MAPPING AND CHARACTERIZATION OF THE UPPER LAKE AGASSIZ BEACHES ALONG THE MANITOBA ESCARPMENT BETWEEN THE INTERNATIONAL BORDER AND THE ASSINIBOINE RIVER

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BY

KYLE MCMILLAN

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

Abstract

The paleo-shorelines of glacial Lake Agassiz are inferred from beach ridges and wave-formed scarps. Shoreline features of the oldest, uppermost beaches, the Herman, Norcross, and Tintah groups of beaches, were mapped from aerial photographs in southern Manitoba between about the Canada – U.S. border and the Assiniboine River (~49.0° - 49.5° N latitude). Aerial photo maps were initially made on transparent overlays and later digitized. This mapping was supplemented by fieldwork, including ground penetrating radar surveys, power augering, and by data from existing boreholes, pit surveys, and soil surveys.

The Herman, Norcross, and Tintah beach sets each contain several low-relief beach ridges that extend discontinuously over tens of kilometres; these ridges are generally less than 3 m in relief, and a few tens of metres wide. In places, beach ridges are replaced by erosional scarps, metres to tens of metres in relief and continuous over distances of tens of kilometres. Sediments in the Herman, Norcross, and Tintah beaches range from units of well sorted sand to sand-gravel diamictons; sediments between beaches include clayey to sandy silts, and gravel lags. These three beach sets predate the well-developed Upper Campbell Beach, which was deposited about 9.4 ^{14}C ka, and are distinct from it because of their lateral discontinuity and much poorer sorting.

Based on their small size, poor sorting of sediments, discontinuous development, and multiplicity, the Herman, Norcross, and Tintah beaches, are concluded to have formed by storms during shoreline regression, probably in sequence over only a few centuries, as there is no pronounced break in the continuum of beach ridges nor major

differences in their size or characteristics. The effects of lake ice may also help explain the discontinuous nature and sedimentological immaturity of these beach ridges.

The Herman beach is thought to have formed about 11 ^{14}C ka, based on other dated events in the Lake Agassiz basin. It is concluded therefore that the Herman, Norcross, and Tintah beach sets represent a continuous period of episodic formation between about 11.0 – 10.8 ^{14}C ka. The Upper Campbell beach is well dated at 9.3 – 9.4 ^{14}C ka, and is too well-developed to be a storm beach; this beach was deposited following a transgression from a low-water lake phase that was initiated after the deposition of the lowest Tintah beach.

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Finally, I would like to thank my parents for being a couple of great guys, my friends from school and elsewhere, and the faculty and students at the Department of Geological Sciences, for keeping me afloat in the often murky waters of Lake Agassiz.

CHAPTER 1:

RESEARCH BACKGROUND AND OBJECTIVES

1.1 Background to Lake Agassiz research

Lake Agassiz was the largest proglacial lake along the margin of the Laurentide Ice Sheet during the last deglaciation of North America. It inundated the Red River Valley in Manitoba, North Dakota, and Minnesota, as well as adjacent areas in Saskatchewan and Ontario at the periphery of the retreating ice sheet. The existence of Lake Agassiz was first recognized in 1823 by William Keating (Elson, 1983). The first large scale map of Lake Agassiz was made by Warren Upham in 1890 (Upham, 1890) based on his own field work during the 1880's, as well as on the work of others. Since the time Upham produced his map, much research has been conducted on mapping the full extent of the lake, particularly to the north (e.g., Smith and Fisher, 1993; Klassen, 1983; Dredge, 1983), studying the Quaternary stratigraphy in areas within the basin (e.g., Fenton et al., 1983; Clayton and Moran, 1982; Teller, 1976a, 1976b; Harris et al., 1974; Elson, 1959; Matile and Keller, 2004), determining the paleohydrology of overflow (e.g., Teller and Thorleifson, 1983; Teller et al., 2005a; Teller and Leverington, 2004), and the effects of Lake Agassiz on paleoclimate (e.g., Barber et al., 1999; Broecker et al., 1989; Teller, 1990; Hostetler et al., 2000; Teller et al., 2002).

Elson (1983) provides a comprehensive review of the history of Lake Agassiz research from the lake's first recognition to the early 1980's. He notes that research trends have been largely determined by changing opportunities and interests. From the time of Upham's 1895 maps (Upham, 1895) to the time of Elson's 1983 review paper, the most notable changes in research opportunities were the advent of aerial photographs, increased accessibility to all parts of the Agassiz basin, stratigraphic borehole information, and the development of radiocarbon dating. In terms of research interests, much of the research between the 1880s and 1980s focused on working out the hydrologic history of the lake. Technology has advanced since the time of Elson's 1983 article; increased use of computers for geological modelling and mapping, and developments in the use of satellites for positioning and remote sensing have facilitated new research. In terms of research goals, examining the details of the lake's history has continued; interest in global climate change has increased dramatically since 1983, and has become an important aspect of Lake Agassiz research.

1.2 Objectives and general methodology of this study

The objectives of this study are to:

1) map the upper beaches and scarps (including those grouped together in the Herman, Norcross, Tintah, and Campbell beaches) along a ~95-km-long part of the Manitoba Escarpment in the Lake Agassiz basin, approximately between the Assiniboine River and the Canada – USA border (~ 49.0° – 49.7° N latitude),
2) examine the morphology and stratigraphy of these beaches and determine their mode of formation,
3) search for datable organic matter in lowlands between beaches that may have been lagoons in order to more precisely constrain the ages of the Herman, Norcross, and Tintah beaches, and consider the applicability of luminescence dating to Agassiz beach sands, and

4) critically examine the existing models of Agassiz beach formation and propose a paleohydrological history for the Herman, Norcross, and Tintah beaches, based on the age, sedimentology, and geomorphology of Lake Agassiz shoreline features in the study area.

The extent of the current study area in southern Manitoba is shown in Figure 1-1. Aerial photo mapping was done onto Mylar or cellophane (overhead transparencies) from February to November 2004 to show beaches and scarps of the Herman, Norcross, Tintah, and Campbell shorelines. In some places beaches were defined well enough to map the full width, but in most places lines were used to represent the beach crest or scarp crest because beaches were too faint and closely-spaced to map the entire beach width at the scale of the photo. The hard-copy maps were digitized using ESRI's ArcView® GIS package with a Calcomp® Summa-sketch III digitizing tablet. Some parts of the study area were not mapped on Mylar or cellophane, but were mapped directly from digital orthophotos in ArcView. Detailed mapping techniques are discussed in Chapter 3.

Field work was carried out during the summer of 2004. Selected beach and scarp features mapped from aerial photos were ground-truthed. Power augering was done in July to examine sediments at selected sites. A truck-mounted auger was used, which allowed sediments to be collected from the ~30-cm-diameter auger bit as it was pulled out of the ground. Holes were deepened by adding 5-foot-long (1.5 m) bits until the complete beach accumulation had been penetrated.

Ground-penetrating radar (GPR) was done in August for the purpose of determining sediment geometry, stratigraphy, and internal structure of Agassiz beaches; GPR methodology is discussed in Chapter 5. Samples for optical luminescence dating were also collected in July of 2004.

Data from field work, as well as water well stratigraphic data, provincial aggregate reports, and soils maps and reports were integrated with the map of shoreline features; representative well-logs from this study and pertinent provincial water well logs are included in Appendix 2 (CD in back cover).

Unless otherwise noted, all towns and cultural features referred to in the text are in Manitoba, and all coordinates are in universal transverse Mercator (UTM) format, zone 14, North American 1983 datum. All digital orthophotos used in this study came from the Linnet orthophoto library at the Elizabeth Dafoe Library, University of Manitoba.

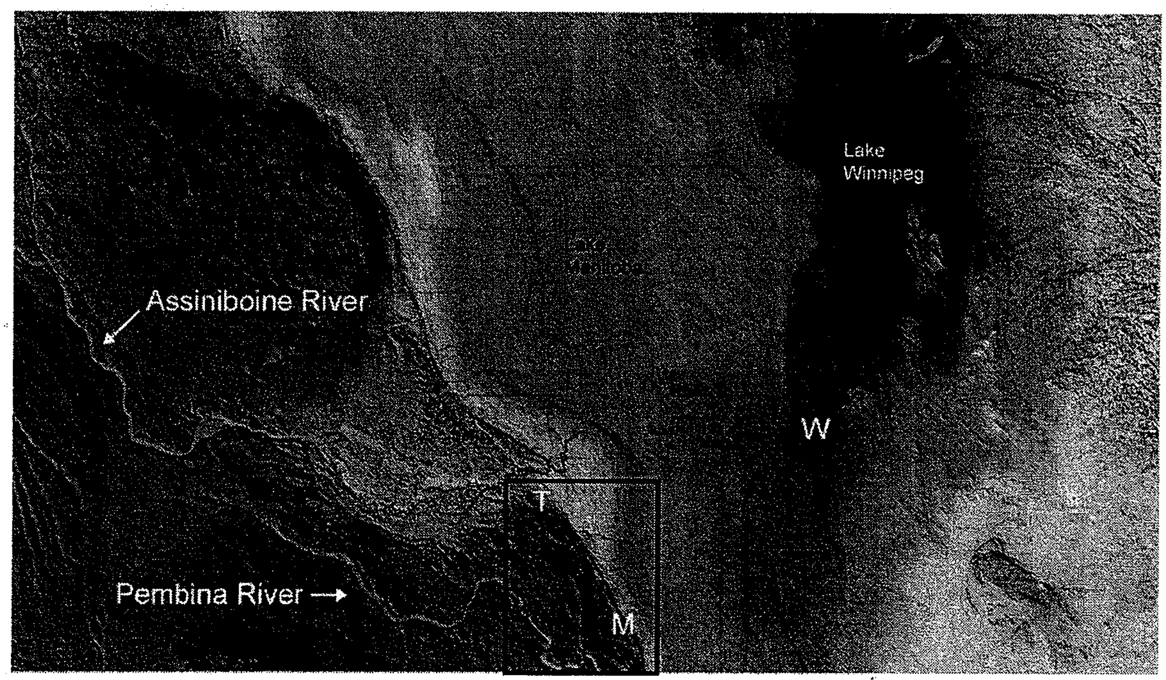


Figure 1-1. Shaded relief map of southern Manitoba showing the extent of the current study area (outlined in black). Letters refer to towns / cities: W – Winnipeg, T – Treherne, M – Morden. Colours represent elevation increasing from cooler to warmer tones (~ 200 m, blue – 850 m, red); after Matile and Keller (1999).

CHAPTER 2:

LAKE AGASSIZ AND ITS GEOLOGICAL BACKGROUND

2.1 Introduction

Glacial Lake Agassiz existed in central North America during the final stages of the retreat of the Laurentide Ice Sheet (LIS) between about 12.0 and 7.7 ^{14}C ka (Fenton et al., 1983; Barber et al., 1999). The load of the ice accentuated an already low topography along the margin of the LIS and dammed northward-flowing drainage. The history of Lake Agassiz was complex—its bathymetry, basin geometry, and hydrodynamics were controlled by a combination of differential isostatic rebound, availability of outlets and their erosion, and glacial advances and retreats. Routing of drainage from Lake Agassiz changed several times during its existence; four different outlet systems are recognized as having carried drainage from Agassiz: the southern outlets through the Minnesota and Mississippi River Valleys to the Gulf of Mexico, the eastern outlets through a series of channels to the Great Lakes then to the St. Lawrence Valley and the North Atlantic Ocean, the northwestern outlet through the Clearwater-Athabasca-Mackenzie River Valleys to the Arctic Ocean, and the northern outlet through Hudson Bay and Hudson Straight to the North Atlantic Ocean (Teller and Leverington, 2004); Figure 2-1 shows the general locations of these outlets, and the patterns of water-routing to the oceans. All the upper beaches of Lake Agassiz (Herman, Norcross, Tintah, Upper Campbell, and Lower Campbell) are connected to the southern outlet and were formed when overflow was through this outlet (Upham, 1895).

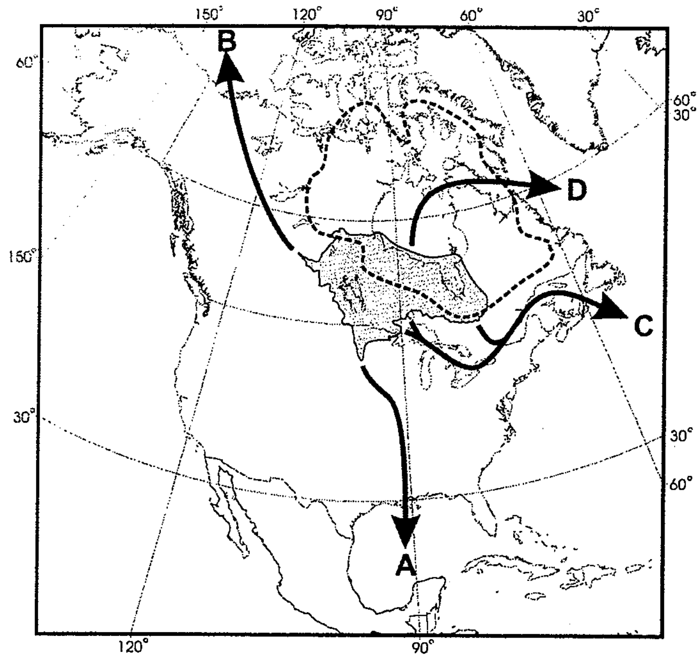


Figure 2-1. Routing of overflow drainage from Lake Agassiz. A: southern outlets, B: northwestern outlet, C: eastern outlets, D: northern outlet. Ice margin at ~ 9 ^{14}C ka is shown as dashed line (Teller and Leverington, 2004, p. 730).

2.2 Regional Geology

2.2.1 Bedrock geology

Teller and Bluemle (1983) divide the bedrock of the Agassiz basin into four geological provinces: the granitic Precambrian Canadian Shield, the Paleozoic carbonate region beneath the Red River Valley (and Interlake of Manitoba), the Paleozoic carbonate region beneath Hudson Bay, and the Mesozoic-Cenozoic shale region to the west of the Red River Valley. The study area of this thesis is along the western shorelines of Lake Agassiz—the Canadian Shield and Hudson Bay lowland are well outside the study area and will not be further discussed. Within the present study area, bedrock generally occurs between 3 – 35 m below the surface (Teller, 1976a).

The Paleozoic carbonate bedrock of the Red River Valley and Manitoba Interlake consists of westward-dipping rocks of the Williston basin; most of these rocks are carbonates, particularly dolostone, although some shale and coarser clastic beds occur (Teller and Bluemle, 1983). The eastern boundary of Paleozoic rocks is along the eastern margin of the Red River Valley in Minnesota and Manitoba. Mesozoic rocks below the Agassiz basin are generally shales, and some sandstones (Teller and Bluemle, 1983). All of the bedrock directly beneath Quaternary sediments in the study area is Cretaceous (Teller, et al., 1976a). Table 2-1 shows the geological formations of Manitoba from Precambrian to Quaternary, focusing mainly on Paleozoic and Mesozoic formations.

