites (>90 percent) and cherts. Gravel clasts were rounded and well rounded and blade- to disc-shaped. The largest clasts were about 15 cm long.

The lower zone had a sharp, but conformable horizontal contact with the underlying gravel. No bedding structures were noted in the matrix - it was uniformly massive. Long-axis orientation of clasts in the lower zone was near-vertical through the lower zone, but became near-horizontal towards the transition into the upper zone (Plate 20).

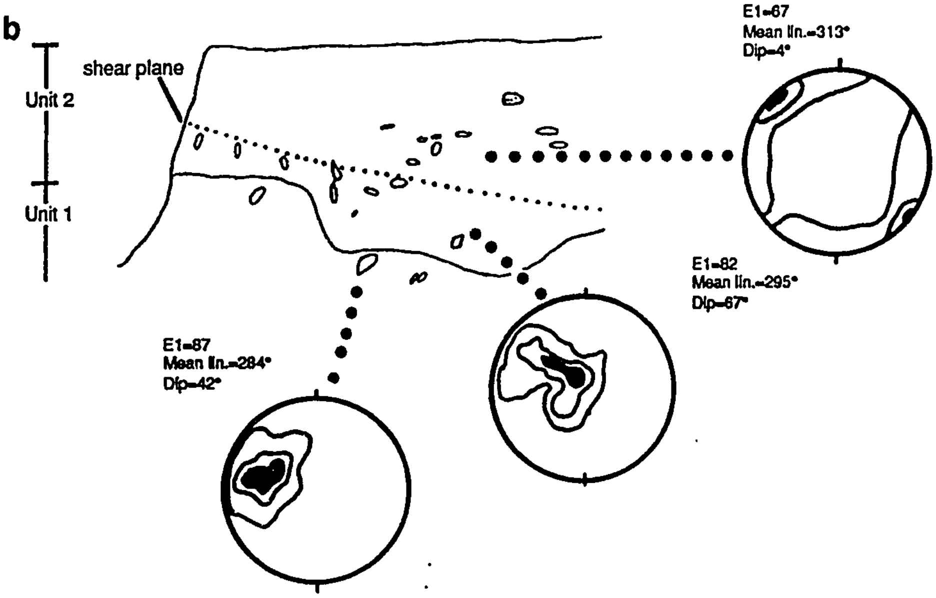
The upper diamict was darker and exhibited a series of dark bands, similar in appearance to the shear planes in section 1. The bands were thin (~3 mm) and laterally continuous (Plate 20). The bands were interrupted by



a

Plate 20, a and b: The long axes of clasts below the shear line were generally near-vertically oriented, whether they were in Unit 1, or Unit 2. Above the shear line, the long axes had a near-horizontal orientation.

b



gravel clasts, but continued at the same elevation and angle on the other side. Clasts in the upper zone were fairly strongly oriented to the southeast (Plate 20). The contact between the two zones was near-planar, dipping to the southeast. Canadian Shield clasts were common on the surface, but could not be found in the section. There were no prairie dog fossils or trace fossils found in Section 2.

Interpretation - sections 1 and 2

Unit 1 is likely a member of the Hand Hills gravel. Unit 2, the silty diamicton, probably originated as overbank or low energy alluvium deposited contemporaneously with the gravel. Clasts in the silty diamict were probably originally deposited during short-lived high energy events (likely small-scale floods or avulsions). The clasts in the silty diamict were oriented to near-vertical attitudes during an old (pre-Middle Wisconsinan) phase of intense periglacial conditions, as at the Seward site. Near-horizontal orientation of the clasts in the silty diamicton, direction of deformation of soft-sediment structures, and dip direction of the shear planes, indicate redeposition/deformation by thrusting of saturated materials by a glacier flowing from the northwest. Clasts with near-vertical orientation that were below the shear plane were not reoriented by the glaciotectonism. The black organic material in section 1 was deposited between two stacked blocks of silty diamict. Two conventional radiocarbon dates were obtained on the black material collected from section 1. The first date was performed after pretreatment with HCl alone to remove older carbonate, transported in by solution. A date of 22,710 ±480 B.P. (AECV 632C) was returned after the first pretreatment. Extra material was treated also with

NaOH in order to remove modern organics - a procedure which should yield an older date. The second treatment yielded a younger date of 19,730 ±360 B.P. (AECV 654C). The black material was tested for palynomorphs three times, using two strengths of HF acid pretreatment, and one untreated sample. None of the treatments revealed any palynomorphs although the sample was rich in organic material (Bachhuber, pers. comm. 1990). While the dates seem to correspond with bone-collagen dates from the area (Table 6), the results after different pretreatments (giving younger instead of older dates) and lack of palynomorphs suggest dates derived from this material be viewed cautiously. The dark coloration of the shear planes/zones may have resulted from deposition by thrusting of smaller amounts of the same organic matter from the same source as the layer found higher in the section, or as a result of perching of translocated organics. The dark organic material may have originated as Cretaceous coal (common in the area) which had been transported uphill and deposited glacially. If the organics are coal, the material could have been contaminated with young ^{14}C from at least two sources: the exudates from the numerous rootlets found in it, and the translocation of humates from the surface (as demonstrated at the Seward site).

Section 3

This section constituted most of the south wall of the pit (Figure 15). It contained the most complete stratigraphy at the site, but was complicated by several post-depositional features.

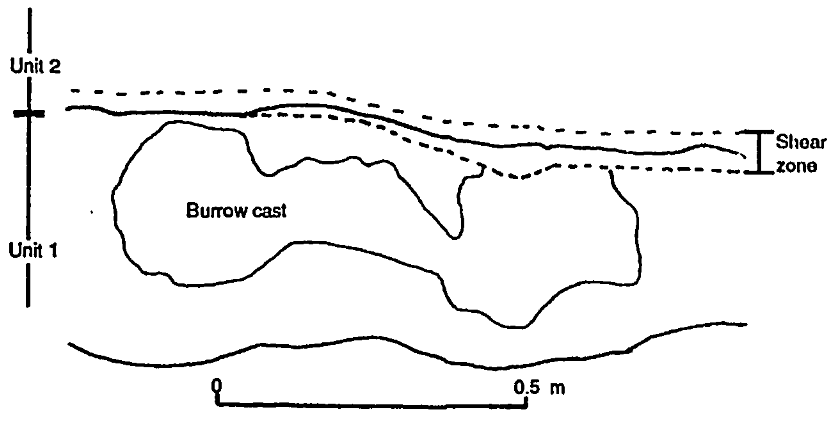
Unit I: Interbedded gravel and sand,

This unit was comprised of interbedded gravel and sand in the lower two-thirds (about 2 m), and well-sorted sand in the upper third that was either cross-stratified or had deformed bedding. Gravel lithologies were primarily Cordilleran quartzites and cherts. The contact between the gravel and sand was gradational and conformable. The upper sand lens was undisturbed for about 3 m at either end of the section, but had increasing amounts of deformation towards the middle of the section. The contact with the disturbed part of the sand was approximately planar (Plate 21), but both sides dipped down towards the centre of the section. The deformed sands had asymmetrical soft-sediment deformation structures which indicate thrusting from the northwest (Plate 22a). Prairie dog bones and burrow casts were numerous in the bedded sand but only prairie dog bones were found in the deformed sand (Plate 22b).

A wedge-shaped structure was located in the section (Plate 23). The wedge was about 1.8 m wide, and descended to almost 3 m below the surface. All lithologic units in the section were deformed downwards within the cast. The deformed sand unit, containing attenuated prairie dog burrow casts, was deformed down within the wedge in a series of faults instead of by soft-sediment deformation (Plate 23).

Unit 2: Silty diamicton

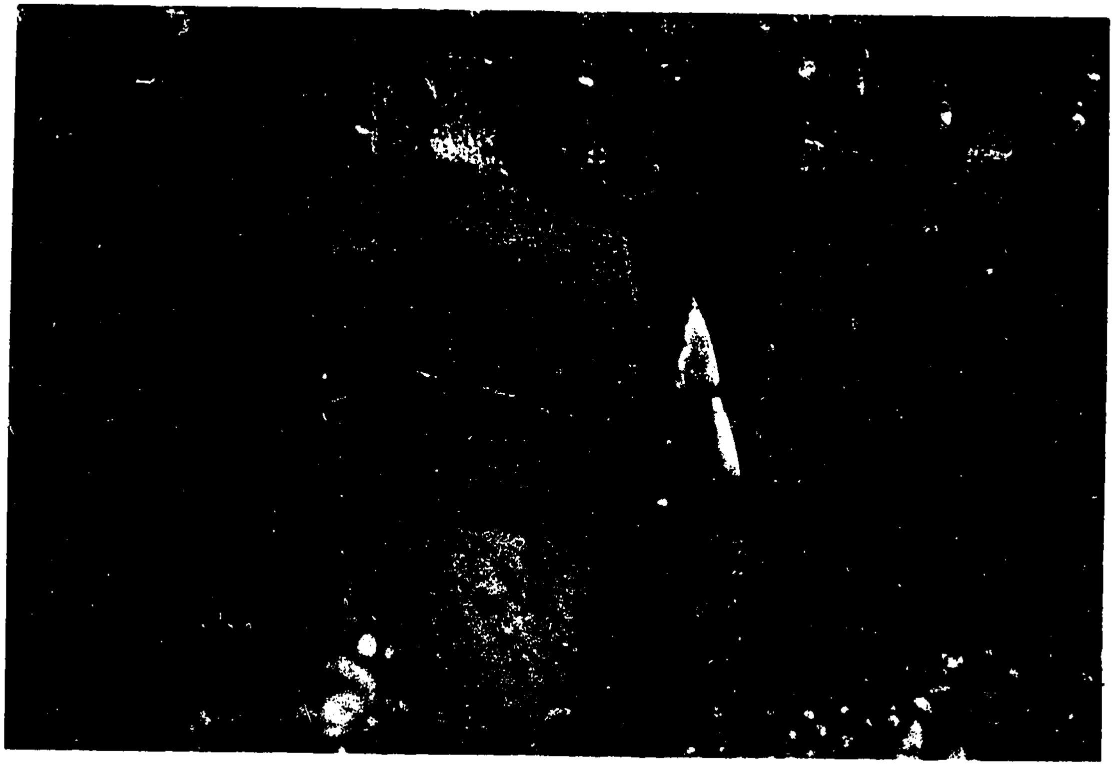
This unit is laterally continuous with the olive-gray diamict described in sections 1 and 2. The lower contact is abrupt, and gives the impression that shearing has occurred where burrow casts are at the contact in the sand lens, because the cast is truncated by thin beds of sand just before entering the



b

Plate 21, a and b: A single burrow cast in the sediments of Unit 1, section 3 at the K&T site. The burrow cast was truncated along the shear plane at the top of Unit 1.

a



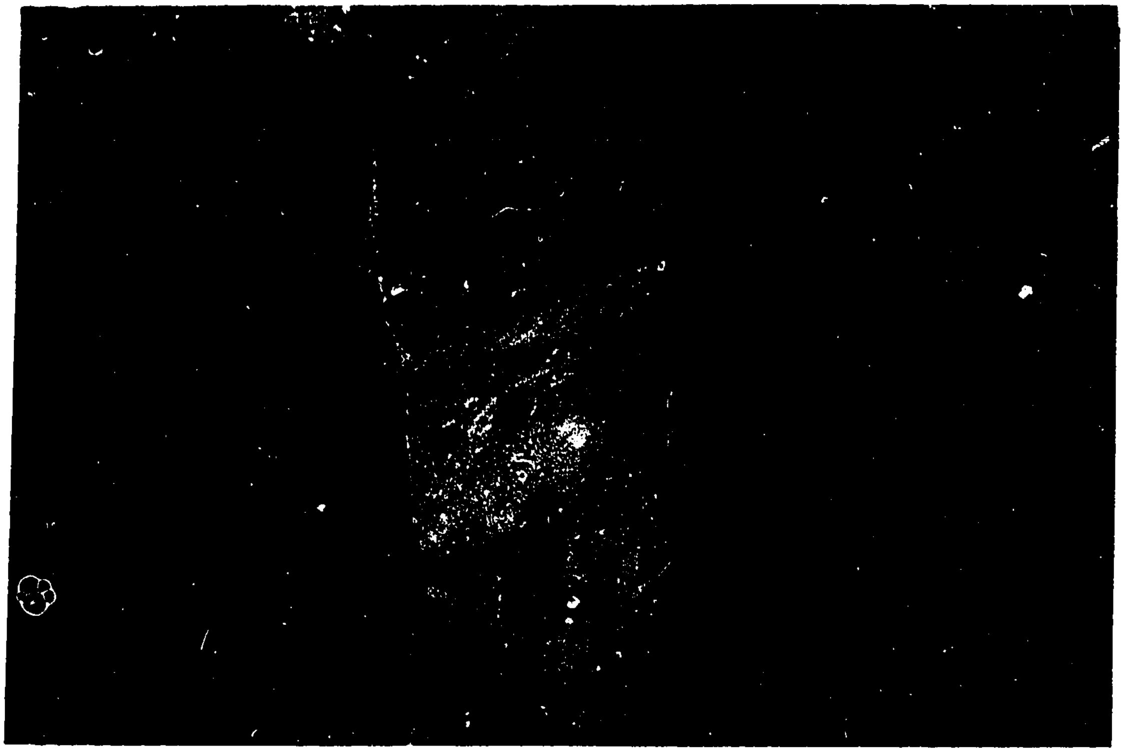
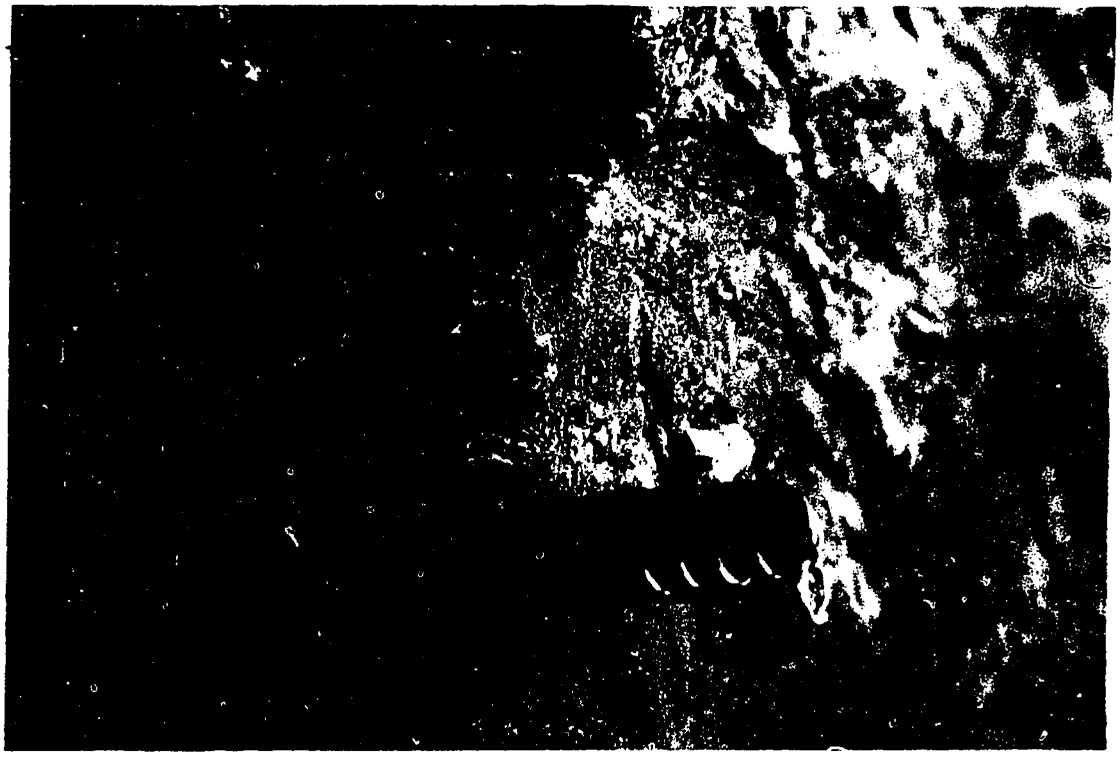