ERA	PERIOD		FORMATION (GROUP)	MEMBER	BASIC LITHOLOGY	THICKNESS FEET
CENOZOIC	Quat.	Recent			Soil, alluvial deposits, sand dunes, bogs.	
CENOZOIC	Quat.	Pleistocene			Glacial deposits	0 – 850
CENOZOIC	Tertiary	Eocene to Pliocene	Not reported in Manitoba			
CENOZOIC	Tertiary	Paleocene	Turtle Mountain ?		Shale, sandstone, lignite	– 480+
MESOZOIC	Cretaceous		Boissevain		Sand and sandstone, greenish grey; kaolinitic shale	100 – 150
MESOZOIC	Cretaceous		Riding Mountain	Odanah	Hard grey siliceous shale	– 800+
MESOZOIC	Cretaceous		Riding Mountain	Millwood	Greenish bentonitic shale	50 – 500
MESOZOIC	Cretaceous		Vermilion River	Pembina	Non-calc. shale, bentonite beds	100 – 400
MESOZOIC	Cretaceous		Vermilion River	Boyne	Calcareous speckled shale	100 – 400
MESOZOIC	Cretaceous		Vermilion River	Morden	Carbonaceous shale; septarian concretions	50 – 200
MESOZOIC	Cretaceous		Favel		Calc. speckled shale, limestone bands	60 – 130
MESOZOIC	Cretaceous		Ashville (Ashville Sand)		Non-cal. silty shale; 0-90' sand	120 – 370
MESOZOIC	Cretaceous		Swan River		Sand, sandstone, shale, clay, lignite	0 – 400
MESOZOIC	Jurassic		Waskada		Varicoloured shale	0 – 160
MESOZOIC	Jurassic		Melita		Varicoloured shale, calc. shale, limestone	340 – 480
MESOZOIC	Jurassic		Reston		Argillaceous limestone and shale	0 – 170
MESOZOIC	Jurassic		Amaranth	Upper: evaporite	Anhydrite, gypsum; shale, dolomite	0 – 170
MESOZOIC	Jurassic		Amaranth	Lower: red beds	Dolomitic shale to siltstone, anhydritic	0 – 140
MESOZOIC	Triassic		Not reported in Manitoba except Permian? Lake St. Martin cryptoexplosion structure			
PALEOZOIC	Permian		Not reported in Manitoba except Permian? Lake St. Martin cryptoexplosion structure			
PALEOZOIC	Pennsylvanian		Not reported in Manitoba except Permian? Lake St. Martin cryptoexplosion structure			
PALEOZOIC	Mississippian		Charles		Dolomite and anhydrite	– 120
PALEOZOIC	Mississippian		Mission Canyon		Limestone, dolomite, anhydrite; oil production	270 – 320
PALEOZOIC	Mississippian		Lodgepole	Whitewater Lake, Virden, Scallion, Routledge	Limestone argillaceous and cherty; shale; oil production	480 – 580
PALEOZOIC	Mississippian		Bakken		Black shale and siltstone	10 – 50
PALEOZOIC	Devonian		Qu'Appelle Group	Lyleton	Red dolomitic shale	35 – 180
PALEOZOIC	Devonian		Saskatchewan Group	Nisku	Fossiliferous limestone and dolomite	40 – 140
PALEOZOIC	Devonian		Saskatchewan Group	Duperow	Shaly limestone, dolomite, anhydrite; cyclical	400 – 640
PALEOZOIC	Devonian		Manitoba Group	Souris River (First Red)	Limestone, evaporite, shale; cyclical	210 – 310
PALEOZOIC	Devonian		Manitoba Group	Dawson Bay (Second Red)	Limestone, anhydrite, basal red shale	140 – 220
PALEOZOIC	Devonian		Elk Point Group	Prairie Evaporite	Halite, with potash, anhydrite, dolomite	0 – 425
PALEOZOIC	Devonian		Elk Point Group	Winnipegosis	Dolomite, reef and inter-reef	30 – 350
PALEOZOIC	Devonian		Elk Point Group	Elm Point	High-calcium limestone	0 – 45+
PALEOZOIC	Devonian		Elk Point Group	Ashern	Dolomite and shale, brick red	5 – 60
PALEOZOIC	Silurian		Interlake Group		Dolomite	175 – 370
PALEOZOIC	Ordovician		Stonewall		Dolomite	30 – 70
PALEOZOIC	Ordovician		Stony Mountain	Gunton	Dolomite, upper part shaly	100 – 160
PALEOZOIC	Ordovician		Stony Mountain	Penitentiary	Argillaceous dolomite	100 – 160
PALEOZOIC	Ordovician		Stony Mountain	Gunn	Fossiliferous calc. shale; red, grey, green	100 – 160
PALEOZOIC	Ordovician		Red River	Fort Garry	Dolomite, minor limestone	175 – 500
PALEOZOIC	Ordovician		Red River	Selkirk	Dolomitic limestone, mottled.	175 – 500
PALEOZOIC	Ordovician		Red River	Cat Head	Dolomite, cherty	175 – 500
PALEOZOIC	Ordovician		Red River	Dog Head	Dolomitic limestone, mottled	175 – 500
PALEOZOIC	Ordovician		Winnipeg		Quartzose sand, sandstone; shale	0 – 220
PALEOZOIC	Cambrian		Deadwood		Glauconitic sandstone	?
Precambrian						

Table 2-1. Geological formations of Manitoba showing geological members, basic lithologies, and thicknesses (McCabe, 1971, p. 171).

2.2.2 Quaternary geology

2.2.2.1 Glacial sediments

The Lake Agassiz basin was glaciated repeatedly during late Wisconsinan time. Earlier Lakes must certainly have existed in the Lake Agassiz basin, but geological evidence of these lakes is absent, perhaps because of incomplete stratigraphy data, but mainly because they were eroded by later glaciations (Fenton et al., 1983). Figure 2-2 shows pre-glacial and modern topography within the study area.

Describing the till stratigraphy in southwestern Manitoba, Klassen (1971) notes that sand content ranges from 22 to 41 %, and silt and clay occur in about equal proportions and collectively make up about 60 percent, with gravel making up 5 to 20 % of the till, but is commonly less than 10 percent. In southeastern Manitoba, the various tills range from about 22 to 68 percent sand, 30 to 48 % silt, and 6 to 30 % clay (Teller and Fenton, 1980). Figure 2-3 shows time vs. distance stratigraphy of till and Lake Agassiz sediments for the southern part the Red River Valley (North Dakota and Minnesota), and SE Manitoba.

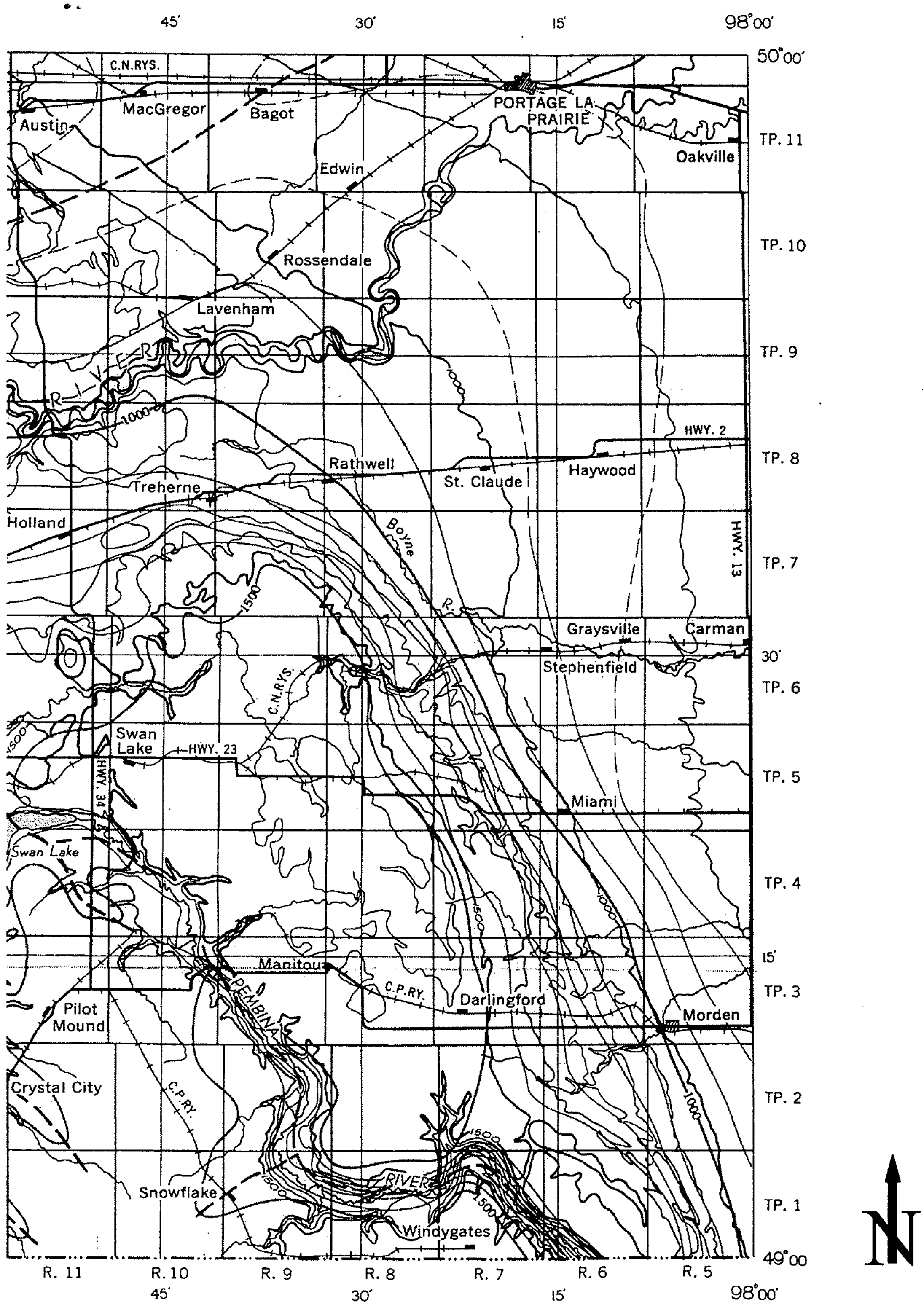


Figure 2-2. Preglacial topography (red lines) and modern topography (black lines) within the study area over Manitoba township grid (Halstead, 1959, Figure 2).

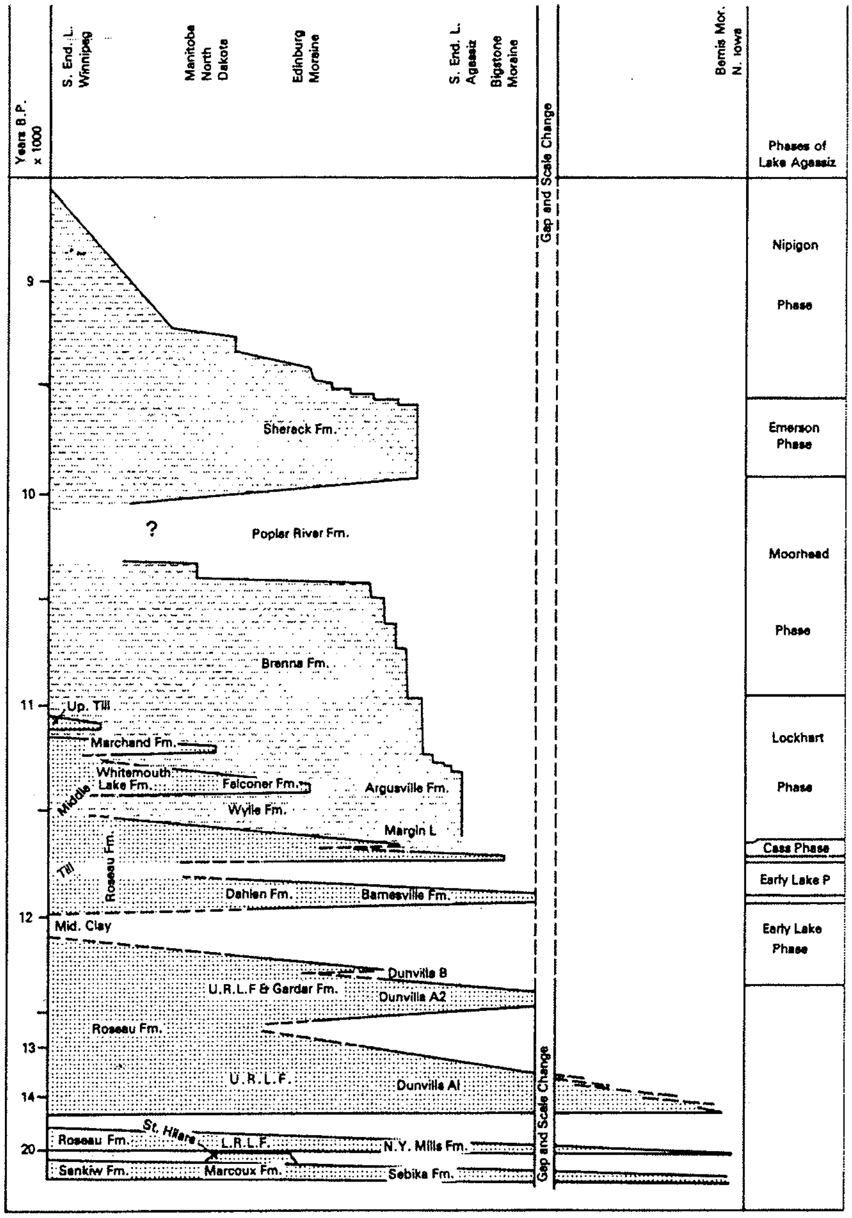


Figure 2-3. Time vs. distance relationships of glacial and offshore Lake Agassiz sediments in the southern Red River Valley, showing lake stages and ^{14}C ages (after Fenton et al., 1983).

2.2.2.3 Lake Agassiz offshore sediments

Offshore Lake Agassiz sediments overlie till of the last Wisconsinan glaciation. Figure 2-4 shows the general stratigraphy of Lake Agassiz sediments in the southern part of the Lake Agassiz basin (also see Fig. 2-3). The offshore units of Lake Agassiz are mainly defined by their mineralogy and texture, and secondarily by stratigraphic position and radiocarbon dates (Fenton et al., 1983). Most of the offshore sediments in the main basin of Lake Agassiz in southern Manitoba, North Dakota, and Minnesota are silty clay, with the sand fraction seldom exceeding 5%, except in the Assiniboine underflow fan (Teller, 1976b). The distribution of lacustrine sediments is time-transgressive toward the north, with older sediments in the south at the base of the sequence.

During the early stages of Lake Agassiz, silty clays of the Wiley and Argusville Formations were deposited in the southern Red River Valley, beginning about 11.6 ^{14}C ka (Fenton et al., 1983); these formations occur as far north as the international border (Clayton and Moran, 1982). These sediments overlie a very clayey, largely pebble-free till (Barnesville Formation), and are partially overlain by a siltier and sandier till (Falconer Formation) as far south as the Edinburg moraine in North Dakota, deposited by a readvance of the Red River Lobe ~ 11.4 ^{14}C ka (Fenton et al., 1983). As this readvance retreated northward, the clayey Brenna Formation was deposited in North Dakota and Minnesota beginning about 11.3 ^{14}C ka. As ice retreated farther, opening a lower outlet, the level of Lake Agassiz dropped. During the Moorhead low-water phase, Lake Agassiz regressed from North Dakota and Minnesota and the Poplar River fluvial formation was deposited there. By about 10.1 ^{14}C ka, Lake Agassiz had again inundated the Red River Valley in North Dakota and Minnesota, and deposited the mainly clayey Sherack Formation (Fenton et al., 1983).

Teller (1976b) has informally named three units of offshore Lake Agassiz sediments in Manitoba (Units 1, 2, and 3 from stratigraphically lowest to highest). Teller's (1976b) Unit 1 is correlated to the Brenna Formation in the USA; Unit 2 is correlated with either the upper part of the Brenna Formation or the lower part of the Sherack Formation; no unconformity or fluvial unit associated with the Moorhead low-water phase has been found in Manitoba (Teller, 1976b). Unit 3 is correlated with the upper part of the Sherack Formation in the USA. Figure 2-5 shows these units and their correlation to units in the USA.

Underflow fans formed at the mouths of large rivers entering Lake Agassiz from the west. Only the Assiniboine and Pembina fans occur in this study area; the extents of these fans are shown in Figure 2-5. These fans may have Gilbert-type deltas at their apices, but were generally deposited in deep water, and are not true deltas, but rather subaqueously-deposited sediments related to density underflows (Fenton et al., 1983). The fan sediments grade laterally from boulder conglomerates at their apices to offshore silts and clays in the deepest parts of the Agassiz basin.

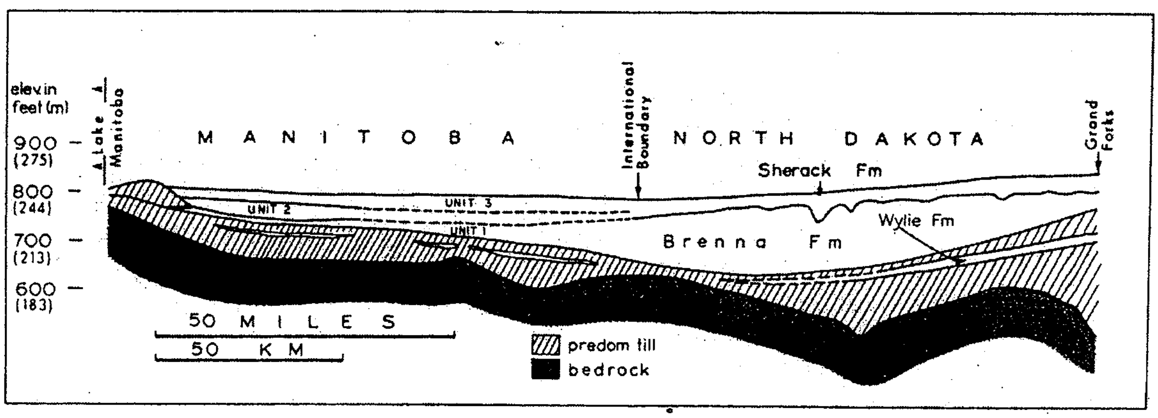


Figure 2-4. Simplified cross-section of offshore sediments in the southern part of the Lake Agassiz basin (Teller, 1976b, p. 38).

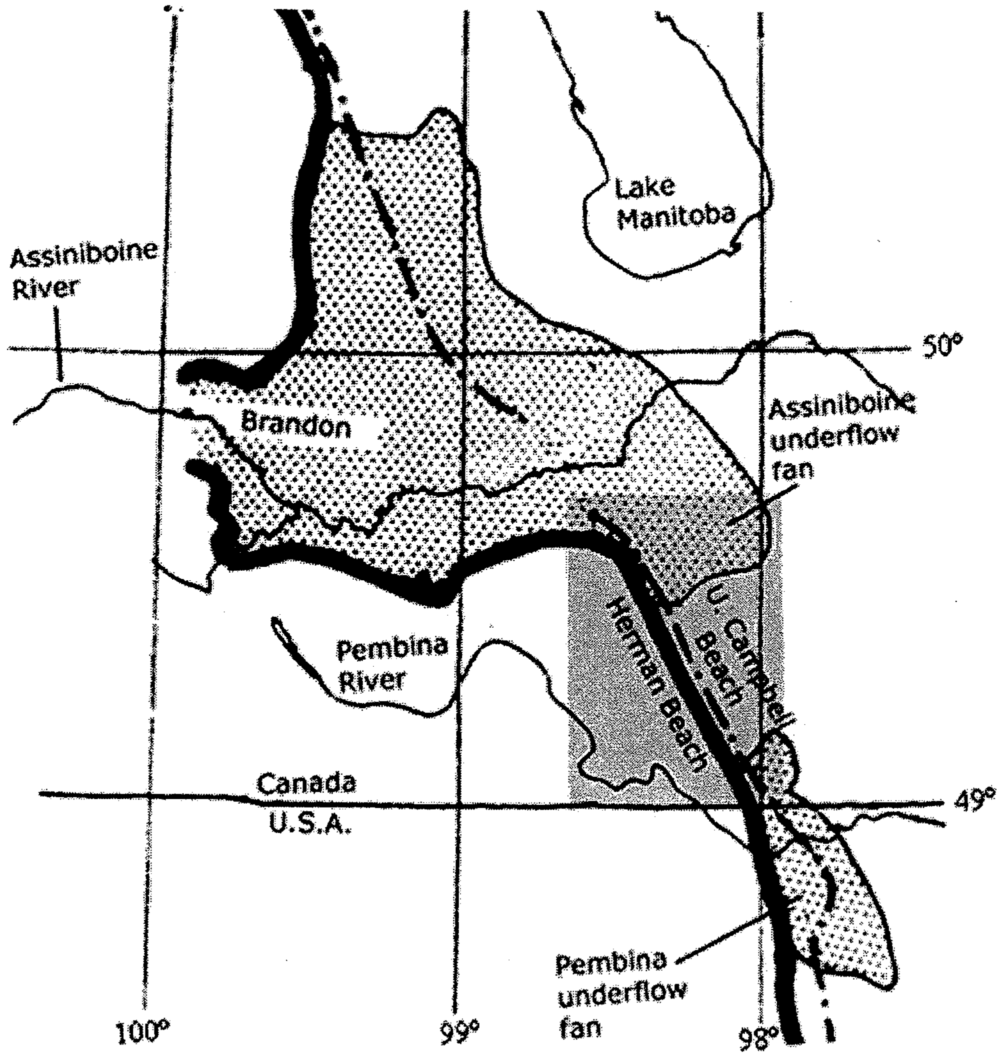


Figure 2-5. Map showing the extent of Lake Agassiz in southern Manitoba; present study area shown as grey rectangle (after Teller et al., 1983).

2.3 Glacial Lake Agassiz

2.3.1 Introduction

Lake Agassiz was probably a cold polymictic lake, with a mean annual temperature of 5 °C or lower (Mann et al., 1997). The lake itself did not support much life. Although nearshore fossils (e.g., Klassen, 1983) and organic lagoonal sediments (e.g., Teller, 1989; Mann, 1999) have been found, the vast majority of Lake Agassiz sediments are non-fossiliferous (Risberg et al., 1999). Lake Agassiz was probably ice-covered for part of the year (Hostetler et al, 2000; Mann et al., 1997) which limited the length of time for beach formation each year.

2.3.2 Lake levels and phases

2.3.2.1 Introduction

The history of Lake Agassiz is divided into phases, usually demarcated by changes in the routing of overflow. Lake stages refer to specific lake levels associated with specific beaches (e.g., Herman stage). There has been controversy about the timing and routing of overflow events and the development of beaches. All researchers agree that drainage was initially through the southern outlet during the Lockhart phase of Lake Agassiz from about 11.7 to 11.0 ^{14}C k.a, and that the final drainage of Agassiz was into the Tyrrell Sea about 7.7 ^{14}C ka, however the timing of outlet operation between these earliest and latest stages of Lake Agassiz remains controversial.

The uppermost (Herman) beaches in the study area and Upper Campbell beach are generally accepted as being 11.0-10.8 ^{14}C ka and 9.4-9.3 ^{14}C ka, respectively (Teller and Leverington, 2004). However, the ages of the Tintah and Norcross beaches remain disputed. Initially, these beaches were thought to have formed by 'stair-step' dropdowns from the Herman level as lower overflow routes to the Superior basin opened (Johnston, 1946; Fenton et al., 1983); Fisher (2003) supports this interpretation, arguing that these beaches formed some time between 10.9 and 10.8 ^{14}C ka (also see Boyd, in press). Thorleifson (1996), Teller and Leverington (2004), Teller (2001) and others concluded that the Norcross and Tintah beaches formed later, after the Moorhead low-water phase of Lake Agassiz, arguing that the lake rose to the Norcross level due to isostatic rebound sometime between 10.4 and 10.1 ^{14}C ka (followed by overflow through the northwestern outlet); they argue that a glacial readvance at 10.0 ^{14}C ka closed the northwestern outlet, and caused a rise to the Tintah level, before retreating and allowing overflow through the northwestern outlet to resume.

There is considerable uncertainty about the routing of overflow between 10.8 and 10.1 ^{14}C ka (Teller et al., 2005b). It had long been assumed that routing was through the eastern outlets (Teller and Thorleifson, 1983; Fenton et al., 1983), however new research indicates that drainage may have been through the northwestern outlets at this time, possibly interrupted by an ice advance at 10.0 ^{14}C ka (Teller et al., 2005a; 2005b; Thorleifson, 1996).

Figures 2-6, 2-7, and 2-8 graphically show the interpretations of Thorleifson (1996), Fisher (2003), and Teller (2004). These diagrams each show relative lake elevation versus time, as well as the timing of beach formation and outlet use.

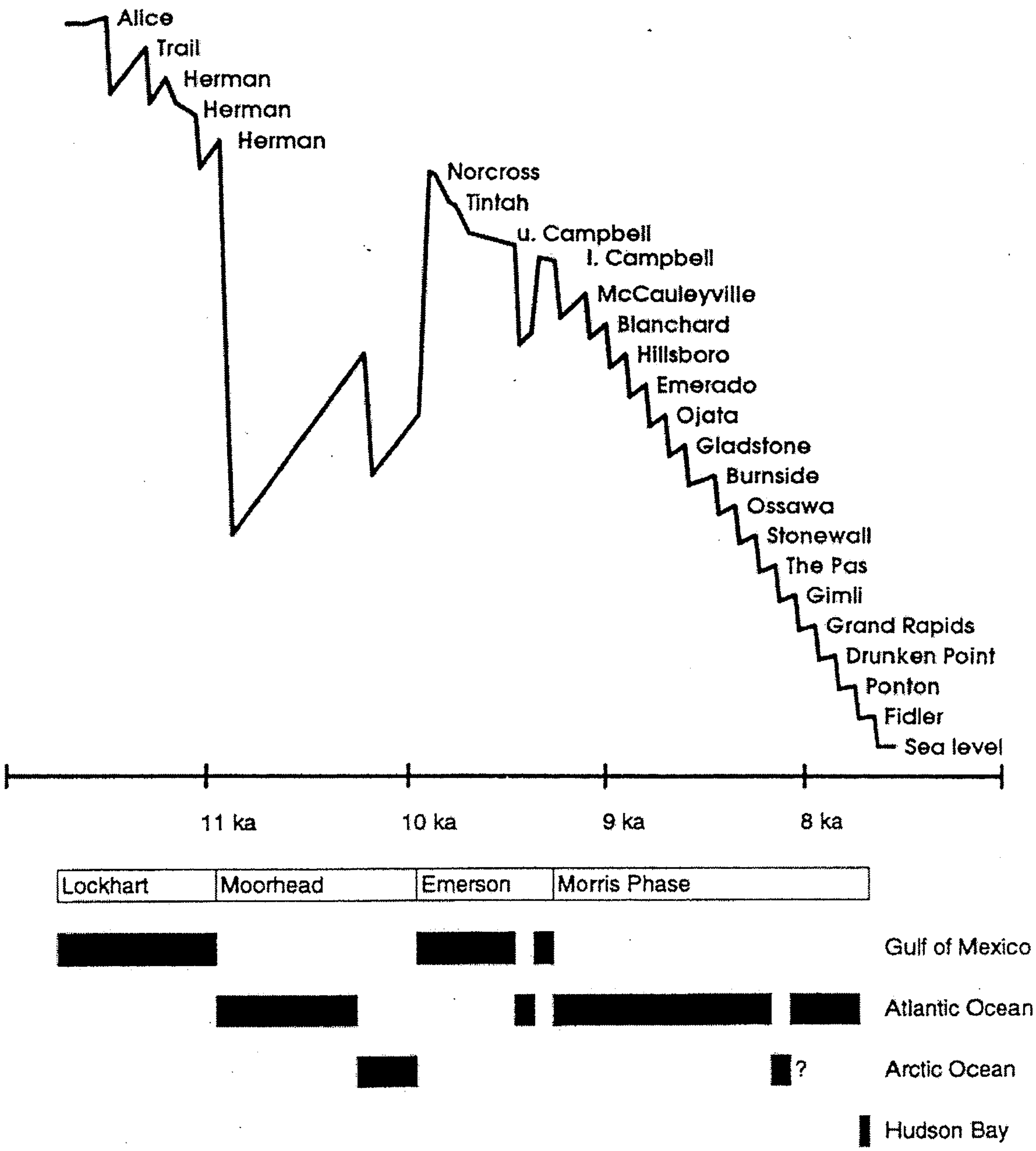


Figure 2-6. Thorleifson's (1996, p. 66) interpretation of the timing and routing of Lake Agassiz overflow, showing timing of beach formation. Note that 'Morris phase' refers to both the Nipigon and Ojibway phases, discussed below.

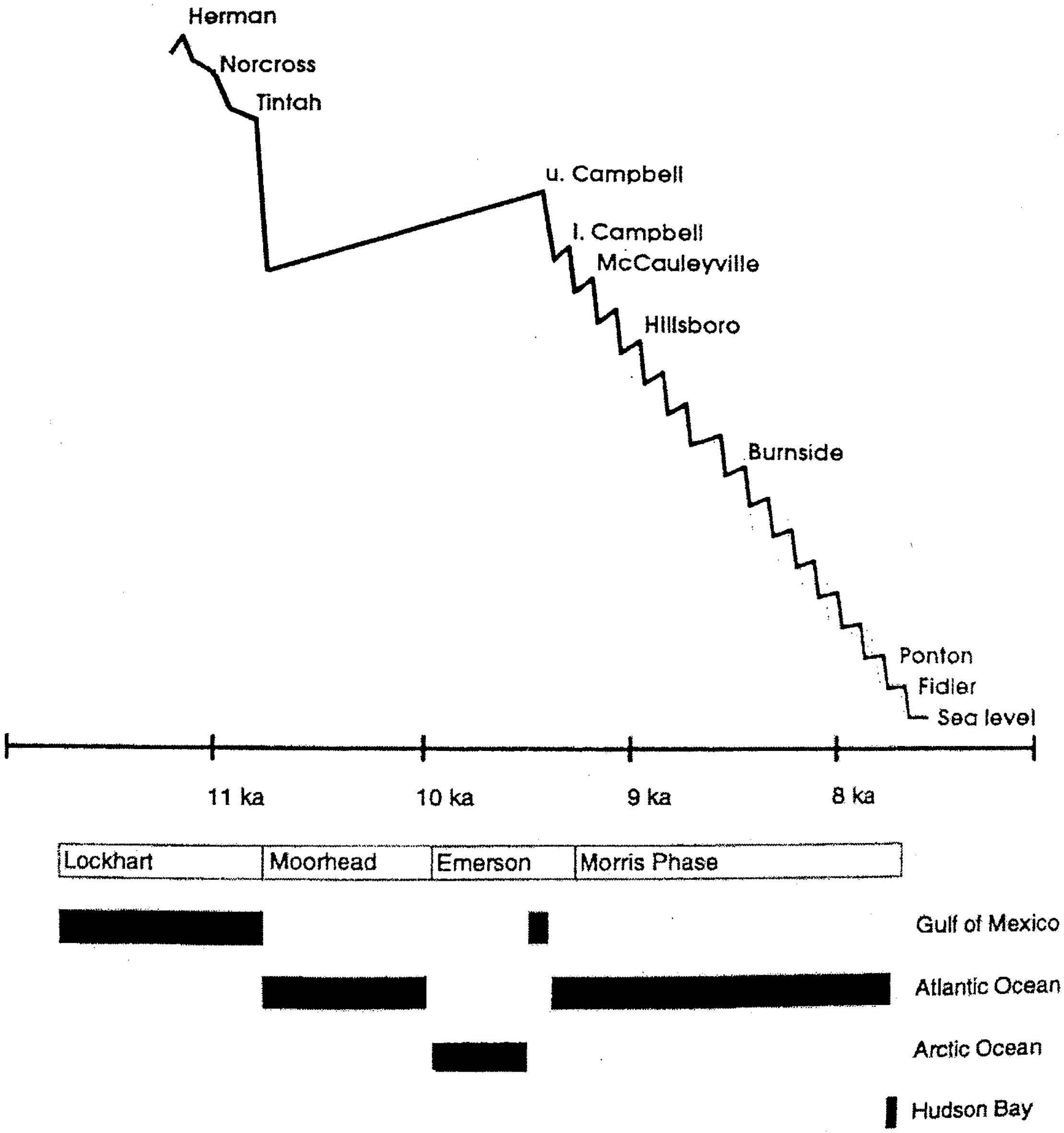


Figure 2-7. Fisher's (2003) interpretation of the timing and routing of Lake Agassiz overflow, showing timing of beach formation (compiled from information in Fisher, 2003, however not all information in this diagram is specifically discussed in that paper).