Plate 22a: Soft-sediment deformation structures in Unit 1, section 3, the K&T site. These structures occurred below the shear plane which was as low as the sand-gravel contact in the middle of the section (Figure 15).

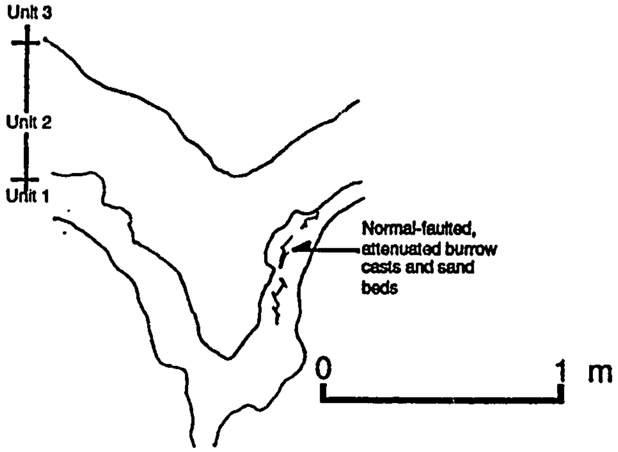
Plate 22b: A close-up of the sediments in Plate 22a. Prairie dog bones were common in the sand, but the burrow casts were attenuated and deformed so that they could not be detected until bones were found. Note the bone protruding from the sand directly above the knife handle.



a

Plate 23, a and b: An ice-wedge pseudomorph in section 3, the K&T site. Deformed burrow casts and sand beds slumped into the degrading ice wedge, indicating the ice wedge post-dated the glaciotectonism.

b



overlying diamict (Plate 21). The diamict was massive, and matrix-supported. Clasts only comprised about 15 percent of the volume of the unit of which nearly [illegible] percent of the clasts had a Canadian Shield provenance. These clasts were relatively angular, and more variable in size, than the clasts of Cordilleran provenance. This unit was also deformed downward into the wedge, but no faulting could be detected. The diamict was slightly blockier within the wedge.

Unit 3: Poorly-sorted sand,

This unit was only exposed through the middle third of the section. It was massive, poorly-sorted, and contained a few clasts of Canadian Shield provenance. It was thickest in the wedge, where it was approximately 1 m thick, but it was discontinuous laterally.

Interpretation - section 3

The beds of sand and gravel are equivalent in age to the Hand Hills gravel found elsewhere in the area. The sand bed in this older unit was excavated during the Middle Wisconsinan by a colony of prairie dogs. The prairie dogs were extirpated during climatic change of the latest Middle Wisconsinan, near the onset of Late Wisconsinan glaciation. The burrows were infilled partly by a silty unit overlying the sandy unit, forming the burrow casts. During the Late Wisconsinan, the prairie dog burrow casts were deformed by thrusting in a subglacial, saturated environment. Thrusting was responsible for the emplacement of Canadian Shield erratics into the diamicton. During deglaciation, the poorly-sorted, bedded sand was deposited on top of the unit. The wedge structure is identified as an ice-wedge pseudomorph on the basis of the rock lining down its sides. This site was likely one of the first areas to become exposed as the ice thinned during deglaciation, subjecting it to extreme periglacial conditions that formed the large ice wedge . Later, during climatic amelioration, the ice wedge melted out, allowing the surrounding and overlying material to slump inwards. The glaciotectonically deformed burrow casts and encasing sands faulted and slumped into the wedge more by brittle failure than by movement due to simple soft-sediment deformation. The overlying diamict, however, slumped into the wedge through soft-sediment deformation. The difference in slumping activity may have been due to the fact that the sand was not completely saturated during ice-wedge meltout. The diamict, being relatively rich in fine-textured materials, would have been more easily saturated.

Section 4

This section only contained two units, likely because the overlying units were scraped off when the pit was open. It was the longest (>100 m), and simplest of the sections.

Unit I: Interbedded gravel and sand,

This unit was laterally continuous with, and virtually identical to, the unit 1 found in section 2. Clast composition was almost purely Cordilleran quartzite. Close to the upper contact, several zones of near-vertically oriented clasts were noted. This unit lacked the sand bed overlying the gravel as found in section 3.

Unit 2: Silty diamicton

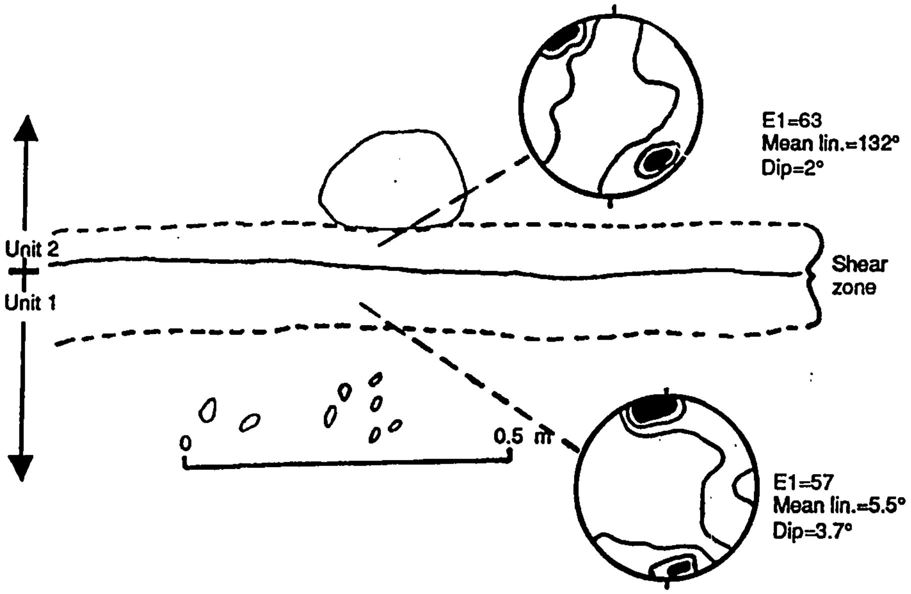
Like unit 2 in section 2, this unit displays upper and lower zones that differ slightly in colour, the upper being gray (Munsell 10Y 6/1) and the lower being a slightly different shade of gray (Munsell 7.5Y 6/1), and greatly in clast orientation (Plate 24). The lower part of the lower zone contained clasts which were primarily vertically oriented, but the upper part of the lower zone exhibited a near-horizontal clast orientation that dipped slightly to the southeast. The matrix was somewhat blocky and dark in the transition between the upper and lower zones. The upper zone was massive, and less blocky than the underlying diamict. It also contained fewer clasts per unit volume (approximately 10 percent compared to about 40 percent), and contained clasts of Canadian Shield provenance as well as Plains ironstone. Long-axis orientation of clasts in the upper diamict displayed a northwest-southeast trend (Plate 24).

Interpretation - section 4

The silty diamict is probably equivalent to the silty diamict in section 2 on the basis of relative position. Glacial erratics, in the form of Plains ironstone and Shield clasts, were likely thrust into place by the Laurentide glacier. Fabrics (Plate 24) indicate Late Wisconsinan glacial flow was in a northwest-southeast direction.

Summary and interpretation - the K & T site

Most of the sediments at the K&T site were originally deposited with the Hand Hills gravel, which forms the base unit of the site. The silty diamict was



b

Plate 24, a and b: Units 1 and 2 in section 4, the K&T site. A 20 cm shear zone was located along the contact between the two units. Granite erratics were found in and above the shear zone.

a

likely deposited as a low-energy fluvial deposit that was subject to periodic fluctuations in flow. The variations in flow were responsible for the deposition of thin gravel layers in the silty units. Subsequently, the clasts in the silty unit, as well as those in the underlying clast-supported gravel, were reoriented by intense periglacial processes to a near-vertical position. Prairie dogs occupied the site sometime after the first periglacial event, seeming to have favoured only the sand lens at the south end of the pit. They were subsequently made extinct by climatic change during the onset of Late Wisconsinan glaciation. During that glaciation, their burrow casts were attenuated through soft-sediment deformation by glacial thrusting/shoving in a zone above a shear plane which could be traced around the gravel pit. Other features indicative of glaciotectonism are: deformed soft-sediment clasts in the silty diamict, near-horizontal northwest-southeast oriented clasts, and the stacked organic layers and diamict blocks in section 1. The deformed soft-clasts were attenuated or rolled up in a manner that suggests thrusting towards the southeast. Fabrics from near-horizontally oriented clasts reflect shearing in a northwest-southeast direction. Dip-directions of shear planes between stacked organic and diamict blocks also reflect forcing from the northwest. The presence of Canadian Shield erratics above the shear plane/zone indicates that the thrusting was done by the Laurentide ice sheet. The thrusting was done under saturated conditions, as indicated by the numerous instances of soft-sediment deformation. Deglaciation saw the deposition of only a few erratics on the surface and limited deposits of poorly-sorted sand. Extreme periglacial conditions existed only after the first stages of deglaciation during the Late Wisconsinan when the ice thinned over the Hand Hills. Dating of the younger

Site description

Only one wall was logged in the summer of 1988 as the pit was very actively excavated for the short time it was open. The logged section was destroyed when the pit was backsloped during reclamation.

Unit 1: Clast-supported gravel

This unit was near-horizontally bedded and comprised of well-rounded clasts of Cordilleran quartzite and chert (Plate 25). Clasts were mainly either blade- or disc-shaped. Wedge-shaped structures containing a gravel lining were exposed in other walls during excavations. A single, medium length (approximately 2 m) burrow cast was noted in this unit (Figure 16) along the southern wall. The cast did not penetrate very deeply, but was near-horizontal for most of its length. Matrix of the cast fill was an olive yellow (Munsell 5Y 6/4) silty diamict with clasts comprising only about 15 percent of the volume. No Canadian Shield clasts were found in the cast fill. The cast was truncated by a shear plane that occurred along the top of Unit 1 (Plate 25). Secondary carbonates were deposited throughout the cast-fill material, creating a mottled appearance.

Unit 2: Silty diamicton

The base of the unit was a shear-plane along the gravel-diamict contact. The shear-plane was at the base of a 15 cm thick shear-zone (Plate 25). The colour for most of the diamict was grayish olive (Munsell 5Y 5/3), except in the shear plane where the deposition of secondary carbonates had caused mottling and local colour variations (Plate 25). The silty diamicton at this site was matrix-

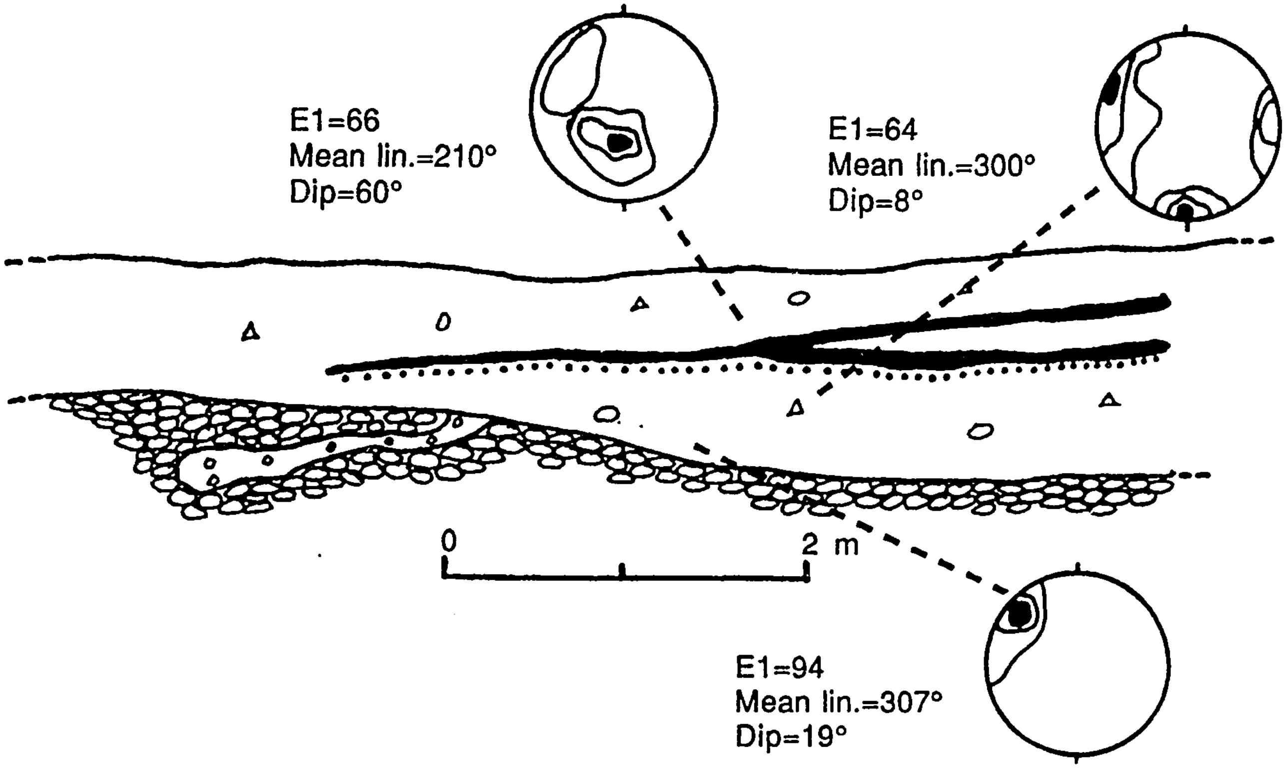


Figure 16: The south wall at the Courtney East site. The site had a prairie dog burrow cast truncated at its top by a shear plane. Granite erratics and stacked organic beds were found above the shear plane.