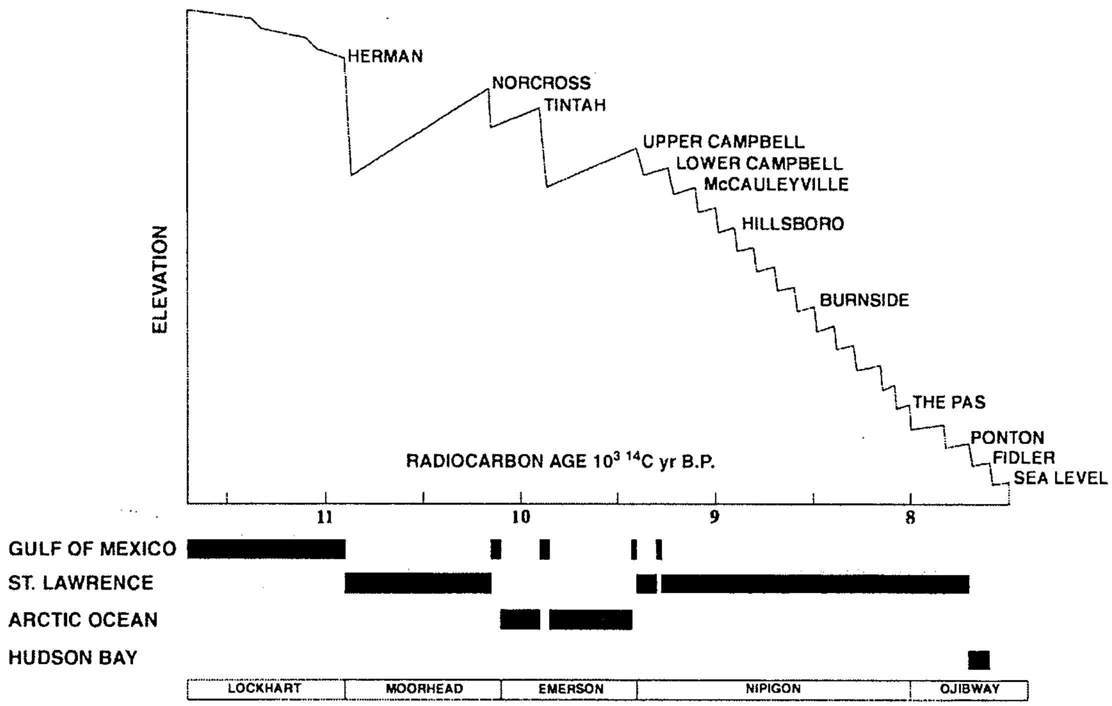


Figure 2-8. Teller's (2004, p. 56) interpretation of the timing and routing of Lake Agassiz overflow, showing timing of beach formation.

2.3.2.2 Cass phase

The oldest named phase of Lake Agassiz is the Cass phase, which began as Lake Agassiz developed in the southern Red River Valley of North Dakota and Minnesota (Clayton, 1983; Fenton et al., 1983). The Cass phase could not have started before about 12.0 ^{14}C ka because ice advanced into South Dakota and northern Iowa about 12.3 ^{14}C ka (Clayton, 1983). Two additional undated readvances occurred after this, responsible for about 1000 km of glacial advance and retreat, and almost certainly lasting a few hundred years (see Fig. 2-3).

2.3.2.3 Lockhart phase

The Lockhart phase began with the amalgamation of glacial Lake Koochiching (a small lake in Minnesota) with Lake Agassiz at about 11.7 ^{14}C ka (Fenton et al., 1983). The Lockhart was a high-water phase, during which the Herman beaches were deposited. Some workers (e.g., Johnston, 1949; Fenton et al., 1983; Fisher, 2003) have attributed the Norcross and Tintah beaches to the Lockhart phase, but others (e.g., Teller, 2001; Thorleifson, 1996) suggest they formed much later, during the Emerson phase (see discussion in Section 2.3.2.1). Drainage from Lake Agassiz was through the southern outlets during the Lockhart phase (Fenton et al., 1983).

The Argusville, Wylie, and Falconer were deposited during the early Lockhart phase (see Fig. 2-4; Fenton et al., 1983). During the late Lockhart phase, deposition of the Brenna Formation began in the USA, and deposition of Teller's (1976b) corelatable 'Unit 1' began in Manitoba. Additionally, three glacial readvances deposited tills of the Whitemouth Lake, Falconer, and Marchand Formations, as well as the Upland Till. The Pembina underflow fan was deposited between about 11.4 and some time after 11.2 ^{14}C ka; deposition of the Assiniboine underflow fan began just after deposition of the Pembina fan had ceased, some time after wastage from an ~ 11.2 ^{14}C ka glacial advance (but probably before 11.1 ^{14}C ka; Fenton et al., 1983; Clayton and Moran, 1982). Deposition of the Assiniboine underflow fan probably ceased just before 10.8 ^{14}C ka.

The Lockhart phase ended when the LIS retreated to the north of Thunder Bay, Ontario, opening drainage from Agassiz into the Lake Superior basin (Fenton et al., 1983) around 10.8 ^{14}C ka (Fenton et al., 1983; Fisher, 2003; also see Teller et al., 2005a).

2.3.2.4 Moorhead phase

The Moorhead phase is thought to have begun ~10.8 ^{14}C ka with the retreat of the Laurentide Ice Sheet past Thunder Bay, Ontario, and the beginning of Lake Agassiz overflow to Lake Superior and the Atlantic Ocean through the eastern outlets (Fenton et al., 1983; Bajc et al., 2000). However, some new research has questioned whether most overflow was through the eastern outlets or the northwestern outlet during the Moorhead (Teller, 2005a; 2005b). A glacial readvance at about 10.0 ^{14}C ka would have blocked drainage through the northwestern outlets if they were operational (Thorleifson, 1996; Teller, 2001).

The level of Lake Agassiz dropped by ~110 m at the beginning of the Moorhead (Leverington et al., 2000). The Moorhead was a low-water phase, but because of differential isostatic rebound, the lake continually deepened and transgressed southward, south of the rebound-isobase extending through the operating outlet, and regressed everywhere to the north (Teller, 2001).

The fluvial Poplar River Formation was deposited during the Moorhead phase along the large expanse of newly exposed Agassiz lakebed (Fenton et al., 1983). The unconformable Poplar River Formation has only been mapped in the USA; Teller's (1976b) shallow-water 'Unit 2' was deposited in Manitoba during the Moorhead phase.

The Moorhead phase ended about 9.9 ^{14}C ka with the Marquette readvance of ice into the Nipigon basin, which closed the eastern outlets and caused Lake Agassiz levels to rise (Teller and Thorleifson, 1983; see Figure 2-4). The youngest dates obtained by Bajc et al. (2000) for Moorhead sediments are about 9.9 ^{14}C ka.

2.3.2.5 Emerson phase

The Emerson phase of Lake Agassiz began with the Marquette readvance into the Superior basin about 9.9 ^{14}C ka BP, which cut off overflow to the eastern outlets and caused Lake Agassiz to rise (Teller and Thorleifson, 1983). Overflow was mainly through the northwestern outlet during this period (Teller, 2001). Teller (2001, p. 1652) notes that "Because Lake Agassiz transgressed over the Moorhead surface, the start of the Emerson phase is time transgressive, with submergence occurring last in the southern end of the basin. Thus it is somewhat arbitrary where the boundary between the low-water Moorhead phase and the high-water Emerson phase is drawn—at the start of the rise, at the peak, or in-between." For a few decades at the start of the Emerson phase, Lake Superior overflowed west of Thunder Bay into Lake Agassiz, as indicated by a series of red varves (typically about 24 couplets), before ice retreated and allowed Agassiz to overflow into the Superior basin (Teller and Thorleifson, 1983). The Sherack Formation in the USA and Teller's (1976b) Unit 3 in Manitoba continued to be deposited in the southern end of the basin during the Emerson phase (see Fig 2-4), until the lake receded from North Dakota and Minnesota (Fenton, et al., 1983).

Offshore sediments of the Sherack Formation were deposited over the Poplar River Formation in North Dakota and Minnesota (Fig. 2-3) and related shallow-water sediments in Ontario during the Emerson phase (Fenton et al., 1983); Teller's (1976b) 'Unit 3' was deposited in the main offshore basin in Manitoba (Fig. 2-4). There is some disagreement over which beaches were deposited during the Emerson phase. Teller (2001) and Thorleifson (1996) attribute the Norcross beach to the beginning of the Emerson when Lake Agassiz reached its maximum transgressive level after the eastern outlets were closed, causing overflow to return to the southern outlet at this time. Fisher (2003) however attributes the Norcross and Tintah beaches to the earlier Lockhart phase, explaining that they formed simply as water levels dropped from the Herman beaches shortly after 10.9 ka. Teller (2001) considers the Tintah beach to have formed by a second Emerson phase transgression that resulted from damming the newly-opened northwestern outlet. The Upper Campbell beach is well dated at about 9.4 ^{14}C ka; the Lower Campbell beach formed just after this, no later than 9.3 ^{14}C ka (Teller et al., 2000).

Drainage during the Emerson phase was mainly through the northwestern outlet (between ~ 9.9 – 9.4 ^{14}C ka; 1983; Teller, 2001; Fisher, 2003). Differential isostatic rebound during use of the northwestern outlet caused Lake Agassiz to transgress southward during the Emerson phase, briefly spilling over through the southern outlet and depositing the Upper Campbell beach (Teller, 2001). The Emerson phase ended when ice retreated from the Superior basin 9.4 – 9.3 ^{14}C ka, causing Lake Agassiz to drain rapidly through the eastern outlets (Teller et al., 2000).

2.3.2.6 Nipigon and Ojibway phases

The Nipigon phase began with ice retreat from the eastern outlets about 9.4 – 9.3 ^{14}C ka, opening outlets west of Lake Nipigon to overflow from Lake Agassiz (Teller et al., 2000).

Overflow from Agassiz was through the eastern outlets throughout the Nipigon phase. About 8.0 ^{14}C ka, Lake Agassiz stopped draining through the Great Lakes and drainage was routed northeast into glacial Lake Ojibway in northern Ontario and then out the Kinojévis outlet near Ottawa, marking the end of the Nipigon phase and the beginning of the final Ojibway phase of Lake Agassiz (Teller, 2004). Glacial Lake Agassiz-Ojibway drained into the Tyrrell Sea around 7.7 ^{14}C ka (Barber et al., 1999).

2.4 Late-Wisconsinan climate and Lake Agassiz

Severe storms were probably more common during late-glacial summers because of the greater latitudinal temperature differential resulting from the presence of the LIS (Broecker, 2001); summer temperature gradients were as high as 5.5 °C per 100 km adjacent to the LIS (cf. 1° C per 100 km today; Hostetler et al., 2000). Figures 2-9 and 2-10 show climate parameters from about 11,000 cal yrs BP based on computer modelling and pollen-based reconstructions.

Hostetler et al. (2000) analyzed the probable effects of Lake Agassiz on North American climate, and concluded that the presence of a large lake at the margin of the LIS (vs. no lake) should have caused differences in atmospheric circulation because of differences in atmosphere-lake heat transfer. The presence of Lake Agassiz probably led to stronger anticyclonic flow at the surface and more cyclonic flow in the midtroposphere during late-glacial summers, which would have blocked moist winds from the south and west. The overall effect of Lake Agassiz would be to reduce annual precipitation by as much as 30% from 'no-lake' values, and cause a negative correlation between lake size and precipitation in the region around the lake. These authors suggest that the reduction of precipitation caused greater wasting along the southern margin of the LIS during the time of Lake Agassiz. However, Krinner et al (2004), who modeled similarly large proglacial lakes in Siberia, found that the presence of these lakes caused regional summer cooling, due to their large heat capacity, along the southern margin of the Barents-Kara Ice Sheet about 90 ka. These authors note, as did Hostetler et al. (2000), a reduction in precipitation; however they found that the effects of decreased snowfall were outweighed by the reduction of summer temperatures, causing an overall growth of the ice sheet. Krinner et al. (2004) also suggest that this may have been the case along the southern margin of the LIS during the time of Lake Agassiz, since Hostetler et al. (2000) did not explicitly calculate ice melt.

Outbursts from Lake Agassiz have been correlated to changes in oceanic circulation and global climate. Broecker et al. (1989) speculated that the Younger Dryas cold event was caused by catastrophic overflow from Lake Agassiz, through the eastern outlets to the North Atlantic Ocean between about 11,000 and 10,000 ^{14}C years ago, disrupting the conveyer belt of North Atlantic Deep Water. Many computer models confirm the impact that large slugs of freshwater can have on ocean circulation in the North Atlantic Ocean (e.g., Teller, 2002). Although the eastward overflow of Lake Agassiz during the Younger Dryas has recently been called into question by Teller et al.

(2005a; 2005b), routing of meltwater through the northwestern outlet may still have resulted in a major change in thermohaline circulation with an associated climate-cooling.

Teller and Leverington (2004) have correlated outbursts from Agassiz to the North Atlantic Ocean with several other large-scale cooling events, including the Preboreal Oscillation and the 8.2 cal. ka cooling event, based on comparisons of proxy records from the GISP2 ice core from central Greenland.