supported with clasts comprising only about 15 percent of the volume (Plate 25). Clasts were primarily comprised of Cordilleran quartzites, with occasional Shield granites (Plate 25). Fabrics taken from clasts within the shear-zone show strong orientation (E1=94) in a northwest-southeast direction (307°) with a near-horizontal dip (19°). Stacked bands of black (Munsell 5Y 2/1) organics were observed higher in the section (Plate 26). In the east wall of a north-south section, the organic bands were visibly overthrust and faulted (Plate 27). Orientations from the area below the dark organic bands gave less strongly oriented fabrics (E1=64) that still had a mean lineation vector in a northwest-southeast direction (300°), with a gentle dip (8°). Fabrics taken from above the organic-rich area showed a strong orientation (E1=64) in a southwesterly direction (210°), with a high dip (60°) (Figure 16). A single radiocarbon date of 12,560 ±350 (AECV 633C) was produced from the organics, using only HCl pretreatment. Clasts of Canadian Shield provenance were common at the surface, but deposits were only a discontinuous lag.

Summary and interpretation - Courtney East site

The burrow cast was judged to be from the extinct Middle Wisconsinan prairie dog, *C. churcherii*, on the basis of diameter and the compact cast-fill material. A lack of Canadian Shield clasts in the cast material indicates that the only Continental glaciation to submerge this area was the Late Wisconsinan. Sediments in Unit 2 were likely originally deposited in an overbank or low-energy fluvial environment contemporaneously with the gravel. They were likely cryoturbated and/or bioturbated to form the silty diamicton. The truncation of the cast along the shear plane at the contact between Units 1 and 2 indicates

a

Plate 25, a and b: A prairie dog burrow cast was discovered in the gravel of Unit 1 at the Courtney East site. The cast was truncated at the top by a shear plane located at the base of a shear zone at the top of Unit 1.

b

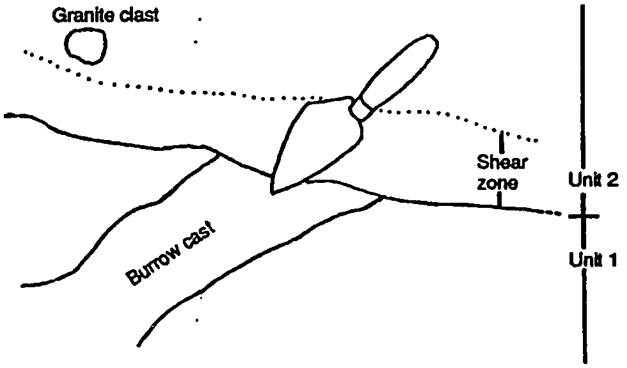
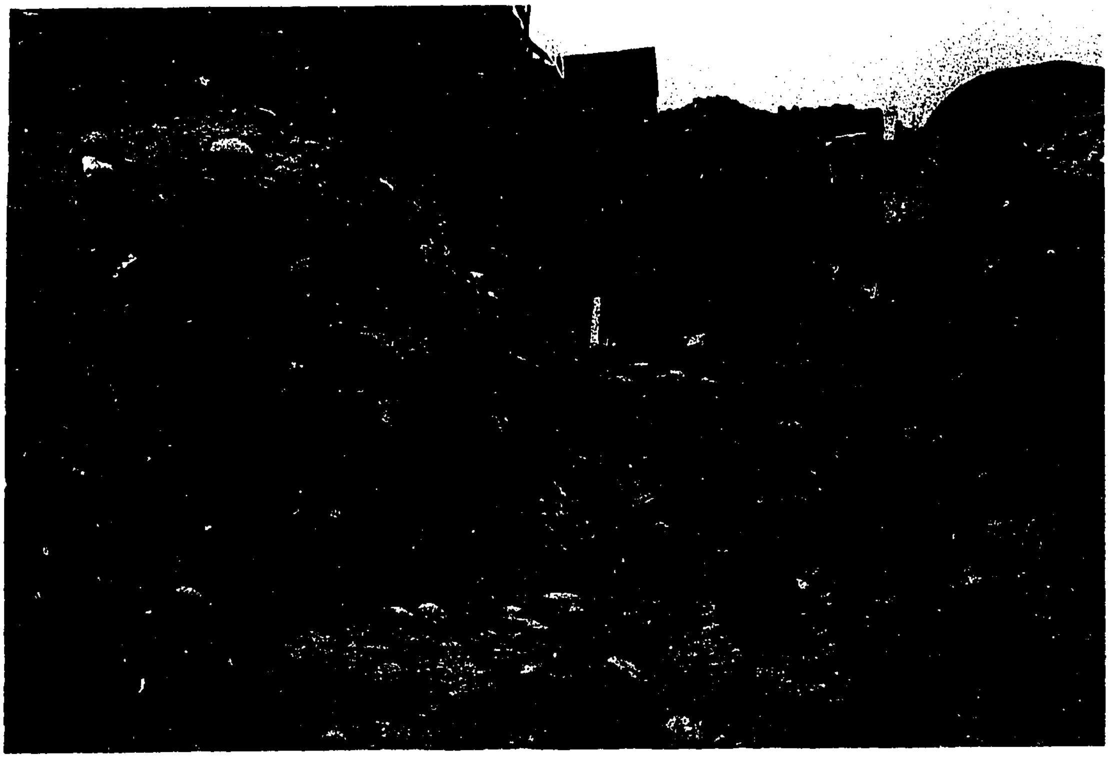


Plate 26: Stacked organics in the upper third of the Courtney East site. A cross-section was dug at 90° to the pit wall in order to get a three-dimensional view of the sediments (Plate 27).



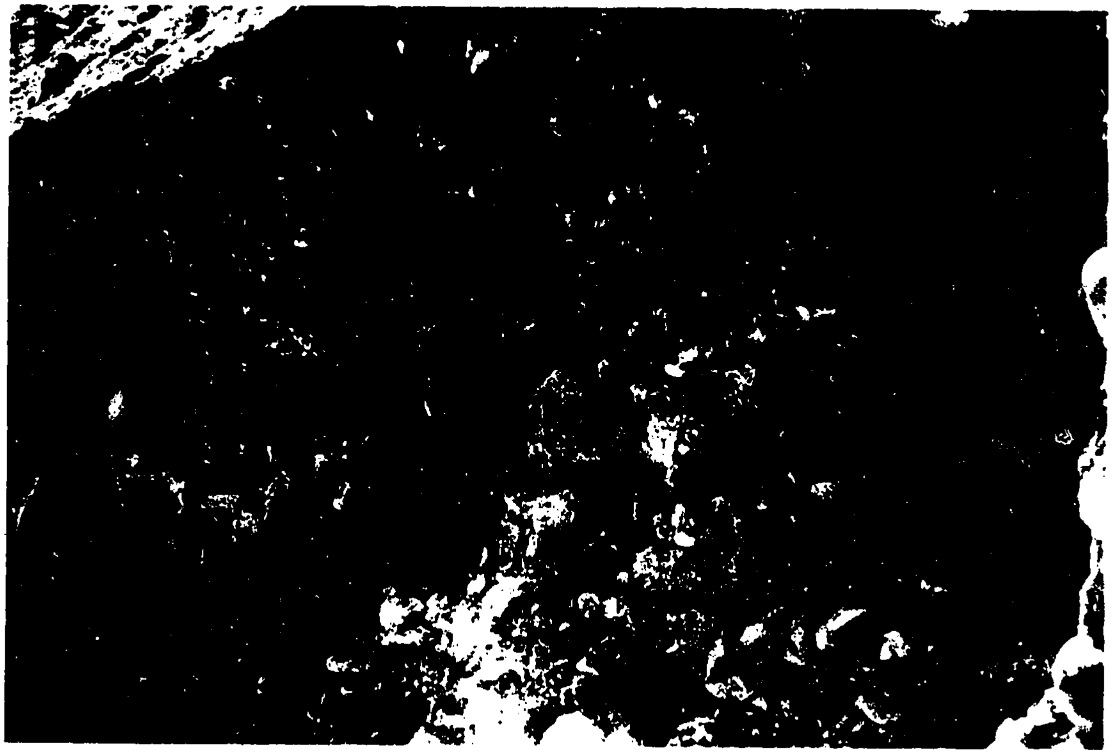
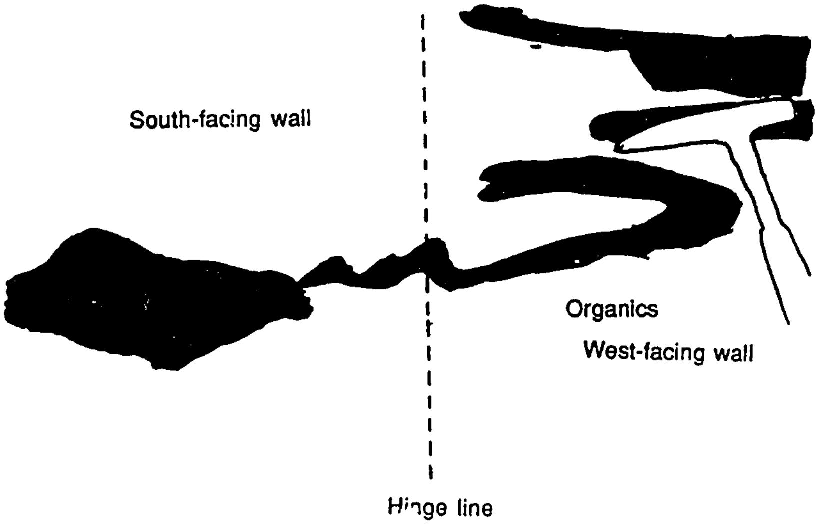


Plate 27: Cross-section of stacked organics at the Courtney East site. The organics were faulted and overthrust several times.



glaciotectonic thrusting caused by Laurentide ice flowing from the northwest during maximum stages of the Late Wisconsinan. At that time, soft clasts of organic material and Canadian Shield clasts were stacked in the diamict. A date was obtained from the organic material (12,560 ±150, AECV 631C) but the samples were pretreated only with HCl due to low organic content. The second pretreatment, NaOH - used to eliminate younger organic contaminants, was not done as that may not have left enough organics to date. The organic material could have been contaminated either by translocated humic acids (a process demonstrated at the Seward site) or exudates from modern rootlets. Therefore, the date on organic material is likely too young, whether the material was paleosolic or Cretaceous coal.

Chapter 4: Summary and discussion

Introduction

This chapter will address three topics. First is the summary of findings from the four sites investigated on the Hand Hills. The site investigations provided evidence from which a reconstruction of stratigraphy for the Hand Hills and the immediate area can be made. The second topic will be an attempt at relating selected processes inferred from events observed in the sediments to the local geomorphology, thereby relating processes inferred from sediment to landforms. The third topic will attempt to relate the local features to others found in the region by inferring processes with the ultimate aim of elucidating the timing and extent of the Late Wisconsinan ice sheets of southern Alberta.

Part 1: Summary of Hand Hills stratigraphy

Several thousand bones from an extinct Late Pleistocene species of prairie dog, *Cynomys churcherii*, were recovered from the Hand Hills area, south-central Alberta. The bones were retrieved from the prairie dogs' own burrow casts which have excavated into the underlying, Miocene-age gravel and sand. The prairie dogs lived in the area for at least 11,000 yrs, from about 33,000 to 22,000 yrs B.P. The climate during the Middle Wisconsinan was likely cooler and dryer than that of today, but was probably more equable, with smaller seasonal extremes in temperature. Burrow structures containing bones were preserved as casts from infilling with overlying and surrounding sediments by fluvial processes and mass movement both during and after the colony's existence. Some of the cast-fill material did not resemble any of the sediments found at the first (Winter) site and was described as "anomalous." It was theorized that the anomalous cast fill parent material may have come from a unit of sediment that was present at the site when the colony was active during the Middle Wisconsinan, but not later, when the site was investigated. Burrow casts were found at depths very near the maximum of burrows dug by the closely related White-tailed prairie dog (*Cynomys leucurus*). Therefore, there was little erosion since the colony was active, so the missing, anomalous sediments were likely not very thick. The presence of Canadian Shield granites and schists at the surface indicated that the Hand Hills had been submerged by a Continental ice sheet, originating from the northeast. The lack of Shield clasts in the cast fill and in dish-shaped deposits in the upper regions of old ice-wedge pseudomorphs indicate that the granites and schists were not present when the colony was active, and were therefore deposited later, by the Laurentide ice sheet. The origin of the anomalous cast fill was unknown at the conclusion of studies at the Winter site. The casts cross-cut ice-wedge pseudomorphs indicating that the intense period of periglacial activity responsible for most of the ice wedge formation occurred before the Middle Wisconsinan.