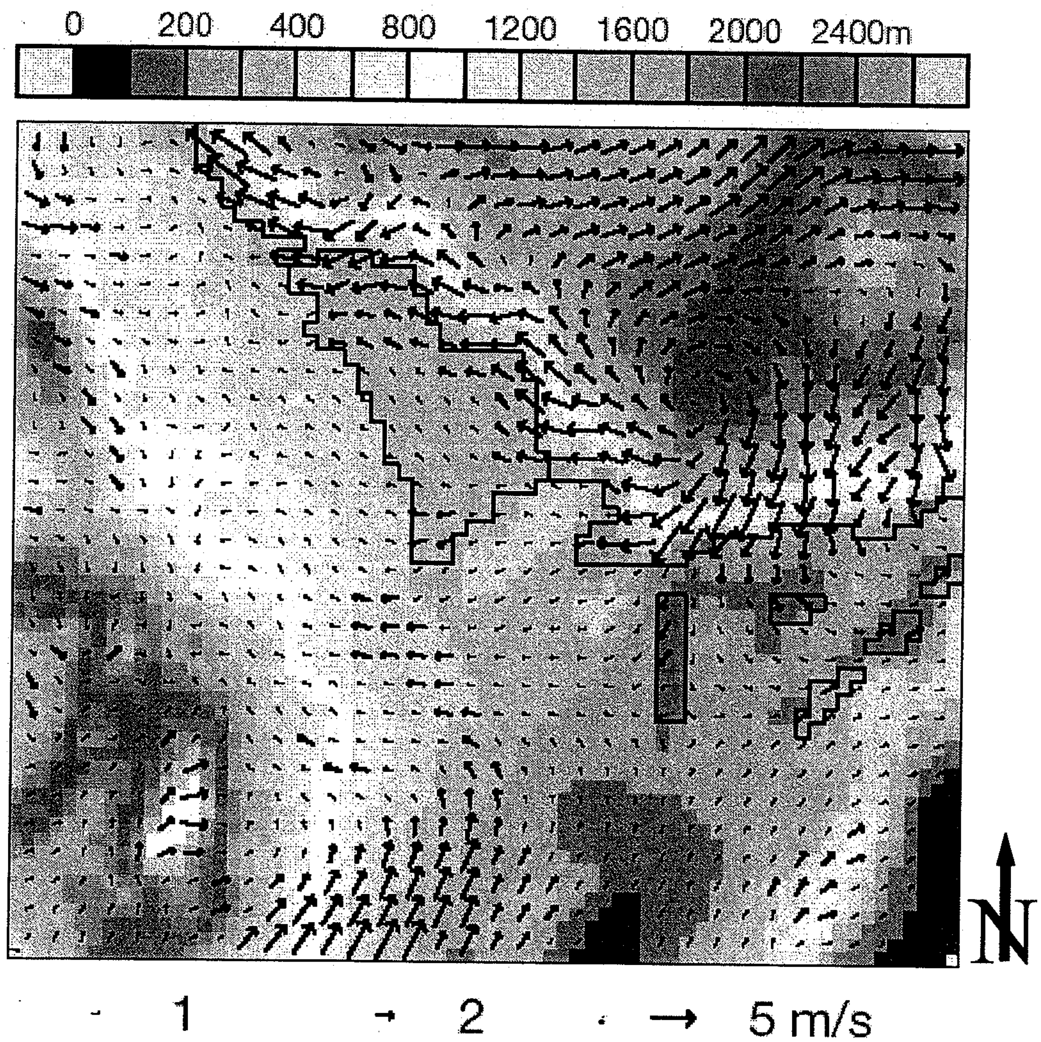


Figure 2-9. Simulated surface winds plotted over elevation of the Lake Agassiz basin. Modelled for July, 11,000 years ago (Hostetler et al., 2000, p. 336). Map area is between about 36 ° – 60 ° N latitude and 74 ° – 117 ° longitude.

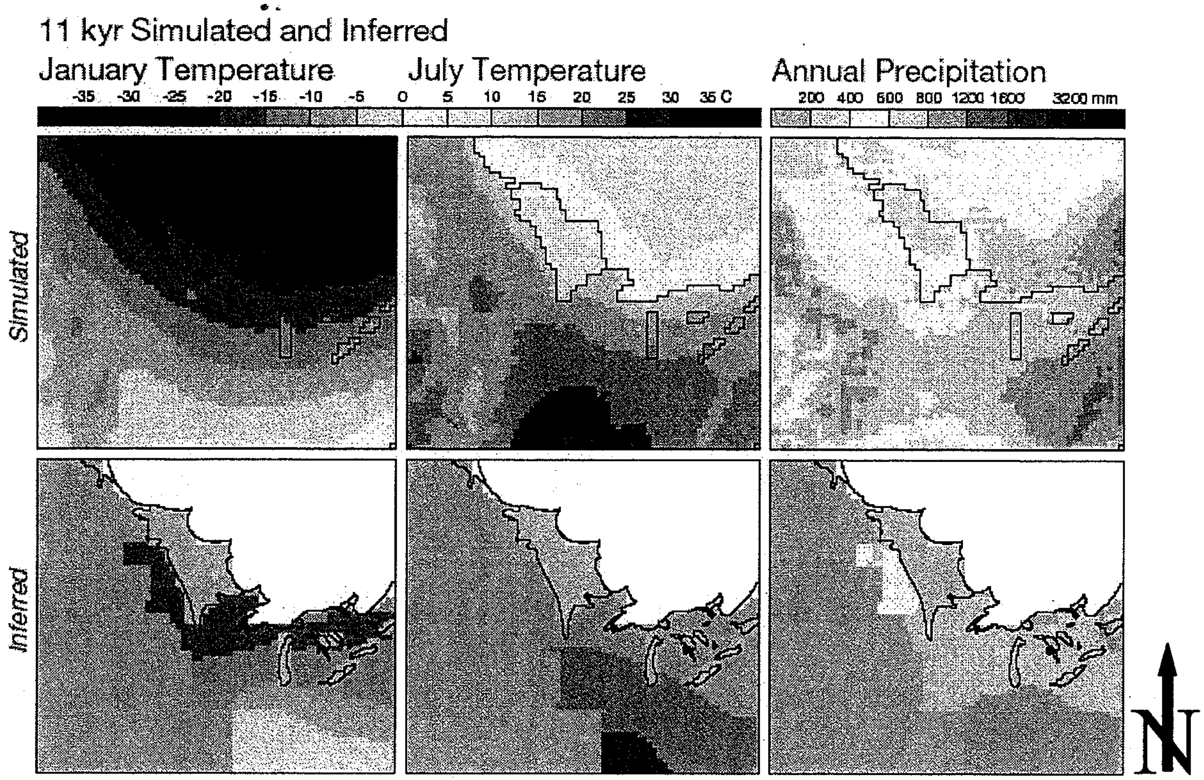


Figure 2-10. Simulated (from computer modelling) and inferred (from pollen data) July and January temperatures, temperature anomalies, and annual precipitation in the Lake Agassiz basin 11,000 cal yrs BP. Temperature anomalies refer to the difference between observed (present) and simulated or inferred data. (Hostetler et al., 2000, p. 336). Each square is between about 36 ° – 60 ° N latitude and 74 ° – 117 ° longitude.

CHAPTER 3:

MAPPING

3.1 Aerial photo mapping

3.1.1 Introduction

Aerial photo mapping was done for the area along the Manitoba Escarpment between about the Assiniboine River and the Canada – USA border. The Herman beaches continue along the southern side of the Assiniboine Delta to about Brandon, but that area was not included in this study.

Upham's 1895 maps of the Agassiz basin were the basis for the original framework of this map; i.e., these (1895) maps used to identify the general location of the older Lake Agassiz beaches in this region, specifically the different groups beaches mapped as Herman, Norcross, and Tintah.

3.1.2 Mapping

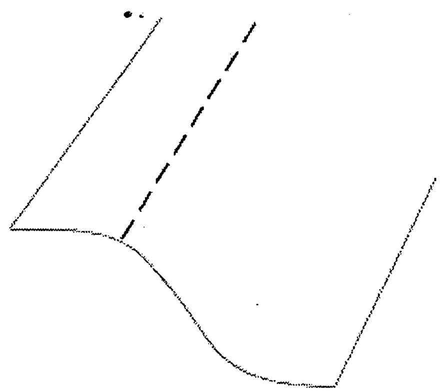
The majority of hard-copy mapping was done on Mylar, mainly from 1:12,000 scale aerial photos taken in 1978. Some 1:16,000 scale aerial photos from 1958/59 were also used. For a few areas where aerial photos were not obtained, but which contained mappable beaches, digital 1:60,000 scale orthophotos taken in 1998 were used to map shoreline features in ArcView® (see Table 3-1); maps prepared from standard aerial photos were, in places, supplemented by these digital images. Few cultural features were included on these maps, except for section roads, which provide a mile-wide reference framework for the mapped area.

Township/Range	Hard-copy aerial photos	Digital orthophotos
1/5W	*	*
2/5W	*	*
2/6W	*	*
3/5W		*
3/6W	*	*
4/6W	*	*
4/7W		*
5/6W	*	
5/7W	*	*
6/7W	*	*
6/8W	*	*
7/8W	*	*
7/9W		*
8/9W	*	
8/10W	*	*

Table 3-1. Methods used for mapping different townships. Aerial photos were obtained from Manitoba Conservation Branch; digital orthophotos were obtained from Linnet Orthophoto Library (University of Manitoba).

Beach ridges were identified mostly by tonal differences with the surrounding land, with the ridges being lighter in tone (because of increased drainage on the sandy beach ridges and changes in vegetation composition and thickness). Most beaches were not discernable in 3D using overlapping stereopairs, nor were they of enough relief to be expressed on topographic maps. Scarps were commonly identified by 3D viewing of overlapping stereopairs, topographic maps, and by agricultural differences because farmer's fields often stop abruptly at the top and bottom of scarps, with forest along the steeply dipping scarp face.

Beaches were mainly mapped as solid lines down the longitudinal axis of each ridge; scarps were mapped as solid lines indicating the scarp crests, as indicated in Figure 3-1. Green lines denote clear (obvious) beach ridges. Blue lines are used for faint beach ridges. Yellow lines denote beaches that were highly questionable / very faintly visible on photos; most beaches on aerial photographs can be seen as relatively short tonal differences with no visible relief that extend parallel to more distinct beaches. Scarps are indicated by a red line. Most beaches are narrow and poorly defined, and close to adjacent beaches, so are only shown as single lines. Only a few beaches are large or distinct enough to allow mapping of the entire ridge (as an area), rather than just expressing it a crest (or midpoint line) of the beach; the boundaries of these ridges were distinct from other beaches; the same colour convention as the mapped lines was used (green for clear, blue for faint, and yellow for questionable).



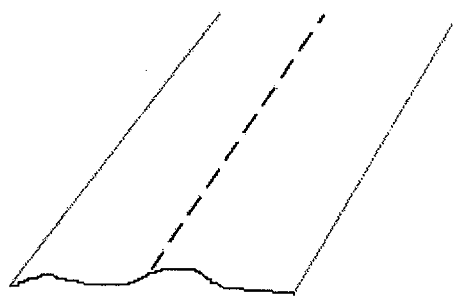


Figure 3-1. Schematic of mapped lines (shown as dashed lines) in relation to 3D cross sections of a beach ridge and a scarp. Lines representing scarps show the scarp crest, lines representing beaches show the axis of the tonally lighter beach, which may or may not represent the crest.

3.1.3 Spatial distortion and errors

3.1.3.1 Spatial distortion of non-orthographic photographs

The regular black and white airphotos used in this study have several inherent distortions; as such, spatial data cannot be given proper coordinates beyond a certain scale. These errors include distortion from the fact that points toward the edges of photographs are farther away from the lens of the camera than the principle point of the photo when the photo was shot. Topographic variations add additional spatial distortion to the image (Lillesand and Kiefer, 1994); however, in the context of the present project, this will only affect the mapping of wave-cut scarps, as the beaches are of such low relief as to have no effect on the spatial continuity. Other factors that cause spatial distortion include 'crookedness' of the camera (i.e., pictures that are taken at angles other than truly vertical), and differences in flight path from the supposed direction. Finally, variations in flying height along the same line or series of lines will cause spatial distortion on the final map. Different photographs will have different errors associated with them, as such, no single value will describe the error of the entire map.

All of these potential distortions can only be corrected by creating an orthophoto map. Orthophotos are usually made digitally (Lillesand and Kiefer, 1994). Parallax measurements can be made to correct individual points relative to other individual points. Of course, to make a map that is fully compliable to universal coordinate systems it must be created with orthophotos, which requires special equipment and expertise. The maps created for this thesis were not corrected to orthophotos, and are considered accurate within the specified scale range of 1:20,000. This scale was chosen because mapping was done at different scales ranging from 1:12,000 to 1:60,000 (the majority being done at 1:12,000, and the 1:60,000 component being relatively small overall), and 1:20,000 is thought to be well outside the range of spatial errors, but detailed enough to show all mapped features clearly.

3.1.3.2. Digitizing error

As mentioned in the above section, ArcView® conforms data to a calibrated grid defined by the user, based on geographically known points they select on the hard-copy map. Although this may help correct some errors, particularly those resulting from imperfectly matched points from two photographs or photographs taken at an improper angle, it may also introduce some error by distorting features relative to one another. Since the user defines the grid by selecting UTM coordinates and defining them in the digital map by clicking on the appropriate points on the hard-copy map, there is also an error associated with both the UTM coordinates and the point the user chooses to click on (that should correspond to those UTM coordinates). The UTM coordinates used were taken from digital orthophotos of road intersections (the middle of the road intersection was sought as the point to define the intersection); there is, however some range of values in both Easting and Northing directions that could be defined as the middle of the intersection.

Because hard-copy maps were digitized into the map at the correct proportions, there is no scale difference between different parts of the final (digital) map (which was created from hard-copy maps of different scales); the scale of the final map is determined by the user (as a specifically defined scale or through use of the zoom tool). As noted above, the maps are only considered accurate at scales at or above 1:20,000.

3.2 Digital mapping and GIS map integration

3.2.1 Digitizing of hard-copy maps

Hard-copy maps were digitized into ArcView using a SummaSketch III® digitizing tablet (see Appendix 1 for complete digitizing procedures). Maps were laid over the tablet, then calibrated by clicking on several (at least 4) points on the hard-copy map, and assigning these clicked points their known geographical (UTM) coordinates. After a hard-copy map is calibrated, the geological features are traced with the digitizing puck (basically a computer mouse) and are automatically entered into the digital map in their proper positions. Road intersections were used as the points for calibration; the UTM coordinates of these intersections were found from digital orthophotos. For consistency, the middle of a given intersection was given a point and recorded to the nearest millimetre.

Each beach type is a separate 'theme' in the final map; scarps are a single 'theme'. Themes (in ArcView) are individual files that can be incorporated in a GIS view. 'Themes' can be viewed alone, or with one or more additional themes (e.g., the theme '*Scarps*' could be viewed over a base map of Manitoba theme, and/or could be viewed with one or more of the beach themes. A single theme may consist of points, or lines, or polygons (areas), but no combination of the three. Once created, themes can be edited and saved by a user, who can incorporate them in as many GIS views as they like; since geographic coordinates are encoded, a theme may be transferred to different computers, or closed and recalled later. In this thesis, the previously mentioned 'themes' were created and can be used with the CD included.

3.2.2 GIS map integration

GIS map integration was done by integrating the shoreline themes with other data, including stratigraphic data from power augering, published stratigraphic data from water well records and aggregate reports, GPR-line coordinates, orthophotos, and public GIS data such as topographic maps, soils maps, and cultural maps.

Power auger stratigraphies were added to the map by creating a 'point theme' with the positions of the auger holes, which the user can link to the text files of stratigraphy (see Appendix 2).

Water well data were added in a similar way as auger data: a point theme representing the positions of wells was created that could be linked to digital well stratigraphy text files. Usually the positions of wells were only described as being in a certain quarter of a certain section, so the potential range of the actual position is ± ¼ mile in the N-S and E-W directions (if placed in the middle of the quarter). Points were placed the centre of the quarter if no reason could be found to do otherwise, but often only one farm existed in a given quarter, so the point was placed within the farm yard, as a well is more likely to be in a farm yard than in the middle of a field. If two farms existed, the well was placed between them. Often some kind of descriptive information (e.g., distances from roads or driveways) was included so the position of the well could be constrained fairly well. For wells placed (by me) in the middle of a farmyard, the position of the well in the GIS map is theoretically up to 0.71 miles away from the site of the actual well (if the actual well and the digital point representing that well were in opposite corners of the quarter).

Aggregate report data were copied from the actual reports, typed into a text file and added to the GIS map the same way as other stratigraphic information. GPR lines were added to the GIS map as point themes defining the endpoints of the lines, which were then used to draw actual lines between them defining the geometry of the GPR lines.

CHAPTER 4:

MAPS

4.1 Introduction

The purpose of this chapter is to include the complete full-colour maps made for this project in an easily navigable and usable way, although at a smaller scale than they could be visualized digitally. Maps are arranged by township then range (i.e., low numbers in south to high numbers in north and then from east to west). The beaches mapped are discussed in Chapter 7. No supplementary information, such as auger hole sites or GPR sites, are included in the maps presented here; full maps with all supplementary information can be found in Appendix 1. Figure 4-1 shows the entire mapped area for reference to the more detailed maps that follow in Figures 4-4 to 4-15; note that beach zones are indicated on these maps by dashed lines, showing areas where beaches of different stages (e.g., Herman) occur. Maps are drawn over the section-grid of Manitoba—each six mile by six mile township is divided into 36 one by one mile sections, as shown in Figure 4-2. These grids are drawn as dots at intersections to minimize the interference of mapped features with grid lines. The legend for all maps is the same, and is shown in Figure 4-3.