The gravel and sand unit at the Seward site was judged to be part of the Miocene-age gravel complex. A thick lens of bedded silt with thin gravel stringers was found interbedded with the gravel, indicating deposition was contemporaneous. The silt beds were turbated into a diamicton by any combination of periglacial, biological, and glacial processes. Periglacial activity occurred first because prairie dog burrow casts clearly crosscut several diagnostic periglacial structures. The silty deposits were heavily bioturbated locally, causing the formation of more silty diamicton as the burrowing activity was deeper and more laterally extensive than the periglacial activity. Prairie dog bones were found in the diamict unit, but burrow casts could not be seen. This was likely due to the diamict's fairly uniform texture and colour. Later, the silty diamict and some burrow casts in the underlying sand and gravel unit, were deformed by Laurentide glaciotectonism related to ice-sheet flow to the south-southeast. Glaciotectonism under saturated conditions was indicated by asymmetrical soft-sediment deformation structures that had their top half deformed to the south. In one location the glaciotectonism caused the silty diamict bed to warp upwards, forming a hump at its upper surface. Erosion during, and subsequent to, the Late Wisconsinan was likely minimal, as the burrow casts occurred to depths similar to those found in a modern, closely related species. Subsequently, at the end of the Late Wisconsinan, englacial bedded sand and diamict melted out and were draped over the microtopography caused by the glaciotectonism. Early in the Holocene, eolian deposits were laid down, and a dark brown organic soil horizon formed on the surface. Organic colloids from the soil were translocated downwards, contaminating some collagen-poor bones.

The K & T site had several forms of glaciotectonic features. A distinct shear plane was traced around the pit, above which clasts with Canadian Shield provenance could be found. Several other glaciotectonic features were found above the shear plane. Near-horizontally oriented clasts (that were near-vertically oriented before glaciation) were aligned to the southeast. Soft-sediment clasts, thrust into the silty diamict, were rolled up or attenuated to the southeast. Shear planes between stacked diamict blocks dipped to the northwest, indicating the direction of thrusting. A bed of organic material was stacked along a shear plane. Burrow casts and beds of sand were truncated at the large shear plane, and attenuated above it. A "young" periglacial phase is indicated by the glaciotectonically attenuated burrow casts slumped into a degrading ice wedge. This would indicate that periglacial activity observed throughout the hills was either "old" (pre-Middle Wisconsinan), or "young" (during an early phase of Late Wisconsinan deglaciation). The climate during the Middle Wisconsinan may not have had the extreme cold season necessary to induce thermal cracking in sorted sand and gravel, and could have therefore been more equable or drier than at earlier times of periglacial activity during the Pleistocene. Late Wisconsinan strata only consisted of local deposits of poorly-sorted, bedded coarse sand, pebbles, and cobbles. A discontinuous lag of Canadian Shield cobbles and boulders was common in areas not excavated. Shield material only occurred above the shear plane and not in the burrow casts, indicating that the only glaciation to submerge the Hand Hills was the Late Wisconsinan Laurentide ice sheet. This ice sheet flowed from northwest to southeast during the Late Wisconsinan maximum and was thick enough to be topographically unconstrained.

Sediments at the Courtney East site also display evidence of glaciotectonism. A burrow cast was truncated along a shear plane located at the gravel/diamict contact. Fabrics obtained from the sheared zone indicated "forcing" from the northwest. Higher in the section were stacked, and overturned organic beds of questionable origin. The lack of Shield clasts in the Middle Wisconsinan burrow cast indicates that the granites and schists found on the surface at the site were deposited during the Late Wisconsinan.

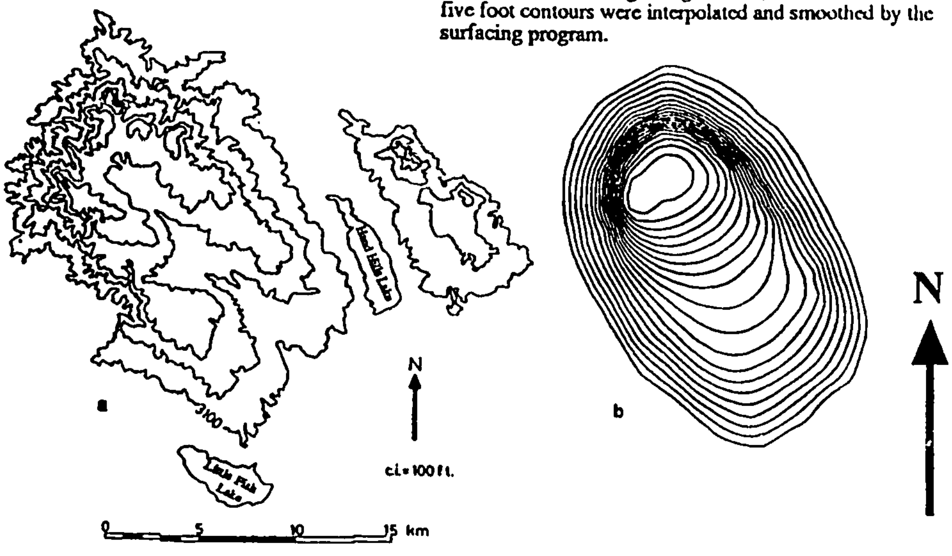
Part 2: Sediment/landform relationships

As the upper surfaces of the Hand Hills are about 180 m (600 ft) above the surrounding prairie surfaces, processes that were pervasive on top of the hills likely had effects over a large area. The widespread evidence of glaciotectonism on the Hand Hills indicates that topographically unconstrained glacial flow from the northwest occurred for some time. Linkages to other evidence of this flow may allow reliable reconstructions of the dynamics and extent of the glaciation responsible for the flow. It is necessary to change the scale of observations to address this possibility as the evidence so far has been on a micro-sedimentary-structure scale.

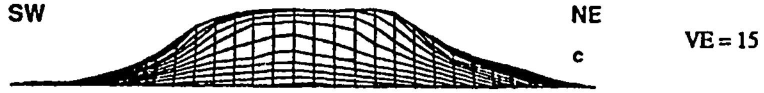
The Hand Hills are large features that are difficult to view in their entirety. Because of this the hill shape cannot be seen except at great distances. Most hill observations, then, are merely of individual slopes so a complete picture of the hills shape cannot be obtained in the field. Observation of the Hand Hills on the NTS 1:250,000 map sheet reveals that the hills are actually comprised of two uplands above the 3,100 ft (945 m) contour (Figure 17a). The hillslopes have been dissected by gullying and headward erosion of minor tributaries of the Red Deer River, resulting in a visually complicated pattern on satellite images, and on air photos or mosaics.

The combination of extrapolating to 25 ft contour intervals, and smoothing of the contours to subdue the effect of fluvial erosion on the contours results in a streamlined landform that closely resembles a drumlin in plan, axial, and oblique view (Figure 17b, c, d, e). Shaw *et al.* (1989) note that much has been written about drumlin shape, with many accompanying attempts to obtain quantitive shape characteristics using axial measurements (Mills 1980,1987) or

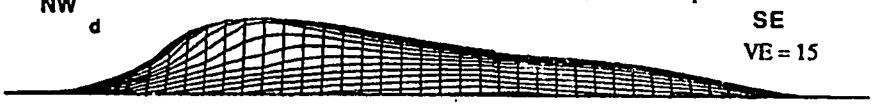
Figure 17: Plan view of Hand Hills: Contours sampled at low resolution, at 100 foot intervals, beginning at the 3,100 foot contour. Twenty five foot contours were interpolated and smoothed by the surfacing program.



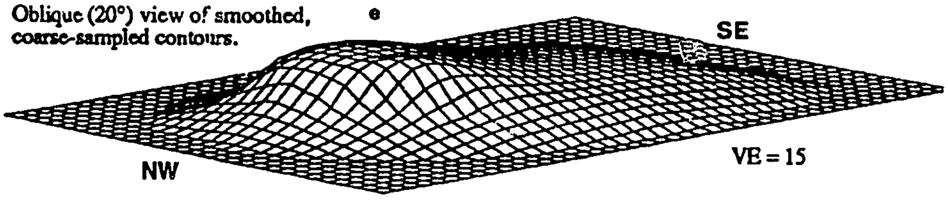
End view of smoothed, coarse-sampled contours



Side view of smoothed, coarse-sampled contours.



Oblique (20°) view of smoothed, coarse-sampled contours.



two- and three-dimensional measurements (Chorley 1959, Reed *et al.* 1962, Evans 1987). However, he prefers to follow the ideas of Kuhn (1974) by using the same cognitive faculties used to recognise objects in our life and experience. Using those cognitive faculties, the Hand Hills are recognized as a large bedrock drumlin. The large drumlin is oriented parallel to the direction of flow derived from several glaciotectonic features at three of the four study sites.

Other possible controls of hill form have to be ruled out before making this assertion. The form is not bedrock-controlled because the contacts between sedimentary rock units are planar, dipping gently to the northeast,. Also, the bedrock is relatively uniform lithologically and does not contain any variations in composition or hardness that may cause preferential erosion. Beaty's (1972) idea that slope form in southern Alberta is partially controlled by moisture availability governed by snowpack accumulation on lee slopes should also be examined. If this were true, the northeast slopes would be significantly steeper than the southwest slopes. However, the end-view axial profile (Figure 17c) shows that the hills are symmetrical on their northeast and southwest slopes. Moisture availability controlled by aspect was therefore not likely a hillslope control.

Interposed between the glacial processes exhibited at the micro, sedimentary sheet scale, and the large giant drumlin (Hand Hills) scale are several intermediate-sized drumlins on top of the Hand Hills (Plate 1). They are oriented parallel to both the hills and the ice-flow direction indicated by several types of glaciotectonic features in the study sites. The intermediate-sized drumlins would have been formed at a time when the hills were submerged by glacial ice flowing from northwest to southeast. Stratigraphy at the study sites indicates that the Laurentide ice sheet was probably the only glaciation to submerge the Hand Hills, so all of the features would have formed during the stage of the last glaciation when necessary conditions of ice thickness and flow were present, likely near or at glacial maximum.

Areas to the west of the Hand Hills have elevations similar to the hills' upper surface, and have thin or discontinuous glacial sediments (Plate 1). Numerous large-scale oriented features are aligned parallel or near-parallel to the streamlined Hand Hills, the drumlins on their upper surfaces, and the flow direction indicated by the sedimentologic data. It is probable that these features were formed roughly synchronously since the only ice sheet to achieve sufficient ice thicknesses to submerge the Hand Hills was the Laurentide. It would be necessary to submerge the hills in order to simultaneously submerge relatively high ground to the west. Also, relative synchronicity is indicated as the northwest-southeast flow direction probably only lasted for a portion of the Late Wisconsinan.

Sediment/landform relationships are present in that sedimentologic features indicate processes that are reflected by landforms of varying scales over a large area. Those processes are glaciotectonism, streamlining of a large relict upland, and formation of numerous streamlined landforms. Evidence for the exact processes in operation, however, is not explicit. The sediments/landforms observed could have been formed through either direct glacial action (e.g. Menzies 1987), or, subglacial glaciofluvial erosion and deposition (Shaw and Kvill 1984, Sharpe and Shaw 1989, Shaw *et al.* 1989). Sedimentologic data indicate pervasive glaciotectonism, but of a particular type. All of the sections displaying glaciotectonism do so alongside features that show materials were saturated during ice deformation. The attenuated burrow casts, rolled up soft clasts, and lack of sole marks on the undersides of shear planes do not indicate shoving under "hard frozen" conditions. Also, the apparently small amount of glacial erosion on top of the hills, as indicated by the depth to which burrow casts are found, do not implicate ice as being a major agent of erosion.

Glacial ice, itself, <u>may</u> not have been the formative factor for all these features. Examination of the western part of the study area reveals that there are numerous anastomosing channels and eskers interposed with drumlins (Plate 1). Locally, eskers either lead into or away from channels. If the channels are, in fact, linked as they appear to be, then they are actually tunnel valleys and not spillways as mapped by Shetsen (1987).

Anastomosing channels are common in extraglacial areas that have streamlined landforms resulting from catastrophic floods, such as the Channeled Scabland of Washington State (Bretz 1969, Baker and Nummedal 19[illegible]). Some authors theorize that drumlins may form as a result of catastrophic subglacial floods. Drumlins are either erosional (Shaw and Sharpe 1987) or depositional (Shaw and Kvill 1984). Shaw *et al.* (1989) feel that subglacially formed tunnel valleys and anastomosing eskers appear to indicate major floods beneath ice. They note that tunnel valleys are commonly closely associated with drumlins. Shaw (1988) suggests that some glaciotectonism could occur during let-down of ice after a catastrophic subglacial flood. At that time the ice would be experiencing accelerated flow, possibly causing loading of underlying surfaces.

Many of the landform/sediment associations can therefore be explained by subglacial fluvial processes. The relationships are suggestive and conclusions only tentative as they require sedimentologic data from western areas of the study region to help elucidate the exact processes responsible.

Part 3: Ice sheet reconstruction

No matter what processes were responsible for the array of northwest-southeast oriented features in the study area, all were responding to a gradient of ice or subglacial meltwater force acting from the northwest. The gradient of that force was probably caused by an ice profile that thickened in that direction. The force caused ice movement and probably controlled subglacial glaciofluvial events, and was ultimately responsible for the oriented features found in the study site.

Reconstructions of the Laurentide ice sheet have differed in whether or not it coalesced with the Cordilleran ice sheet, even though there has been only minor disagreement over its southwestern limit (Figures 6 and 7). Many of the authors who believe that the two ice sheets did not coalesce use the northwest-southeast flow pattern in their reconstructions (Rutter 1984, Fulton 1984, Catto and Mandryk 1990). These authors use the same limit as the terminus for the Laurentide ice sheet (Figure 6). The terminus corresponds to the Lethbridge moraine, an indistinct, discontinuous feature that is indistinct north of latitude 50°. The terminus is nearly the same elevation, about 990 m (3,250 ft) asl, for its whole length, from southeast of Lethbridge to at least the Hinton area, west of Edmonton. Ice-flow indicators are mapped as close as about 20 km from the terminus. There is a question as to whether or not the ice could have flowed continuously to the south and southeast if there was no coalescence and deflection by Cordilleran ice.

Pleistocene, Continental, North American ice sheets are known to have had exceedingly low-angle profiles in southwestern sectors (Mathews 1974). Nonetheless, significant thicknesses developed for the large ice sheet. In order for the western Alberta sector of the Laurentide ice sheet to have flowed from northwest to southeast, it would have developed a profile (along the parallel flow lines indicated by streamlined landforms) behind the proposed terminus that approximately adhered to the formula;

$$h = Ax^{1/2}$$

The values of A could have ranged from 1.0 to 0.67 $m^{1/2}$ (Mathews 1974). Assuming a value of 1.0 $m^{1/2}$, the ice sheet would have thickened from 0 at the terminus south of Lethbridge (Figure 5) to about 710 m (2,320 ft) thick 500 km northwest in the Hinton area (Figure 18). On a transect 90° to the ice flow, the profile should have thickened from 0 at the terminus to a thickness of about 710 m in only about 50 km. The A value along the second transect would have been about 3.2 $m^{1/2}$.

The most plausible reason why the Laurentide ice sheet would have behaved so differently along northwest-southeast and northeast-southwest transects is that it coalesced with and was deflected by the Cordilleran ice sheet. The landscape over much of the area covered by the southwestern Laurentide ice sheet was gently sloping, so coalescence would have been nearly continuous down the front of the Rockies, except in areas where it was grounded against western nunataks (Rains 1990). This would mean that the highest stages of the Laurentide ice sheet in southern Alberta were characterized by coalescent and deflected flow. That flow would have produced the wide, nearly continuous band of northwest-southeast oriented features found in the study area (Figure 18).

The area between the hills and the oriented features to the west is mantled by the lower elevation glaciolacustrine deposits of Glacial Lake Drumheller (Plate 1). Northeast of the Glacial Lake Drumheller sediments is the belt of hummocky, thick glacial deposits (Plate 1). Local glaciolacustrine mantling of the hummocks subdues their relief. To the northeast of the hummocky belt are a number of northeast-southwest trending oriented features (Plate 1). Alignments in this direction are rare beyond (southwest of) the hummocky belt, occurring near the Laurentide limit. These were likely formed at two different times during the same glaciation. The features near the margin were probably formed close to the end of glacial maximum when the Cordilleran ice sheet began thinning. The Laurentide ice sheet would have persisted near its maximum position longer, and locally, may have flowed into areas vacated by Cordilleran ice . Complete decoupling from Cordilleran ice, and some recession, put the Laurentide terminus in the area of the hummocky belt (Figure 19). Glacial Lake Drumheller was ponded in front of the ice, depositing glaciolacustrine sediments over the thinning ice. These deposits would have mantled northwest-southeast oriented features so that only the higher elevation features were preserved. Behind the terminus a radial flow pattern from the centre of ice dispersal was established in the absence of Cordilleran deflection causing the formation of the northeast-southwest oriented features. Flow from this direction destroyed all the low elevation features that reflected glacial maximum flow (northwest-southeast) norteast of the hummocky

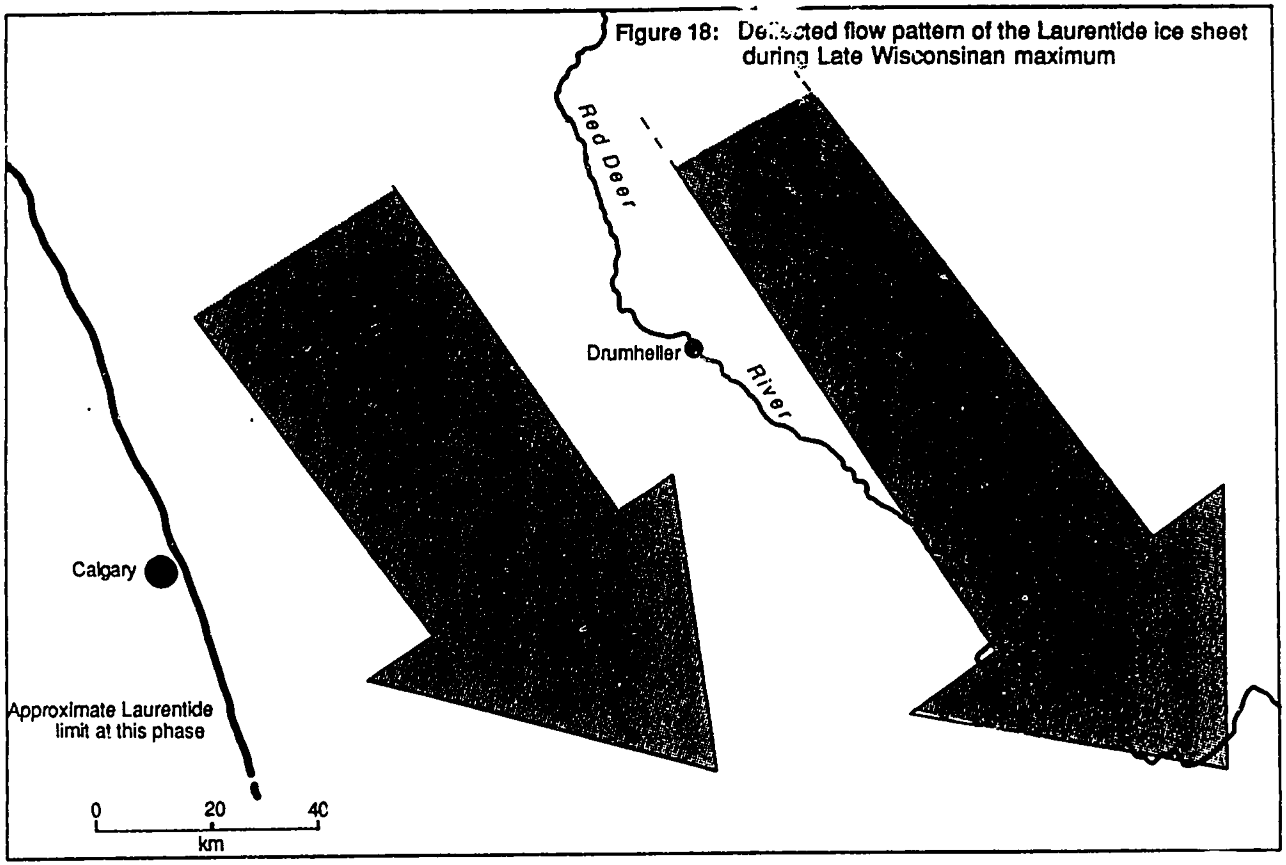


Figure 18: Deflected flow pattern of the Laurentide ice sheet during Late Wisconsinan maximum

belt, while sediments deposited in Glacial Lake Drumheller buried low elevation northwest-southeast orient features proglacially.

This thesis draws on information of several types to make inferences about past events and conditions of the Hand Hills and area. Paleontologic information gives insight to the time and conditions of occupation. The Hand Hills area was likely a cool, dry, steppe or grassland during the Middle Wisconsinan. Dates on bone collagen reveal that the area was occupied by prairie dogs from at least 33,000 yrs B.P. to about 22,000 yrs B.P. Taphonomic study of the burrow casts indicates preservation through infilling by prairie dog activity and inwashing of sediment. The prairie dog fossils help to elucidate the stratigraphy of the hills. The hills were likely only submerged by Continental ice during the Late Wisconsinan. The casts were deformed post-depositionally by glaciotectonism caused by the deflected Laurentide ice sheet flowing from the northwest when it was thick, and topographically unconstrained. Sedimentologic evidence from till fabrics and stacked blocks of diamict also demonstrate the northwest flow pattern. Morphologic evidence also indicates that ice sheet flow was from the northwest during glacial maximum. The hills themselves were probably streamlined by processes related to ice flow. Other morphologic information shows that waning stages of the ice sheet saw the onset of limited periglacial activty, and the deposition of a hummocky, recessional moraine during a period of northeast- southwest flow.

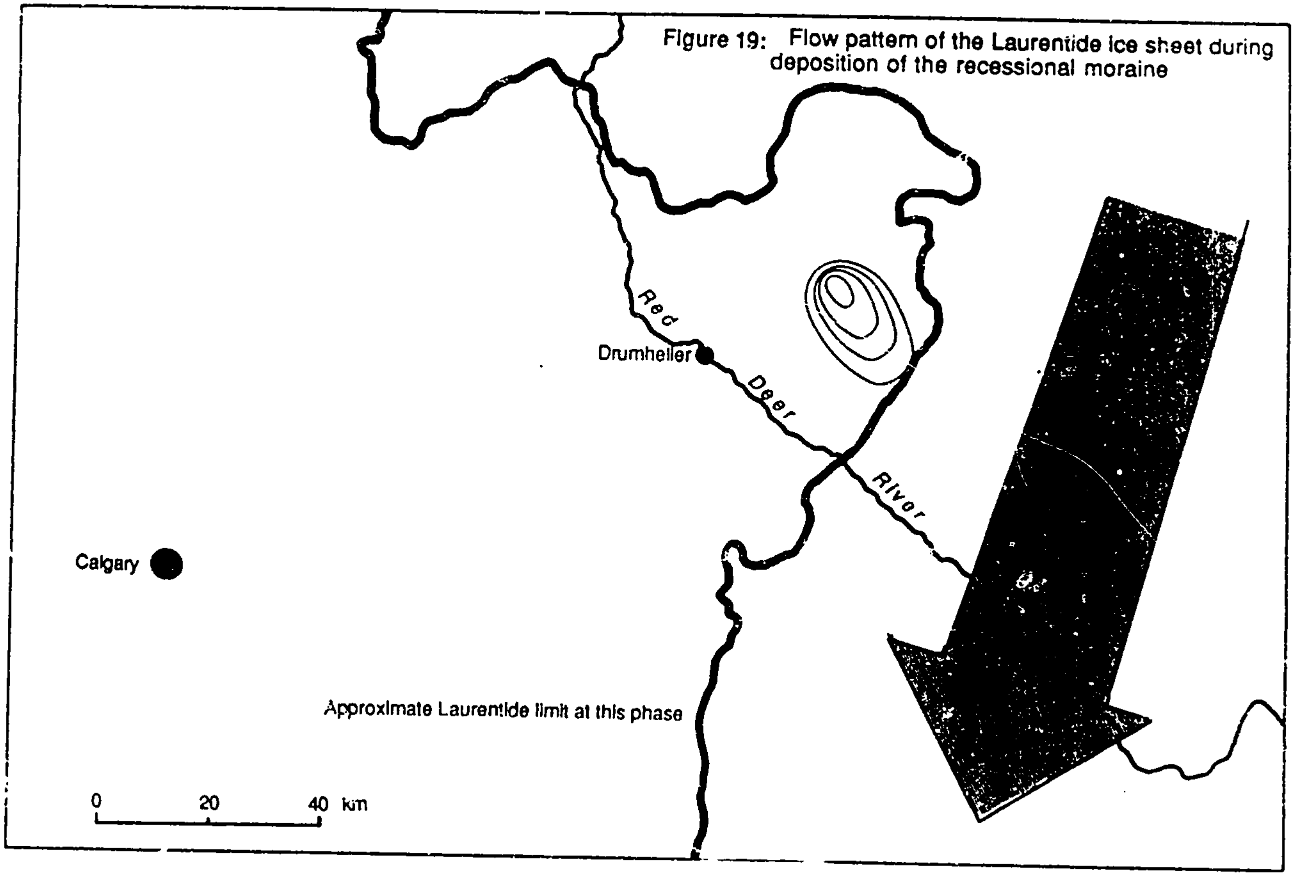


Figure 19: Flow pattern of the Laurentide ice sheet during deposition of the recessional moraine

SELECTED REFERENCES

ADAMS, M.F. 1815. see letter by A. CALLIEUX 1971. Journal of Glaciology, **10**, p. 411.

ALBERO, M.C., ANGIOLINI, F.E., AND PIANA, L.E. 1986. Discordant ages related to reservoir effect of associated archaeologic remains from the Tunel site, Beagle Channel, Argentine Republic. Radiocarbon **28**, pp. 748-753.

ALLEN, J.A., AND SANDERSON, J.O.G. 1945. Geology of the Red Deer and Rosebud sheets, Alberta. Research Council of Alberta, **13**, 115 pp.

ALLEY, N.F. 1973. Glacial stratigraphy and the limits of the Rocky Mountain and Laurentide ice sheet, in Southwestern Alberta, Canada. Canadian Petroleum Geology, Bulletin **21**, pp. 153-177.

AYLSWORTH, J.M., AND SHILTS, W.W. 1987. Bedforms of the Keewatin Ice Sheet, Canada. Sedimentary Geology, **62**, pp. 407-428.

BABCOCK, E.A., FENTON, M.M., AND ANDRIASHEK, L.D. 1977. Shear phenomena in ice-thrust gravels, central Alberta. Canadian Journal of Earth Sciences, **15**, pp. 277-283.

BAKER, V.R., AND NUMMEDAL, D. 1978. The Channeled Scabland: A Guide to the Geomorphology of the Columbia Basin, Washington. Planetary Geology Program, National Aeronautics and Space Administration, 186 pp

BARENDREGT, R.W. 1984. Correlation of Quaternary chronologies using paleomagnetism - examples from southern Alberta and Saskatchewan. *In* Correlation of Quaternary Chronologies. *Edited by* W.C. Mahaney. Geo Books, Norwich, United Kingdom, pp. 597-607.

BARNOSKY, D. W., GRIMM, E.C., AND WRIGHT, H.E. 1987. Towards a postglacial history of the northern Great Plains: A review of the paleoecological problems. Annals of the Carnegie Museum, **56**, pp. 259-273.

BAULIN, W.W., BELOPUKHOVA, Y.B., DUBIKOV, G.I., AND SHMELEV, L.M. 1967. Geokriologcheskie (merzlotnye) usloviya Zapadno-Sibirskoy Nizmennosti. [Geocryology and Permafrost Conditions of West Siberian Lowland]. Izd. Nauka Moskva.

BEATY, C.B. 1972. Geographical distribution of post-glacial slumping in southern Alberta. Canadian Geotechnical Journal, 9(**2**), pp. 219-224.

BEATY, C.B. 1975. The Landscapes of Southern Alberta: A Regional Geomorphology. University of Lethbridge Production Services, Lethbridge, Alberta.