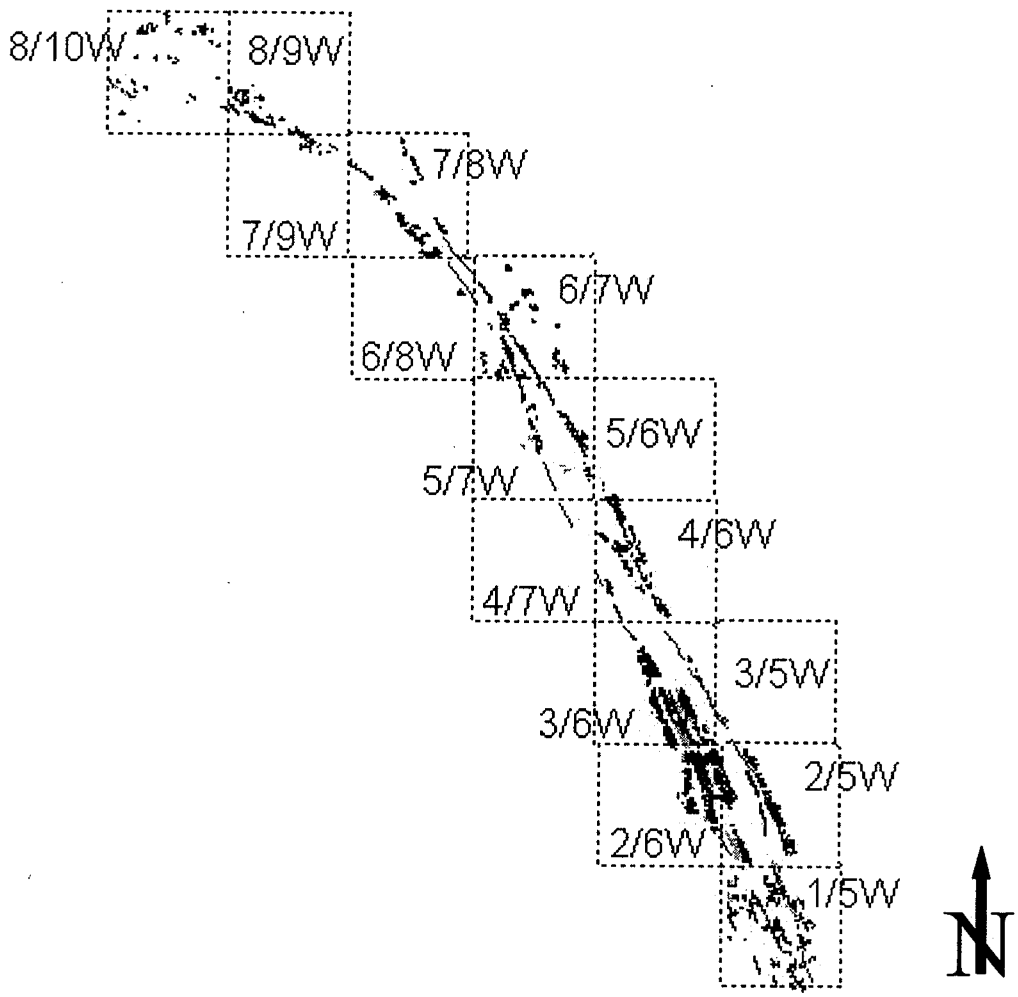


Figure 4-1. Entire mapped area, showing Lake Agassiz beaches (blue, green, yellow), and scarps (red) associated with the Herman, Norcross, Tintah, and Campbell beaches; see Figure 4-3 for legend. Scale is ~ 1 : 508,000; each square is one township, and is 6 miles x 6 miles (9.4 km x 9.4 km).

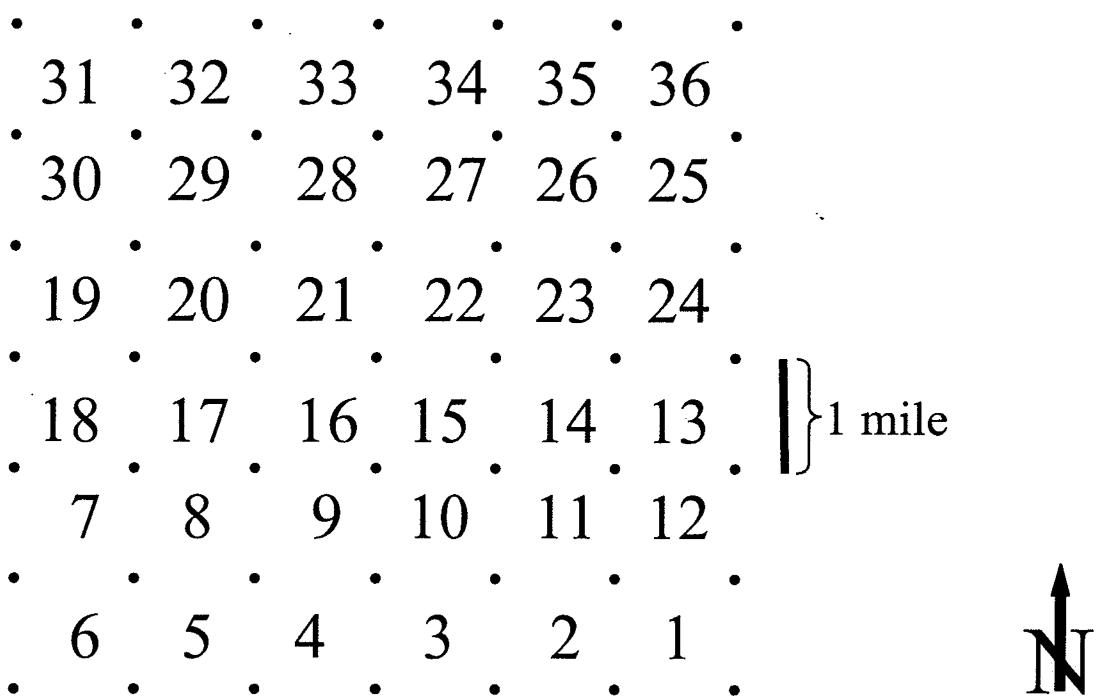


Figure 4-2. Grid system for dividing a single township into sections, in Canada. Sections are defined as the 1 mile by 1 mile square within the dots, numbered as shown.

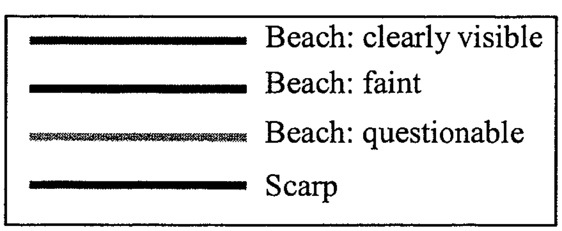


Figure 4-3. Legend for maps of shoreline features (lines not to scale with maps). Lines represent longitudinal centres of mapped beaches and scarp crests; for beaches that were large enough and distinct enough from other beaches, the width of the beach was outlined.

4.2 Maps, by township

4.2.1 Township 1, Range 5W

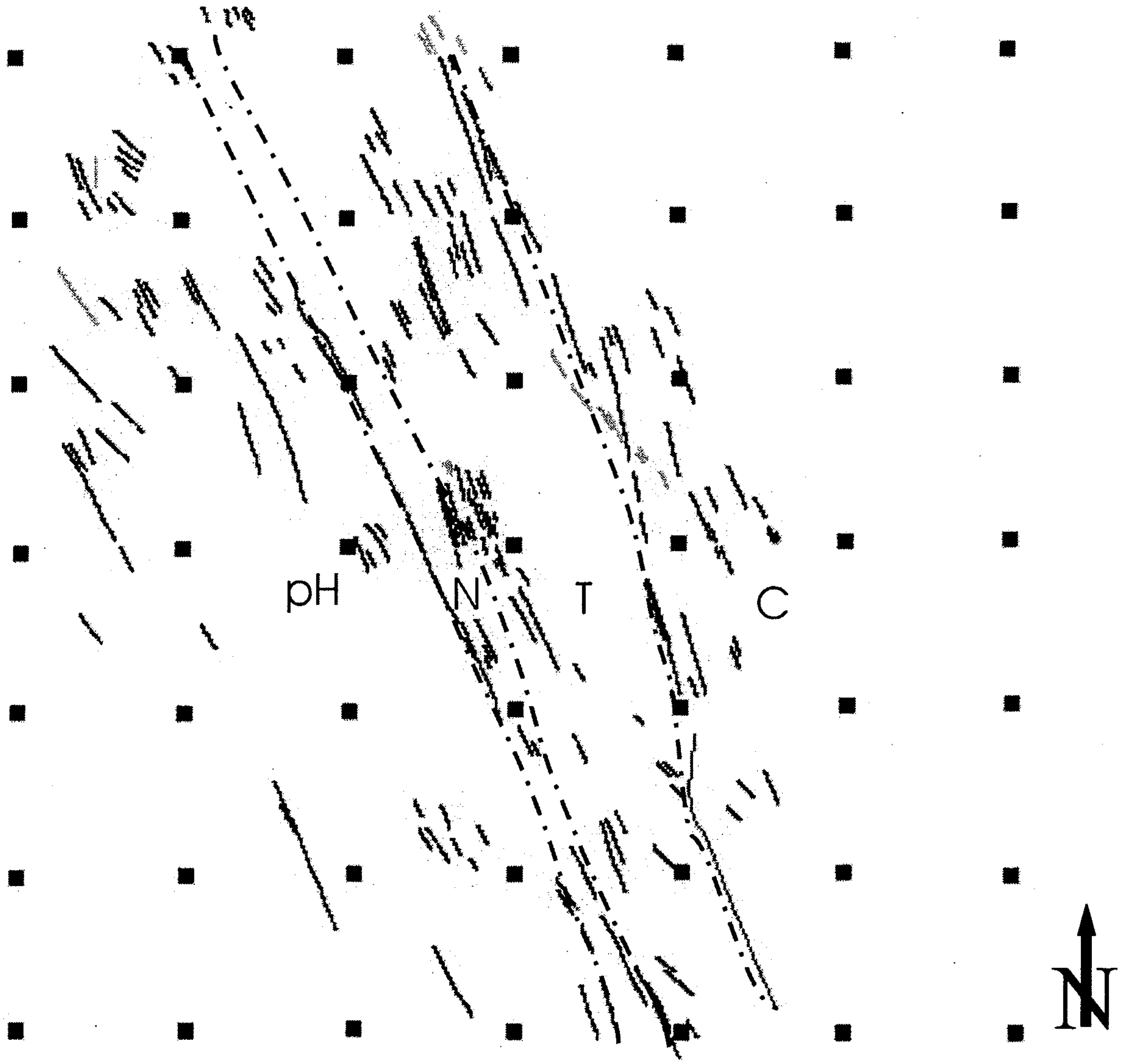


Figure 4-4. Shoreline features in Township 1, Range 5W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: pH – pre-Herman, N – Norcross, T – Tintah, C – Campbell.

4.2.2 Township 2, Range 5W

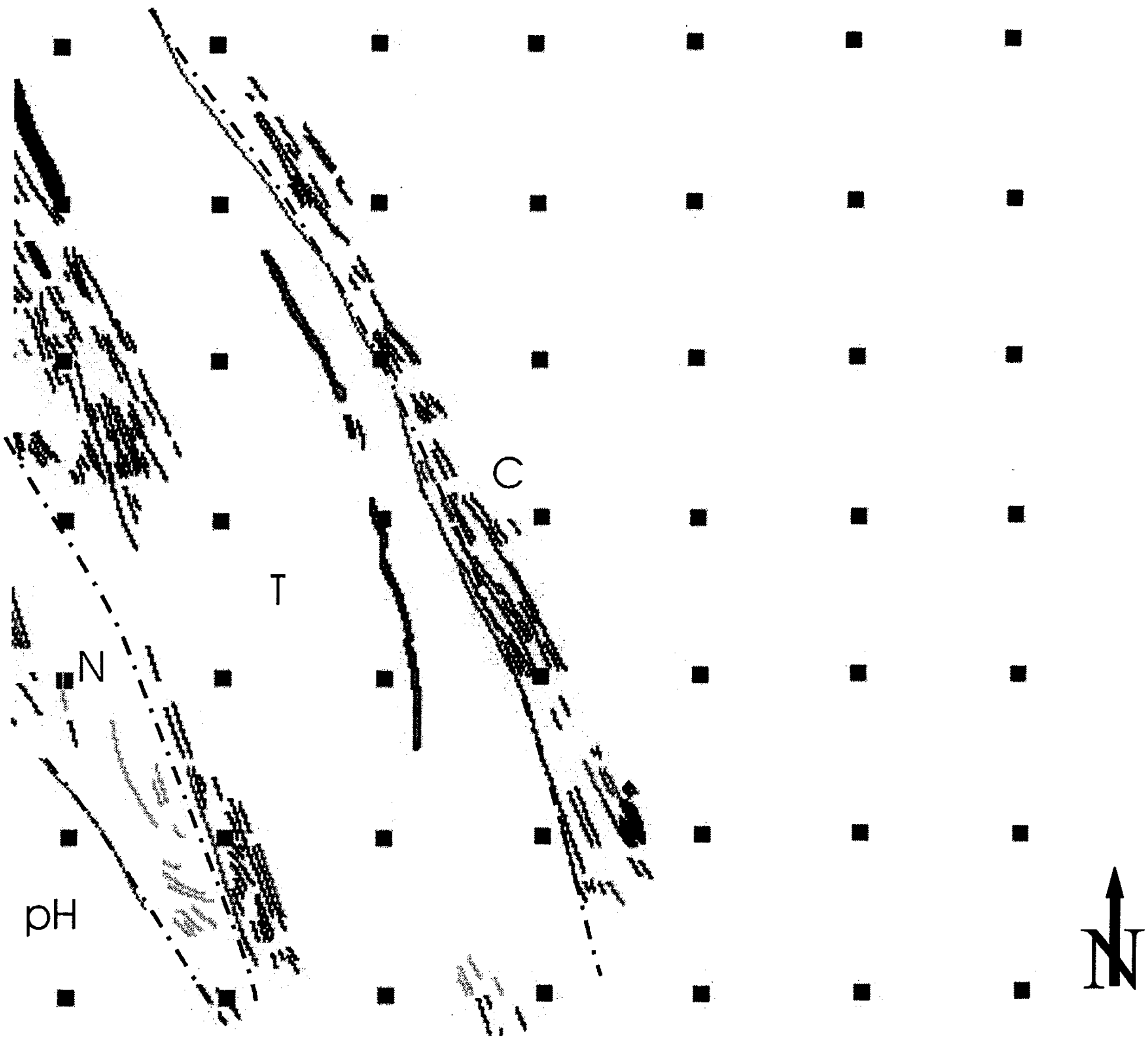


Figure 4-5. Shoreline features in Township 2, Range 5W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: pH – pre-Herman, N – Norcross, T – Tintah, C – Campbell.