BEHRENSMEYER, A.K. 1984. Taphonomy and the fossil record. American Scientist, **72(6)**, pp. 558-566.

BERG, T.E. 1969. Fossil sand wedges at Edmonton, Alberta. Biuletyn Peryglacjalny, **19**, pp. 325-333.

BEUKENS, R.P. 1989. IsoTrace laboratory annual report. IsoTrace Laboratory Accelerator Facility at the University of Toronto.

BLACK, R.F. 1952. Growth of ice wedge polygons inb permafrost near Barrow, Alaska. Bulletin of the Geological Society of America, **63**, 1235-1236.

BLACK, R.F. 1954. Permafrost - a review. Bulletin of the Geological Society of America, **65**, pp. 839-855.

BLACK, R.F. 1969. Climatically significant fossil periglacial phenomena in northcentral United States. Biuletyn Peryglacjalny **20**, pp. 225-238.

BLACK, R.F. 1973. Growth of patterned ground in Victoria Land, Antarctica. *In* Permafrost; North American Contribution, Second International Permafrost Conference, Yakutsk, USSR. National Academy of Science Publication, **2115**, pp. 193-203.

BLACK, R.F. 1976. Periglacial features indicative of permafrost: ice and soil wedges. Quaternary Research **6**, pp. 3-26.

BLACK, R.F. 1983. Pseudo-ice-wedge casts of Connecticut, northeastern United States. Quaternary Research, **20**, pp. 74-89.

BLUEMLE, J.P., AND CLAYTON, L. 1984. Large-scale glacial thrusting and related processes in North Dakota. Boreas, **13**, pp. 279-299.

BOUCHARD, M.A. 1989. Subglacial landforms and deposits in central and northern Quebec, Canada, with emphasis on Rogen moraines. Sedimentary Geology, **62**, pp. 293-308.

BOYD, R., SCOTT, D.B., AND DOUMA, M. 1988. Glacial tunnel valleys and Quaternary history of the Scotian shelf. Nature, **333**, pp. 61-64.

BRAMAN, D.R., AND EBERTH, D. 1988. Paleontology and geology of the Edmonton Group (Late Cretaceous to Early Palaeocene), Red Deer River Valley, Alberta, Canada. Society of Vertebrate Paleontology, 48th Annual Meeting, Field Trip A. Occasional Paper of the Tyrrell Museum of Palaeontology, #8.

BRADLEY, R.S. 1985. Quaternary Paleoclimatology. Methods of Paleoclimatic Reconstruction. Allen & Unwin, Boston.

BRETZ, J.H. 1969. The Lake Missoula floods and the Channeled Scabland. Journal of Geology, **77**, pp. 505-543.

BRIERLY, J.A. 1988. Comparison of two soils from southwestern Alberta. M.Sc. thesis, Department of Soil Science, University of Alberta, Edmonton, Alberta. 169pp.

BRYAN, R.B., CAMPBELL, I.A., AND YAIR, A. 1987. Postglacial geomorphic development of the Dinosaur Provincial Park badlands, Alberta. Canadian Journal of Earth Sciences, **24**, pp.135-146.

BURNS, J.A., FLATH, D.L., AND CLARK, T.W. 1989. On the structure and function of white-tailed prairie dog burrows. Great Basin Naturalist, **49**, pp. 517-524.

BURNS, J.A., AND MCGILLIVRAY, W.B. 1989. A new prairie dog, *Cynomys churcherii*, from the Late Pleistocene of southern Alberta. Canadian Journal of Zoology, **67**, pp. 2633-2639.

BURNS, J.A., AND YOUNG, H.R. 1988. Stratigraphy and Paleontology of the Hand Hills Region. Society of Vertebrate Paleontology, 48th Annual Meeting, Field Trip A. Occasional Paper of the Tyrrell Museum of Palaeontology #9, 13 pp.

CATTO, N. AND MANDRYK, C. 1990. Geology of the postulated ice-free corridor. *In* Megafauna and Man: Discovery of America's Heartland. *Edited by* L. D. Agenbroad, J.I. Mead, and L.W. Nelson. The Mammoth Site of Hot Springs, South Dakota, Inc. Scientific Papers,**1**, pp.80-85.

CHAPPEL, J.M.A., AND POLACH, H.A. 1972. Some effects of partial recrystallisation on ^{14}C dating of late Pleistocene corals and molluscs. Quaternary Research, **2**, pp. 244-252.

CHORLEY, R.J. 1959. The shape of drumlins. Journal of Glaciology, **3**, pp. 339-334.

CLAYTON, L., AND MORAN, S.R. 1974. A glacial process-form model. *In* Glacial Geomorphology. *Edited by* D.R. Coates. State University of New York, Binghampton.

COLEMAN, A.P. 1910. The drift of Alberta and the relations of the Cordilleran and Keewatin ice sheets. Transactions of the Royal Society of Canada, series 3, section IV, **3**, pp. 3-12.

CORTE, A.E. 1963. Particle sorting by repeated freezing and thawing. *In* Periglacial Processes (1976). *Edited by* C.A.M. King. Dowden, Hutchinson and Ross Incorporated, Stroudsburg, Pennsylvania.

DAMON, P.E., LONG, A., AND GREY, D.C. 1978. Temporal fluctuations of atmospheric ^{14}C: causal factors and implications. Annual Review of Earth Planetary Science, **6**, pp. 457-494.

DAWSON, G., AND MCCONNELL, R.G. 1885. Glacial deposits of southwestern Alberta in the vicinity of the Rocky Mountains. Geological Society of America Bulletin, **7**(11), pp. 31-66.

DOTT, R.H. 1988. Something old, something new, something borrowed, something blue - a hindsight and foresight of sedimentary geology. Journal of Sedimentary Petrology, **58**, pp. 358-364

DYKE, A.S. AND PREST, V.K. 1987 The Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. Géographie physique et Quaternaire, **41**, pp. 237-263.

EASTERBROOK, D.J., AND BOELLSTORFF, J. 1982. Paleomagnetism and chronology of early Pleistocene tills in the central United States. *In* Quaternary Glaciations in the Northern Hemisphere. Prague, International Geological Correlation Program Project 73-1-24, Report No.6 on the Session in Ostrava, Czechoslovakia, August 1979, pp. 72-82.

EMBLETON, C. AND KING, C.A.M. 1975. Periglacial Geomorphology. Edward Arnold, London.

EVANS, I.S. 1987. A new approach to drumlin morphometry. *In* Drumlin Symposium. *Edited by* J. Menzies and J. Rose. Balkema, Rotterdam, pp. 119-130.

EVIN, J. 1990. Validity of the radiocarbon dates beyond 35,000 years B.P. Palaeogeography, Palaeoclimatology, Palaeoecology, **80**, pp. 71-78.

FENTON, M.M. 1987. Deformation terrain on the northern Great Plains. *In* Geomorphic Systems of North America. *Edited by* W.L. Graf. Geological Society of America, Centennial Special Volume, **2,6**, Great Plains, pp.176-182

FENTON, M.M., AND PAWLOWICZ, J.G. 1991. Detection of glaciotectonic terrain: Geophysical techniques and indication of glaciogenesis. *In* The Formation and Properties of Glacial Deposits. A.A. Balkema.

FOSTER, J.H., AND STALKER, A. MACS. 1976. Paleomagnetic stratigraphy of the Wellsch Valley site, Saskatchewan. *In* Report of Activities, Part C. Geological Survey of Canada, **76-1C**, pp. 191-193.

FOX, R.C., 1988. Late Cretaceous and Paleocene mammal localities of southern Alberta. Society of Vertebrate Paleontology, 48th Annual Meeting, Field Trip A. Occasional Paper of the Tyrrell Museum of Palaeontology, #6.

FRENCH, H.M. 1983. The Periglacial Environment. Longman Inc., New York. 309 pp.

FRENCH, H.M., and GODZIK, J.S. 1988. Pleistocene epigenetic and syngenetic frost fissures, Belchatów, Poland. Canadian Journal of Earth Sciences, **25**, pp. 2017-2027.

FULLERTON, D.S., AND COLTON, R.B. 1986. Stratigraphy and correlation of the glacial deposts on the Montana Plains. Quaternary Science Reviews, **5**, pp.69-82.

FULTON, R.J. 1984. Late Wisconsinan glacier complex. *In* Quaternary Stratigraphy in Canada - A Canadian Contribution to IGCP Project 24. *Edited by* R.J. Fulton. Geological Survey of Canada, map 1584A.

GRAHAM, R.W., AND SEMKEN, H. 1976. Paleoecological significance of the short-tailed shrew (*Blarina*), with a systematic description of *Blarina ozarkensis*. Journal of Mammalogy. **57(3)**, pp.433-449.

GRAVENOR, C.P., AND KUPSCH, W.O. 1959. Ice disintegration features in western Canada. Journal of Geology, **67**, pp. 48-64.

GLIME, J.M. AND VITT, D.H. 1984. The physiological adaptations of aquatic Musci. Lindbergia, **10**, pp.41-52.

HJORT, C. 1973. A sea correction for East Greenland. Geol. Foren , Stockholm Fornhandl, **95**, 132-134.

HOPKINS, D.M., AND SIGAFOOS, R.S. 1954. Role of frost thrusting in the formation of tussocks. American Journal of Science, **252**, pp. 55-59.

HOPPE, G. 1952. Hummocky moraine regions with special reference to the interior of Norbotten. Geografiska Annaler, **34**, pp. 1-71.

JACKSON, L.E., JR. 1979. New evidence for the existence of an ice-free corridor in the Rocky Mountain Foothills near Calgary, Alberta, during Late Wisconsinan time. Geological Survey of Canada Paper 79-1A, pp.107-111.

JACKSON, L.E., JR. 1983. Comments on chronology of Late Wisconsinan glaciation in middle North America. Quaternary Science Reviews, **1**, pp. vii-xiv.

JACKSON, L.E., JR., AND PAWSON, M. 1984. Alberta radiocarbon dates. Geological Survey of Canada, Paper 83-25, 27 pp.

JAHN, A. 1975. Problems of the periglacial zone. Translated and published for the National Science Foundation, Washington, D.C.

OM, E. 1981. Late Cenozoic soils of the Glacier and Waterton Parks area, northwestern Montana and Southwestern Alberta, and paleoclimatic implications. Unpublished Ph.D. thesis, Department of Geography, University of Calgary, Calgary, 359 pp.

KARLSTROM, E. 1986. Late Cenozoic glacial and pedological history of Glacier-Waterton Park area, southwestern Alberta and Northwestern Montana. *In* Developments in Palaeontology and Stratigraphy. *Edited by* R.W. Barendregt, v.8. Elsevier, New York.

KOSTYAEV, A.G. 1969. Wedge and fold-like diagenetic disturbances in Quaternary sediments and their palaeogeographic significance. Biuletyn Peryglacjalny, **19**, pp. 231-270.

KLASSEN, R.W. 1989. Quaternary geology of the southern Canadian Interior Plains. *In* Quaternary Geology of Canada and Greenland. *Edited by* R.J. Fulton. Geological Survey of Canada.

KLINKEN, G.J.V., AND MOOK, W. G. 1990. Preparative high-performance liquid chromatographic separation of individual amino acids derived from fossil bone collagen. Radiocarbon, **32**, pp. 155-164.

KUHN, T.S. 1974. Second thoughts on paradigms. *In* The Structure of Scientific Theories. *Edited by* F. Suppe. University of Illinois Press, Urbana, Illinois, pp. 459-482.

KURTÉN, B. AND ANDERSON, E. 1980. Pleistocene Mammals of North America. Columbia University Press, New York.

LACHENBRUCH, A.H. 1960. Thermal contraction cracks and ice wedges in permafrost. U.S. Geol. Survey Prof. Papers 400-B. pp. B404 - B406.

LACHENBRUCH, A.H. 1962. Mechanics of thermal contraction cracks and ice wedge polygons in permafrost. Geological Society of America Special Paper No. 70. pp.69.

LEFFINGWELL, E. deK. 1915. Ground ice wedges - Dominant form of ground ice on the north coast of Alaska. Journal of Geology, **23**, pp. 635-654.

LOWE, D.C. 1989. Problems associated with the use of coal as a source of ^{14}C-free background material. Radiocarbon, **31**, pp. 117-120.

LUNDELIUS, E.L., JR., DOWNS, T., LINDSAY, E.H., SEMKEN, H.A., ZAKRZEWSKI, R.J., CHURCHER, C.S., HARINGTON, C.R., SCHULTZ, G.E., AND WEBB, S.D. 1987. The North American Quaternary sequence. *In* Cenozoic Mammals of North America. *Edited by* Michael O. Woodburne. University of California Press, pp. 211-235.

MACKAY, J.R. 1972. The world of underground ice. Annals of the Association of American Geographers, [illegible] pp. 1-22.

MACKAY, J.R. 1984. The direction of ice-wedge cracking in permafrost: downward or upward? Canadian Journal of Earth Sciences, **21**, pp. 516-524.

MACKAY, J.R. 1988. Ice wedge growth in newly aggrading permafrost, Western Arctic Coast, Canada. Permafrost, V International Conference on Permafrost in Trondheim, Norway, August 1988, **1**, pp. 809-814.

MACDONALD, G.M., BEUKENS, R.P., KIESER, W.E., AND VITT, D.H. 1987. Comparative radiocarbon dating of terrestrial plant macrofossils and aquatic moss from the "ice-free corridor" of western Canada. Geology **15**, pp. 837-840.

MANDRYK C.A. 1990. Could humans survive the ice-free corridor?: Late-glacial vegetation and climate in west central Alberta. *In* Megafauna and Man: Discovery of America's Heartland. *Edited by* L.D. Agenbroad, J.I. Mead, and L.W. Nelson. The Mammoth Site of Hot Springs, South Dakota, Inc. Scientific Papers, **1**, pp. 67-79.

MANGERUD, J. AND GULLIKSEN, S. Apparent rediocarbon ages of recent marine shells from Norway, Spitsbergen and Arctic Canada. Quaternary Research, **5**, pp. 263-274.

MATHEWS, W.H. 1974. Surface profiles of the Laurentide ice sheet in its marginal areas. Journal of Glaciology, **13**, pp. 37-43.