4.2.3 Township 2, Range 6W

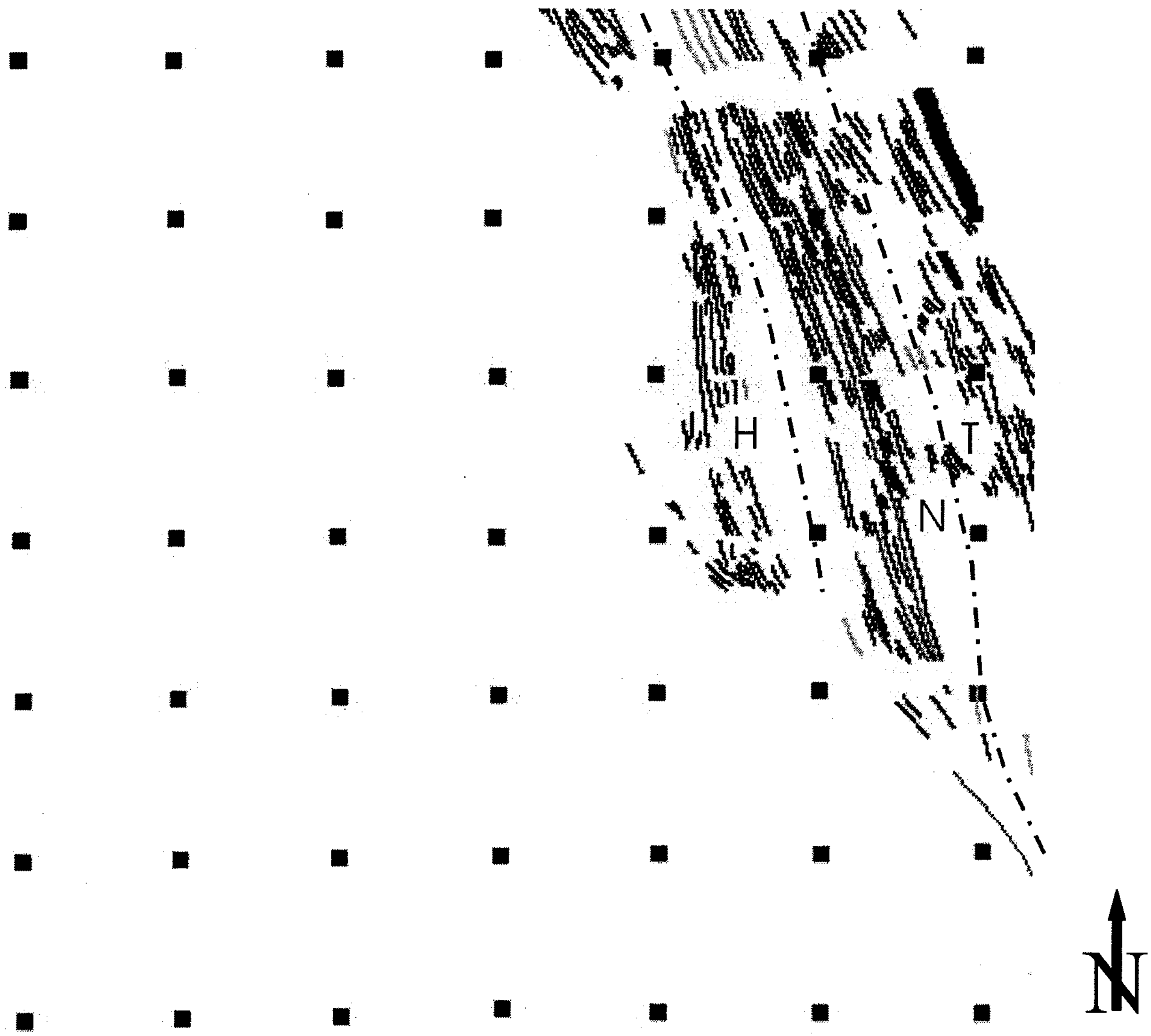


Figure 4-6. Shoreline features in Township 2, Range 6W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: H – Herman, N – Norcross, T – Tintah.

4.2.4 Township 3, Range 6W and part of Township 3, Range 5W

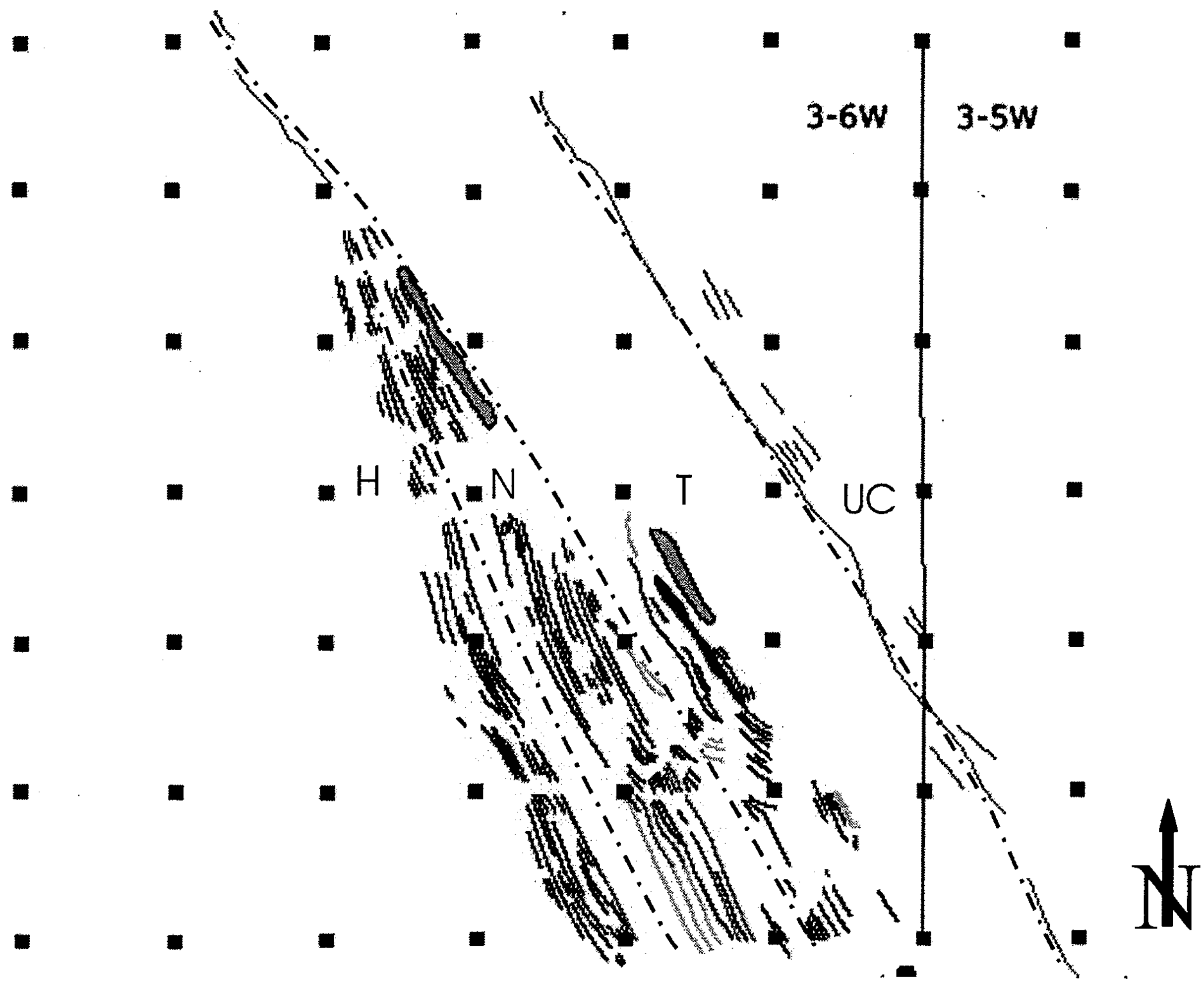


Figure 4-7. Shoreline features in Township 3, Range 6W and part of Township 3, Range 5W. Solid black line indicates boundary between these townships. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: H – Herman, N – Norcross, T – Tintah, UC – Upper Campbell.

4.2.5 Township 4, Range 6W and part of Township 4, Range 7W

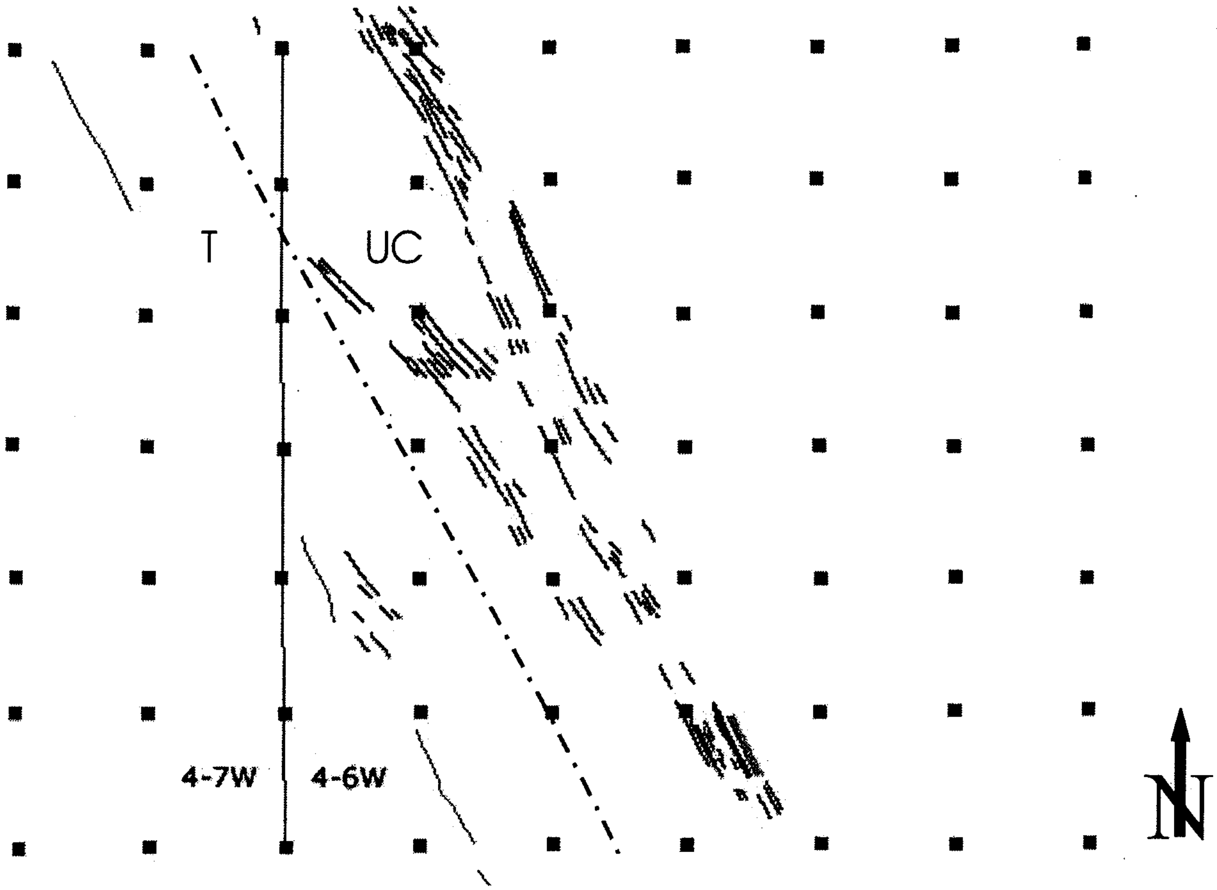


Figure 4-8. Shoreline features in Township 4, Range 6W and part of Township 4, Range 7W. Solid black line indicates boundary between these townships. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: T – Tintah, UC – Upper Campbell.

4.2.6 Township 5, Range 7W and part of Township 5, Range 6W

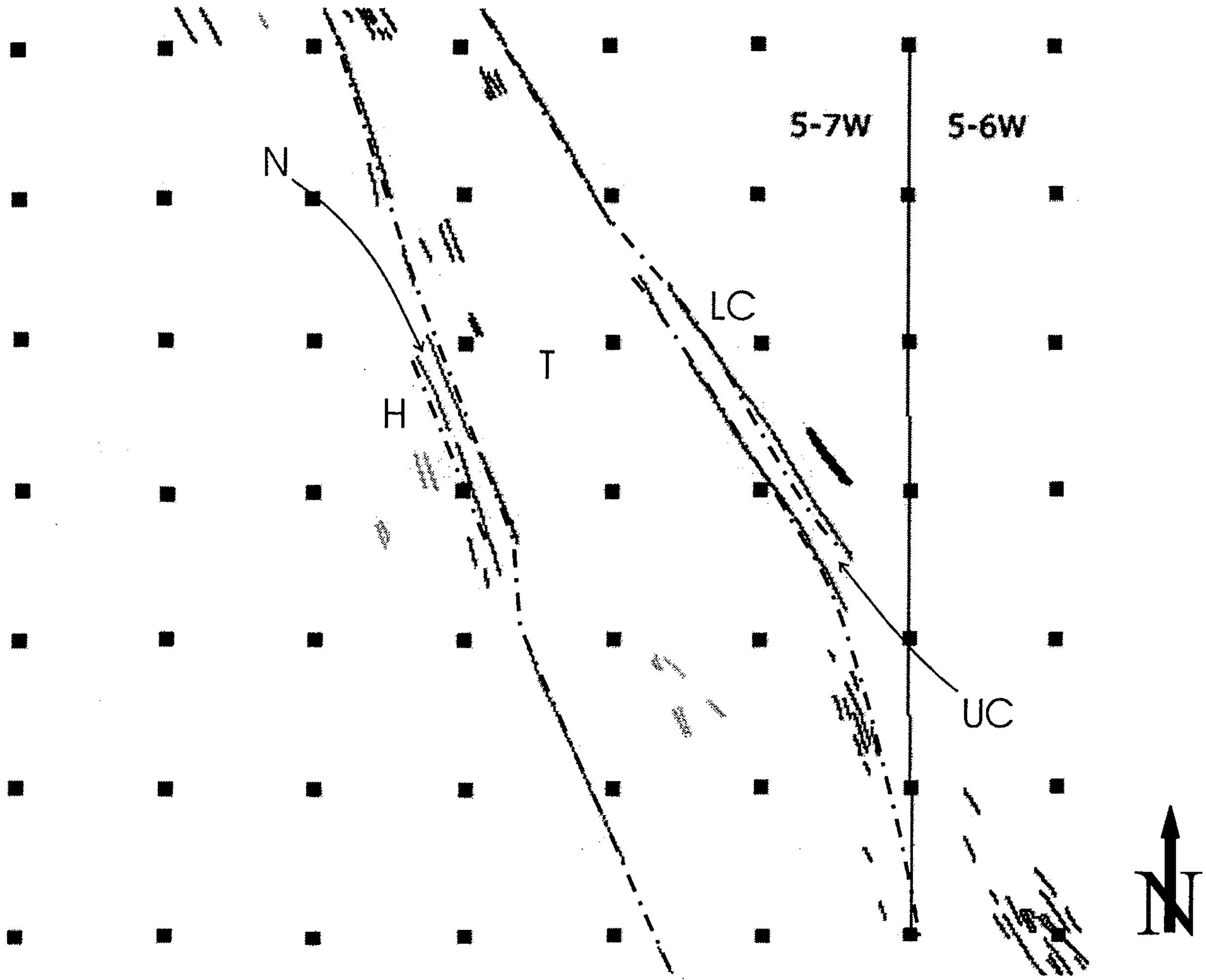


Figure 4-9. Shoreline features in Township 5, Range 7W and part of Township 5, Range 6W. Black line indicates boundary between these townships. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: H – Herman, N – Norcross, T – Tintah, UC – Upper Campbell, LC – Lower Campbell.