MEARS, B., JR. 1981. Periglacial wedges and the late Pleistocene environment of Wyoming's intermontane basins. Quaternary Research, **15**, pp. 171-198.

MENZIES, J. 1987. Towards a general hypothesis on the formation of drumlins. *In* Drumlin Symposium. *Edited by* J. Menzies and J. Rose. Balkema, Rotterdam, pp. 9-24.

MILLS, H.H. 1980. An analysis of drumlin form in the north-eastern and north-central United States. Geological Society of America Bulletin, **1**, **91**, pp. 637-639, and, **2**, **91**, pp. 2214-2289.

MILLS, H.H. 1987. Morphometry of drumlins in the north-eastern and north-central U.S.A. *In* Drumlin Symposium. *Edited by* J. Menzies and J. Rose. Balkema, Rotterdam, pp. 131-147.

MOTT, R.J., AND JACKSON, L.E., JR. 1982. An 18,000 year palynological record from the southern Alberta segment of the classical Wisconsinan "ice-free corridor". Canadian Journal of Earth Sciences, **19**, pp. 504-513.

MIDDENDORFF, A.T. 1862. Voyages to north and east Siberia. SPb, Part 1.

PÉWÉ,T.L. 1963. Ice wedges in Alaska - Classification, distribution, and climatic significance. Permafrost International Conference Proceedings. National Academy of Science Publication, **1287**, pp. 76-81.

PÉWÉ,T.L. 1969. The periglacial environment. *In* The Periglacial Environment. *Edited by* T.L. Péwé. McGill-Queen's University Press, Montreal, pp. 1-11.

PÉWÉ, T.L. 1973. Ice wedge casts and past permafrost distribution in North America. *In* Periglacial Processes. *Edited by* C.A.M. King 1976. Benchmark Papers in Geology volume 27. Dowden, Hutchinson and Ross Inc., Stroudsburg, P.A.

PREST, V.K. 1969. Retreat of Wisconsin and recent ice in North America. Geological Survey of Canada, Map 1257A, 1:5,000,000.

RAINS, R.B. 1990. Quaternary geomorphology, North Saskatchewan River basin. Canadian Association of Geographers Field Trip Guide, Edmonton.

RAINS, R.B., KVILL, D., AND SHAW, J. 1990. Evidence and some implications of coalescent Cordilleran and Laurentide glacier systems, western Alberta. *In* A World of Real Places. *Edited by* P.J. Smith and E.L. Jackson, pp. 147-161.

REED, B., GALVIN, C.J., AND MILLER, J.R. 1962. Some aspects of drumlin geometry. American Journal of Science, **260**, 200-210.

REEVES, B.O.K. 1983. Bergs, barriers, and Beringia: Reflections on the peopling of the New World. *In* Quaternary Coastlines and Marine Archaeology: Towards the Prehistory of Land Bridges and Continental Shelves. *Edited by* P.M. Masters and N.C. Fleming. Academic Press, London.

REPENNING, C.A. 1987. Biochronology of the Microtine rodents of the United States. *In* Cenozoic Mammals of North America. *Edited by* Michael O. Woodburne. University of California Press, pp. 236-268.

ROED, M.A. 1975. Cordilleran and Laurentide multiple glaciation, west-central Alberta, Canada. Canadian Journal of Earth Sciences, **12**, pp. 1493-1515.

ROMANOVSKIJ, N.N. 1973. Regularities in formation of frost-fissures and development of frost-fissure polygons. Biuletyn Peryglacjalny, **23**, pp. 237-277.

RUSSELL, L.S. 1958. A horse astragalus from the Hand Hills Conglomerate, Alberta. National Museums of Canada, Natural History Papers **1**, pp. 1-3.

RUST, B.R., AND KOSTER, E.H. 1978. Depositional models for braided alluvium. *In* Fluvial Sedimentology. *Edited by* A.D. Miall. Canadian Society of Petroleum Geologists, Memoir **5**, pp. 605-625.

RUTHERFORD, R. 1937.Saskatchewan gravels and sands in central Alberta. Royal Society of Canada, Transactions, **IV**, series 3, **31**, pp. 81-95.

RUTTER, N.W. 1984. Pleistocene history of the Canadian ice-free corridor. *In* Quaternary Straigraphy in Canada - A Canadian Contribution to IGCP Project 24. *Edited by* R.J. Fulton. Geological Survey of Canada, Paper 84-10, pp. 49-56.

SCHAEFER, J.P. 1949. Some periglacial features in central Montana. Joumal of Geology, **57**, pp. 154-174.

SHARP, R. 1942. Periglacial involutions in north-eastern Illinois. Journal of Geology, **50**, pp. 113-133.

SHARPE, D.R. 1987. The stratified nature of drumlins from Victoria Island and southern Ontario. *In* Drumlin Symposium. *Edited by* J. Menzies and J. Rose, Balkema, Rotterdam, pp. 103-118.

SHARPE, D.R., AND SHAW, J. 1989. Erosion of bedrock by subglacial meltwater, Cantley, Quebec. Geological Society of America Bulletin, **101**, pp. 1011-1020.

SHAW, J. 1983. Drumlin formation related to inverted melt-water erosional marks. Journal of Glaciology, **29**, pp. 461-479.

SHAW, J. 1988. Models of terrestrial glacial sedimentation. *In* Glacial Facies Models; Continental Terrestrial Environments. *Edited by* J. Shaw and G. Ashley. Geological Society of America. Short Course.

SHAW, J., AND KVILL, D. 1984. A glaciofluvial origin for drumlins of the Livingstone Lake area, Saskatchewan. Canadian Journal of Earth Sciences, **21**, pp. 1442-1459.

SHAW, J., KVILL, D., AND RAINS, B. 1989. Drumlins and catastrophic floods. Sedimentary Geology, **62**, pp. 177-202.

SHETSEN, I. 1987. Quaternary geology, southern Alberta. Alberta Research Council Map, 1:500,000.

SHETSEN, I. 1990. Quaternary geology, central Alberta. Alberta Research Council Map, 1:500,000.

SHILTS, W.W., AYLSWORTH, J.M., KASZYCKI, C.A., AND KLASSEN, R.A. 1987. Canadian Shield. *In* Geomorphic Systems in North America. *Edited by* W.L. Graf. Geological Society of America Centennial Special Volume **2**, pp. 119-161.

SHUMSKII, P.A. 1952. Principles of Structural Glaciology. New York, Dover Publications.

SHVETSOV, M. 1954. Concerning some additional aids in studying sedimentary formations. Academy of Sciences of the USSR, Doklady Earth Sciences, **29**, pp. 61-66.

SKOYE, K.R. 1990. Digital Analysis of Low-Relief Topography in a Landsat Snow-Cover Scene in South-Central Alberta. Unpublished M.Sc. thesis, Department of Geography, University of Alberta.

SMITH, W. 1815. Memoir to the map and delineation of the strata of England and Wales with a part of Scotland. London: Cary.

STAFFORD, T.W., JR., JULL, A.J.T., BRENDEL, K.DUHAMEL, R.C., AND DONAHUE, D. 1987. Study of bone radiocarbon dating accuracy at the University of Arizona NSF accelerator facility for radioisotope analysis. Radiocarbon, **29**, pp. 24-44.

STALKER, A. MACS. 1956. The erratics train, foothills of Alberta. Geological Survey of Canada Bulletin 37.

STALKER, A. MACS. 1959. Surficial geology, Fort Macleod, Alberta. Geological Survey of Canada. Map 21-1958, 1:250,000.

STALKER, A. MACS. 1960. Surficial geology of the Red Deer-Stettler map-area, Alberta. Geological Survey of Canada, Memoir 306.

STALKER, A. MACS. 1962. Surficial geology, Fernie, 82G, Alberta portion. Geological Survey of Canada. Map 31-1961, 1:250,000.

STALKER, A. MACS. 1968. Identification of Saskatchewan Gravels and Sands. Canadian Journal of Earth Sciences, **5**, pp. 156-163.

STALKER, A. MACS. 1968. Quaternary stratigraphy in southern Alberta; Report II: Sections near Medicine Hat, Alberta. Geological Survey of Canada, **69-26**.

STALKER, A. MACS. 1973. Surficial geology of the Drumheller area, Alberta. Geological Survey of Canada, Memoir 370.

STALKER, A. MACS. 1976. Quaternary stratigraphy of the southwestern Canadian Prairies. *In* Quaternary Stratigraphy of North America. *Edited by* W.C. Mahaney. Dowden, Hutchinson and Ross, Stroudsburg, Pa., pp. 381-487.

STALKER, A. MACS. 1977. The probable extent of Classical Wisconsin ice in southern and central Alberta. Canadian Journal of Earth Sciences, **14**, pp. 2614-2619.

STALKER, A. MACS. 1983. Quaternary stratigraphy in southern Alberta; Report III: The Cameron Ranch Section. Geological Survey of Canada, **83-10**.

STALKER, A. MACS. 1985. Southern Alberta. Field Trip in Association with the 1985 CANQUA Symposium on the Paleoenvironmental Reconstruction of the Late Wisconsin Deglaciation and the Holocene. Lethbridge, Alberta.

STALKER, A. MACS., AND CHURCHER, C.S. 1972. Glacial stratigraphy of the southwestern Canadian Prairies; the Laurentide record. 24th International Geological Congress (Montreal), Section12, pp. 110-119.

STALKER, A. MACS., AND HARRISON, J.E. 1977. Quaternary geology of the Waterton-Castle River region of Alberta. Canadian Petroleum Geology, Bulletin, **25**, pp. 882-906.

STELCK, C.R. 1975. The record of the rocks. *In* Alberta, A Natural History. *Edited by* W. G. Hardy. M.G. Hurtig, Edmonton, Alberta.

STORER, J.E. 1972. Mammals of the Hand Hills Formation of southern Alberta: preliminary faunal list. Blue Jay, **30**(2), pp. 119-120.

STORER, J.E. 1976. Mammals of the Hand Hills Formation, southern Alberta. *In* Athlon: Essays on Palaeontology in Honour of Loris Shano Russell. *Edited by* C.S. Churcher. Royal Ontario Museum, Life Sciences Miscellaneous Contributions, pp. 186-209.

STUIVER, M., BRAZIUNAS, T.F., BECKER, B., AND KROMER, B. 1991. Climatic, solar, oceanic and geomagnetic influences on late-glacial and Holocene atmospheric ^{14}C/^{12}C change. Quaternary Research, **35**, pp. 1-24.

TEDFORD, R.A., SKINNER, M.F., FIELDS, R.W., RENSBERGER, J.M., WHISTLER, D.P., GALUSHA, T., TAYLOR, B. E., MACDONALD, J.R., AND WEBB, S.D. 1987. Faunal succession and biochronology of the Arikareean through Hemphillian interval (late Oligocene through earliest Pliocene epochs) in North America. *In* Cenozoic Mammals of North America. *Edited by* Michael O. Woodburne. University of California Press, pp. 153-210.

THORPE, J. 1949. Effects of certain animals that live in soils. The Scientific Monthly, vol. LXVIII, March 1949.

TSUI, P.C., CRUDEN, D.M., AND THOMSON, S. 1989. Ice-thrust terrains and glaciotectonic settings in central Alberta. Canadian Journal of Earth Sciences, **26**, pp. 1308-1318.

TYRRELL, J.B. 1887. Report on a part of northern Alberta and portions of adjacent districts of Assiniboia and Saskatchewan, Geol. Nat. Hist. Surv. Can., Ann. Rept., new series, **2**:1E-176E.

VOORHIES, M. 1975. Vertebrate burrows. *In* The Study of Trace Fossils. *Edited by* R.W. Frey. Springer, New York. pp. 325-350.

WALTERS, J.C. 1978. Polygonal patterned ground in central New Jersey. Quaternary Research, **10**, pp. 42-54.

WARREN, P.S. 1939. The Flaxville Plain in Alberta. Transactions of the Royal Canadian Institute, **22**, 2, pp. 341-349.

WASHBURN, A.L. 1956. Classification of patterned ground and review of suggested origins. Bulletin of the Geological Society of America, **67**, pp. 823-865.

WASHBURN, A.L. 1973. Periglacial processes and environments. Edward Arnold. London.

WESTGATE, J.A., AND BAYROCK, L. 1964. Periglacial structures in the Saskatchewan sands and gravels of central Alberta, Canada. Journal of Geology, **72**, pp. 641-648.

WESTGATE, J.A., CHRISTIANSEN, E.A., AND BOELLSTORFF, J.D. 1977. Wascana Creek Ash (Middle Pleistocene) in southern Saskatchewan: characterization, source, fission track age, palaeomagnetism and stratigraphic significance. Canadian Journal of Earth Sciences, **14**, pp. 357-374.

WESTGATE, J.A., BRIGGS, N.D., STALKER, A. MACS., AND CHURCHER, C.S. 1978. Fission-track age of glass from tephra beds associated with Quaternary vertebrate assemblages in the southern Canadian plains. Geological Society of America. Abstracts with program, **10**, **7**, pp. 514-515.

WHITE, J.M., MATHEWES, R.W., AND MATHEWS, W.H. 1979. Radiocarbon dates from Boone Lake and their relation to the "ice-free corridor" in the Peace River district of Alberta, Canada. Canadian Journal of Earth Sciences, **16**, pp. 1870-1874.

WHITE, J.M., MATHEWES, R.W., AND MATHEWS, W.H. 1985. Late Pleistocene chronology and environment of the "ice-free corridor" of northwestern Alberta. Quaternary Research, **24**, pp. 173-186.

WOLFF, R.G. 1981. Taphonomy in the making. Paleobiology, **7(2)**, pp. 284-287.

WOODBURNE, M.O. 1987. Principles, classification, and recommendations. *In* Cenozoic Mammals of North America. *Edited by* Michael O. Woodburne. University of California Press, pp. 9-17.

YEHLE, L.A. 1954. Soil tongues and their confusion with certain indicators of periglacial climate. American Journal of Science, **252**, pp. 523-546.

ZINGG, T. 1935. Beiträge zur schatteranalyse. Schweizerische Mineralogosche und Petrographische Mitteilungen, **15**, pp. 39-140.

Appendix

Till fabric data

CourtE#1- (from diamict, just above bottom contact (1.5m W of burrow cast top) 306 32, 322 7, 316 22, 303 17, 314 17, 323 21, 309 23, 326 11, 313 12, 316 22, 312 37, 312 3, 320 24, 312 30, 293 29, 303 8, 292 15, 296 16, 303 13, 306 32, 308 20, 312 13, 263 12, 290 11, 302 8,

CourtE#2-(from 30 cm above #1) 178 15, 188 14, 175 11, 296 11, 270 3, 176 16, 184 11, 298 27, 289 8, 292 60, 266 8, 139 3, 102 3, 265 28, 227 13, 70 37, 242 12, 185 10, 90 4, 336 2, 313 12, 285 12, 165 14, 288 38, 307 12,

CourtE#3-(from about 30cm over #2-from above stacked organics) 79 17, 115 11, 174 60, 198 62, 193 43, 153 67, 232 55, 253 46, 144 46, 208 48, 182 49, 158 40, 290 21, 330 34, 198 58, 338 10, 272 28, 240 50, 290 38, 178 58, 234 68, 190 58, 176 53, 231 52, 300 52,

CourtE#4-(from diamict directly over burrow-cast mouth) 303 17, 296 16, 296 11, 294 10, 297 18, 294 14, 280 4, 301 21, 200 11, 291 17, 316 4, 307 9, 321 18, 263 13, 296 12, 288 21, 289 9, 288 2, 296 6, 293 4, 236 4, 293 4, 323 11, 313 25, 249 27,

CourtE#5-(from ~ 15 cm below surface, in diamict) 274 43, 280 46, 275 41, 236 9, 280 17, 258 23, 163 5, 243 29, 234 28, 276 22, 281 17, 326 18, 187 28, 251 30, 258 25, 177 17, 268 13, 244 25, 69 24, 251 51, 278 36, 254 57, 241 37, 84 1, 164 25,

CourtE#6-(from between stacked organics) 103 26, 310 51, 120 17, 293 35, 114 58, 138 13, 121 12, 85 21, 299 22, 301 7, 292 16, 312 29, 61 33, 291 12, 108 15, 104 10, 93 32, 254 25, 79 16, 111 8, 121 29, 188 61, 122 3, 131 18, 111 25,

CourtE#7-(from directly below lowest stacked organic layer) 110 3, 122 4, 109 13, 96 36, 81 37, 91 26, 87 32, 89 8, 304 4, 28 11, 293 9, 90 7, 100 20, 118 7, 108 7, 269 4, 310 16, 125 28, 91 3, 67 32, 309 24, 65 20, 290 39, 58 17, 58 17

K&TE#1-((from underlying gravel) 308 32, 298 32, 304 20, 272 30, 0 68, 2 54, 0 52, 214 80, 12 72, 291 9, 325 51, 79 38, 212 53, 236 44, 36 47, 336 28, 144 10, 78 7, 358 62, 312 32, 310 40, 12 38, 352 42, 288 27, 2 50,

K&TE#2-(from gravel) 300 33, 276 48, 260 22, 280 34, 258 60, 296 56, 296 26, 244 43, 280 30, 280 35, 322 48, 279 44, 266 52, 264 45, 268 18, 266 6, 340 50, 310 18, 296 64, 296 48, 296 48, 300 54, 276 20, 276 36, 306 60

K&TE#3-(from diamict ~15 cm above lower contact) 286 36, 210 64, 313 63, 318 80, 306 38, 333 76, 295 31, 304 49, 296 68, 296 60, 308 32, 297 57, 313 27, 6 78, 268 30, 267 88, 303 62, 208 82, 33 80, 216 67, 220 70, 58 83, 36 80, 221 68, 316 41

K&TE#4-(from along shearplane, ~15 cm above #3) 346 28, 353 26, 120 40, 321 4, 304 28, 283 85, 174 18, 3 21, 295 14, 7 20, 319 32, 315 15, 193 3, 320 18, 321 18, 310 20, 295 38, 340 17, 345 10, 320 40, 307 14, 349 3, 299 12, 40 21, 336 19

K&TE#5-(~ 15 cm above #4) 314 5, 302 62, 212 18, 212 76, 356 7, 327 3, 16 4, 264 8, 120 15, 128 8, 321 12, 332 7, 92 2, 294 4, 300 3, 191 9, 64 3, 310 21, 290 12, 164 20, 323 7, 79 19, 312 7, 303 3, 14 1, 314 6

K&TN#1-(from diamict, ~ 10 cm above bottom contact, at north end of section) 17 14, 01 13, 326 22, 352 11, 338 11, 357 04, 352 9, 164 11, 355 5, 344 19, 345 19, 320 9, 334 2, 319 45, 326 22, 138 9, 193 17, 19 24, 340 3, 356 35, 340 8, 198 9, 360 10, 347 24, 350 35

K&TN#2-(from diamict, ~30 cm above #1) 170 9, 160 10, 338 60, 325 5, 334 27, 348 8, 342 8, 350 3, 338 15, 350 11, 170 28, 358 1, 330 13, 24 6, 14 5, 199 48, 175 9, 6 12, 348 2, 218 10, 169 17, 163 12, 1 9, 354 12

K&TN#3-(from diamict at the middle part of the section--30 cm below surface, above organic unit)162 6, 340 13, 163 12, 144 32, 184 25, 145 17, 141 2, 154 8, 159 21, 184 22, 159 3, 139 2, 288 15, 170 12, 15 12, 131 17, 182 37, 174 18, 142 13, 138 24, 169 26, 177 8, 186 35, 359 10, 4 20

K&TW#1-(from diamict, 8m north of south end- ~5 cm above lower contact) 159 2, 197 10, 26 23, 179 3, 153 10, 41 19, 3 19, 192 25, 122 34, 63 23, 167 7, 215 7, 227 3, 93 45, 338 31, 1 10, 90 11, 168 22, 87 11, 343 15, 353 7, 111 21, 338 32, 90 13, 227 5

K&TW#2-(from ~20cm above #1, above shear plane) 316 19, 93 14, 296 42, 30 14, 46 49, 93 22, 135 22, 264 25, 144 13, 143 27, 71 10, 242 10, 336 16, 340 12, 152 6, 138 16, 316 10, 307 8, 120 21, 329 22, 129 22, 292 19, 155 31, 236 37, 178 10

K&TW#3-(from diamict, 8m south of #1-- ~5 cm above lower contact) 145 38, 174 30, 261 48, 174 6, 68 2, 24 5, 183 85, 348 87, 78 24, 40 27, 234 7, 344 5, 30 17, 41 15, 237 17, 216 40, 171 7, 199 15, 2 45, 57 2, 228 70, 113 22, 77 42, 52 12, 39 16

K&TW#4-(from ~30 cm above #3, from shear zone)1 18, 348 8, 118 22, 321 7, 311 9, 333 4, 244 5, 97 75, 63 18, 304 56, 93 76, 149 12, 138 46, 199 52, 257 74, 31 38, 118 18, 153 1, 113 32, 324 3, 18 56, 355 49, 239 78, 105 75, 113 37

K&TW#5-(From 8 m south of #3- ~5cm above bottom contact, below shear zone) 132 13, 116 21, 107 17, 328 10, 245 2, 121 12, 333 7, 2 2, 30 6, 7 19, 25 8, 57 30, 117 12, 83 24, 287 9, 40 11, 319 12, 130 4, 135 13, 293 8, 159 10, 104 16, 251 34, 22 25, 44 22

K&TW#6-(from ~40 cm above #5) 241 25, 9 12, 305 39, 326 21, 334 12, 345 12, 347 4, 137 36, 283 40, 114 27, 235 25, 343 58, 334 40, 330 35, 13 37, 175 22, 329 9, 141 17, 349 8, 0 42, 172 5, 324 46, 228 42, 191 16, 127 38

Seward #1 -(Section 3- .5 m west of east end- Unit 2, 30 cm above lower contact) 180 4, 200 0, 200 18, 340 15, 270 2, 200 6, 40 4,, 340 2, 20 28, 0 5, 341 30, 18 16, 354 3, 22 7, 24 21, 349 11, 195 9, 2 13, 9 14, 20 19, 26 7, 4 19, 358 3, 16 9, 6 11, 240 30, 150 8, 220 80, 32 22, 330 7, 351 8, 20 1, 28 6, 207 7, 2 3, 351 22, 336 10, 210 6, 17 3, 22 8, 290 8, 0 3, 214 48, 333 12, 187 19, 1 49, 332 5, 3 13, 190 17, 204 8

Seward #2-(section 4, Unit 2, 2m south of north end~20 cm above lower contact) 47 12, 332 8, 358 22, 316 18, 337 38, 338 30, 340 16, 18 38, 250 5, 220 7, 1 57, 346 34, 26 54, 220 38, 308 2, 178 27, 346 23, 334 38, 334 33, 204 21, 334 30, 352 56, 29 21, 350 35, 208 50, 14 12, 312 18, 320 18, 332 38, 332 44, 198 26, 204 50, 190 16, 330 7, 345 40, 333 29,320 20, 260 12, 326 38,18 32, 3 20, 210 18, 323 34, 262 23, 2 4, 325 22, 304 25, 140 21

Seward #3-(section 3, Unit 3, 1m west of east end~ 50cm above lower contact) 183 21, 341 11, 231 10, 339 28, 27 17, 341 14, 162 20, 24 16, 336 12, 313 20, 322 33, 29 13, 303 44, 192 18, 316 14, 158 16, 190 38, 326 50, 40 16, 348 20, 326 4, 160 38, 206 22, 188 22, 196 22, 193 6, 198 47, 18 25, 200 18, 150 50, 170 38, 27 32, 213 48, 5 8, 12 11, 59 24, 216 30, 170 33, 200 22, 340 20, 150 16, 54 8, 160 4, 148 22, 48 21, 203 14, 40 18, 323 36, 209 18

Seward #4-(section 4, Unit 2, 2m south of north end, ~5 cm below upper contact) 300 6, 114 2, 270 6, 110 11, 304 8, 302 20, 222 48, 120 26, 294 18, 100 12, 304 1, 90 9, 120 18, 293 9, 25 4, 90 3, 97 8, 40 9, 110 3, 107 1, 120 33, 103 12, 130 16, 260 3, 259 18, 115 12, 243 16

Seward #5-(section 3, Unit 2, 2m west of east end,~10 cm above bottom contact) 316 35, 343 11, 253 10, 322 35, 276 37, 263 11, 73 9, 51 18, 56 20, 39 35, 305 14, 328 22, 91 50, 286 33, 314 27, 339 40, 266 47, 85 18, 328 58, 266 28, 263 37, 290 39, 244 22, 33 11, 19 17

Seward #6-(section 3, Unit 2, 2m west of east end,~25cm above bottom contact) 348 2, 184 8, 235 21, 65 33, 227 3, 41 41, 357 29, 266 7, 265 25, 266 25, 40 9, 244 28, 187 13, 9 16, 335 2, 343 42, 301 14, 350 28, 88 10, 3 2, 45 44, 5 7, 292 12, 128 7, 286 20

Seward #7-(section 3, Unit 2, 2m west of east end,~40cm above bottom contact) 158 26, 281 4, 143 9, 253 11, 355 5, 192 9, 294 16, 204 28, 302 32, 27 23, 18 43, 21 40, 233 7, 351 43, 156 13, 337 38, 253 9, 337 33, 337 10, 320 45, 346 38, 303 31, 295 48, 337 17, 339 23

Seward #8-(section 4, Unit 2, 3.4m south of north end ~10 cm below upper contact, in lee of hump structure) 158 17, 310 53, 107 37, 18 60, 1 62, 216 27, 275 44, 338 41, 82 15, 104 23, 312 22, 320 21, 15 65, 312 47, 289 6, 16 48, 333 40, 303 29, 285 18, 192 10, 111 20, 303 14, 300 1, 42 56, 281 39

Seward #9,-(section 4, Unit2, 3.1 m south of north end, near north end of hump structure) 296 44, 109 17, 332 55, 158 3, 321 38, 57 30, 298 55, 293 65, 214 58, 14 62, 7 25, 359 23, 159 8, 295 38, 28 5, 337 53, 359 31, 311 21, 377 31, 316 37, 70 23, 304 37, 69 41, 306 48, 58 53,

Seward #10-(section 4, Unit 2, 6.2m south of north end, 25cm below upper contact) 313 57, 38 3, 345 40, 29 21, 315 18, 327 10, 19 25, 323 11, 330 28, 25 36, 345 57, 341 62, 5 14, 319 49, 298 60, 317 56, 63 10, 351 55, 348 26, 342 53, 67 10, 345 22, 311 45, 349 30, 3 31

Seward #11-(section 4, Unit 2, 7m south of north end, ~5cm below upper contact) 297 9, 295 9, 86 18, 318 13, 353 55, 323 61, 74 12, 222 20, 295 21, 313 8 , 123 13, 279 12, 269 13, 100 43, 271 22, 287 5, 294 45, 198 37, 292 40, 301 38, 285 31, 318 50, 302 20, 21 57, 285 21,

Seward #12-(section 4, Unit 2, 12.5m west of east end, ~5cm above lower contact) 280 30, 1 26, 326 60, 249 10, 354 18, 27 22, 50 11, 2 2, 226 7, 236 19, 215 22, 7 19, 1 9, 38 11, 353 33, 355 5, 313 25, 13 11, 319 18, 166 26, 355 36, 40 7, 349 11, 2 37, 355 50

Seward #13-(section 3, Unit 2, about 12.5 m west of east end, ~ 5 cm below upper contact, in dark-stained portion) 40 4, 303 3, 311.5, 290 5, 130 7, 159 4, 294 18, 329 20, 318 8, 330 4, 302 5, 124 5, 84 30, 336 18, 294 1, 266 24, 244 10, 318 19, 299 7, 92 25, 291 9, 300 21, 359 10, 359 8, 119 11

Seward #14-(section 3, Unit3, about 12.5 m west of east end, ~20cm above lower contact) 317 29, 351 61, 330 43, 187 28, 243 44, 83 45, 105 33, 125 16, 94 60, 84 22, 3 71, 4 58, 287 47, 321 15, 113 49, 350 22, 336 27, 205 9, 4 43, 350 62, 1 27, 313 30, 324 22, 356 51, 306 40,