4.2.7 Township 6, Range 7W

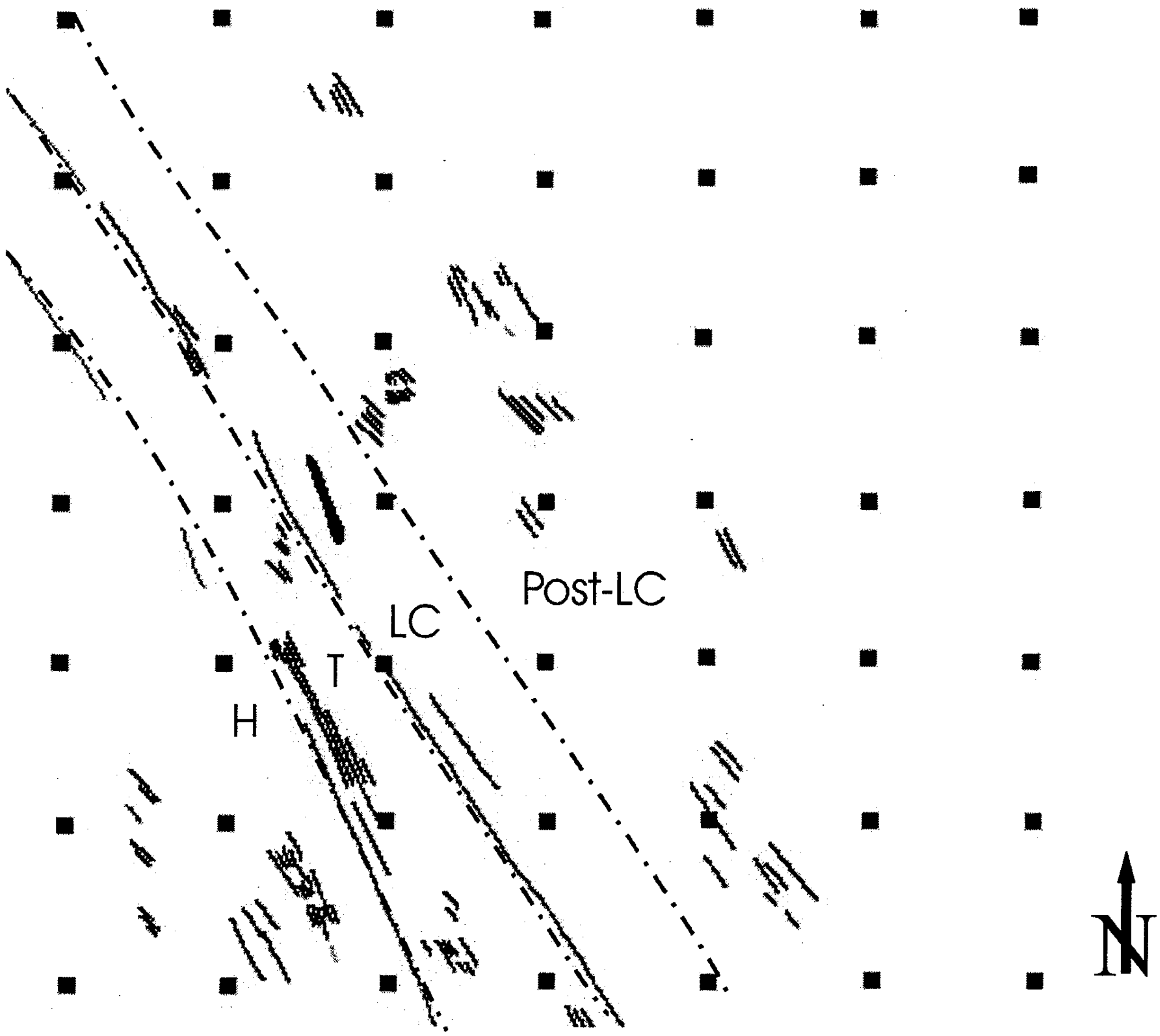


Figure 4-10. Shoreline features in Township 6, Range 7W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: H – Herman, T – Tintah, LC – Lower Campbell. Some post-Lower Campbell beaches were incidentally mapped, but are not part of the objectives of this project.

4.2.8 Township 6, Range 8W

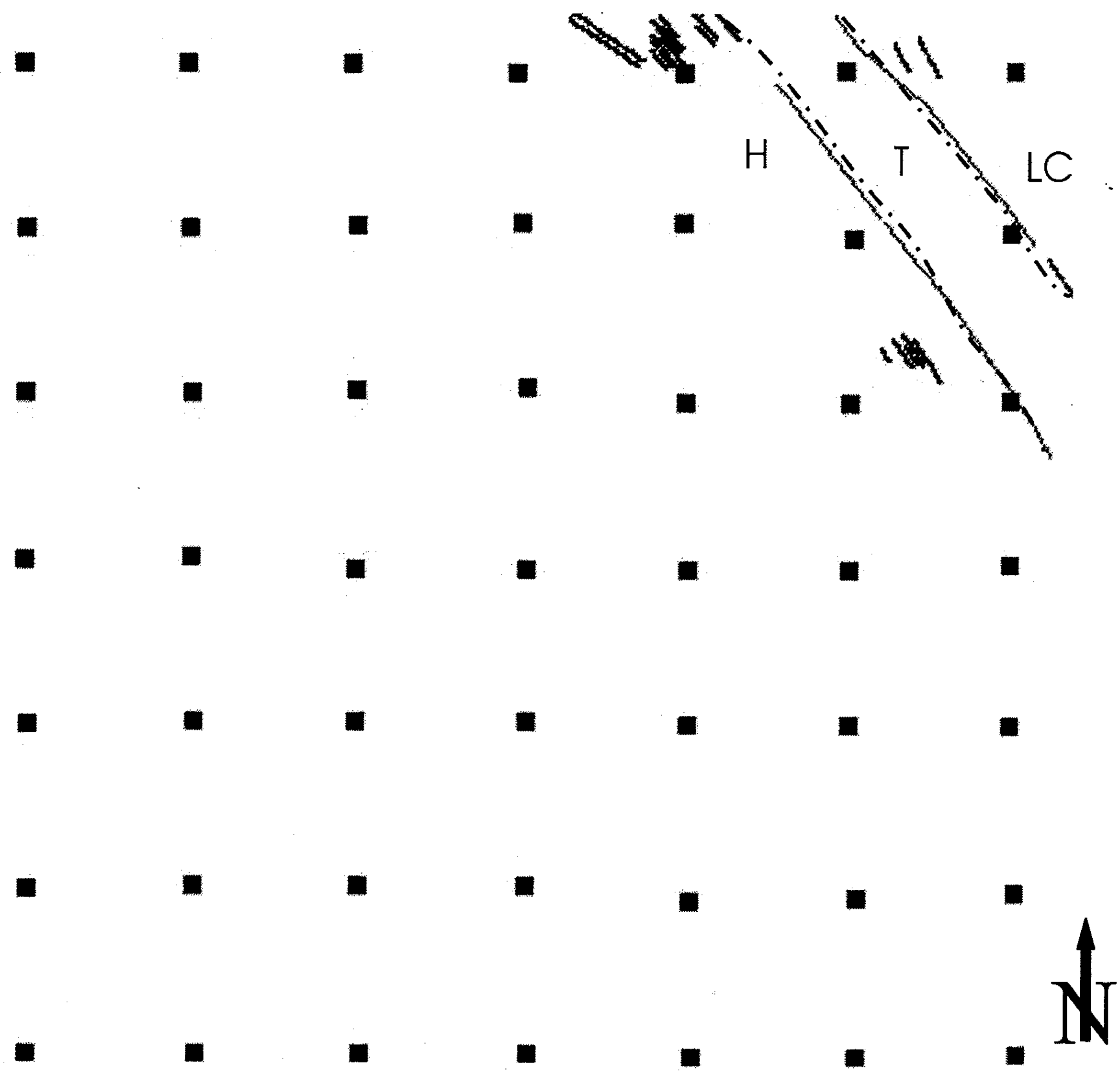


Figure 4-11. Shoreline features in Township 6, Range 8W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: H – Herman, T – Tintah, LC – Lower Campbell.

4.2.9 Township 7, Range 8W

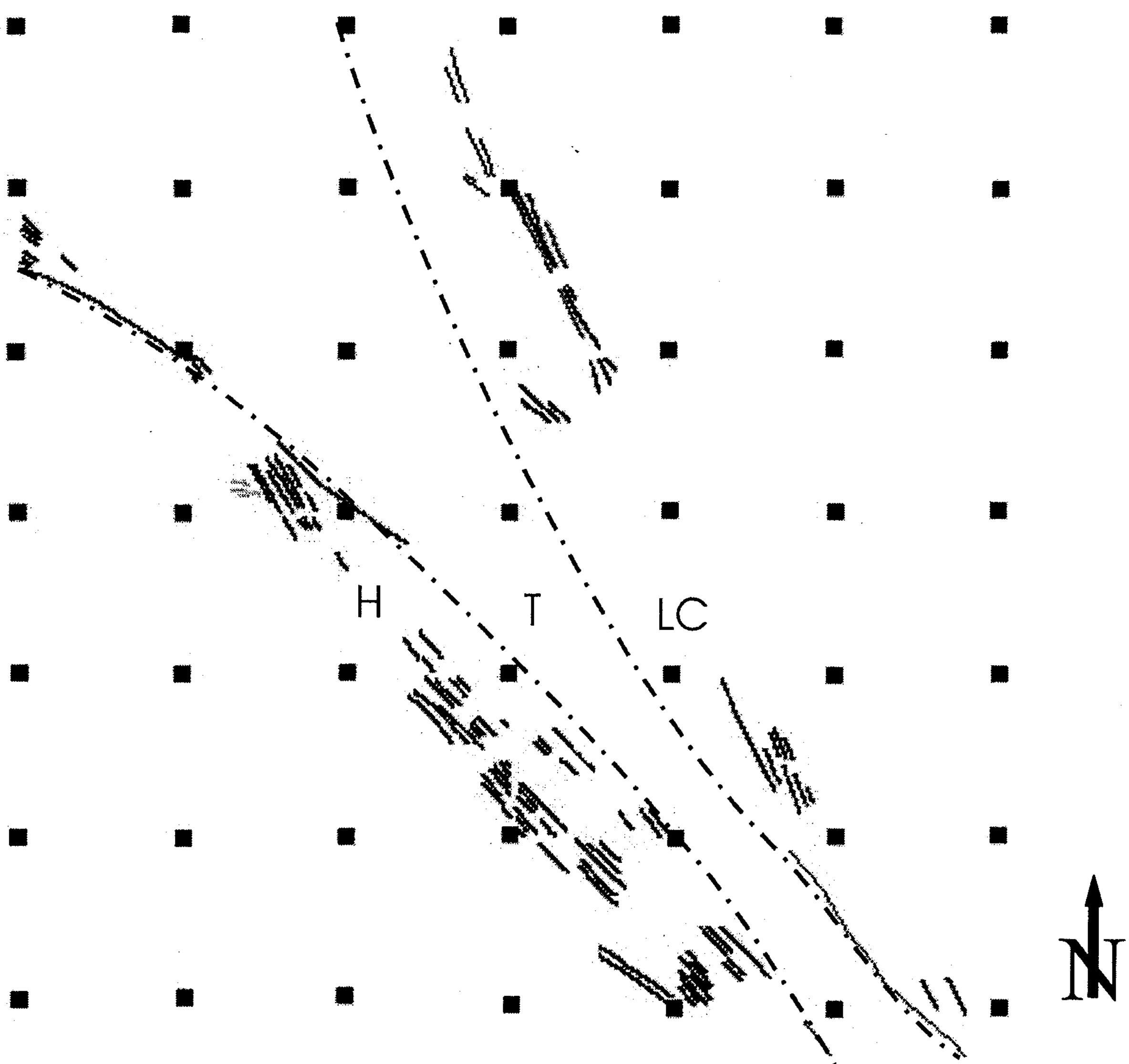


Figure 4-12. Shoreline features in Township 7, Range 8W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. Dash-dot lines separate groups of beaches: H – Herman, T – Tintah, LC – Lower Campbell.

4.2.10 Township 7, Range 9W

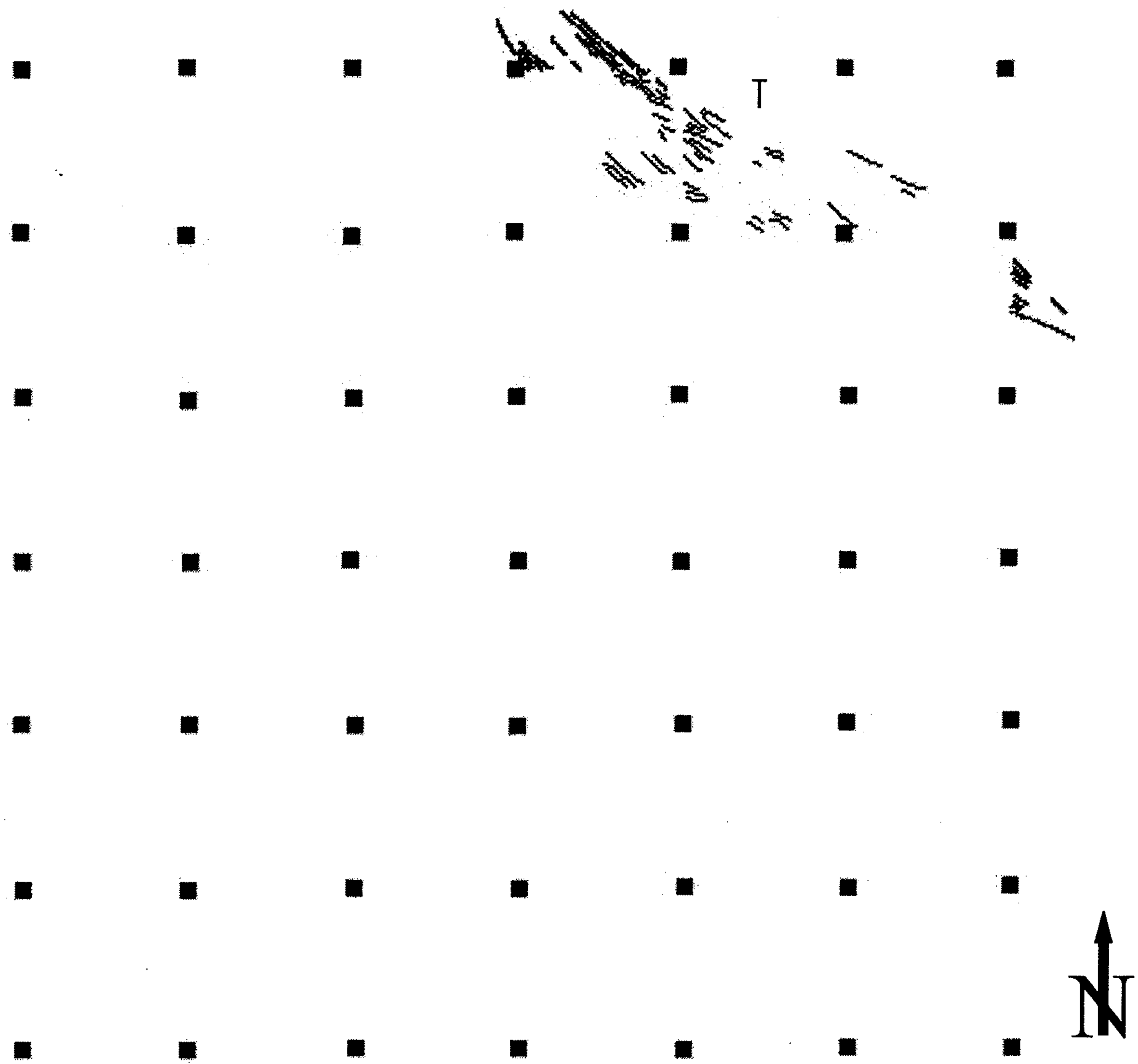


Figure 4-13. Shoreline features in Township 7, Range 9W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. All beach ridges are Tintah (T) stage.

4.2.11 Township 8, Range 9W

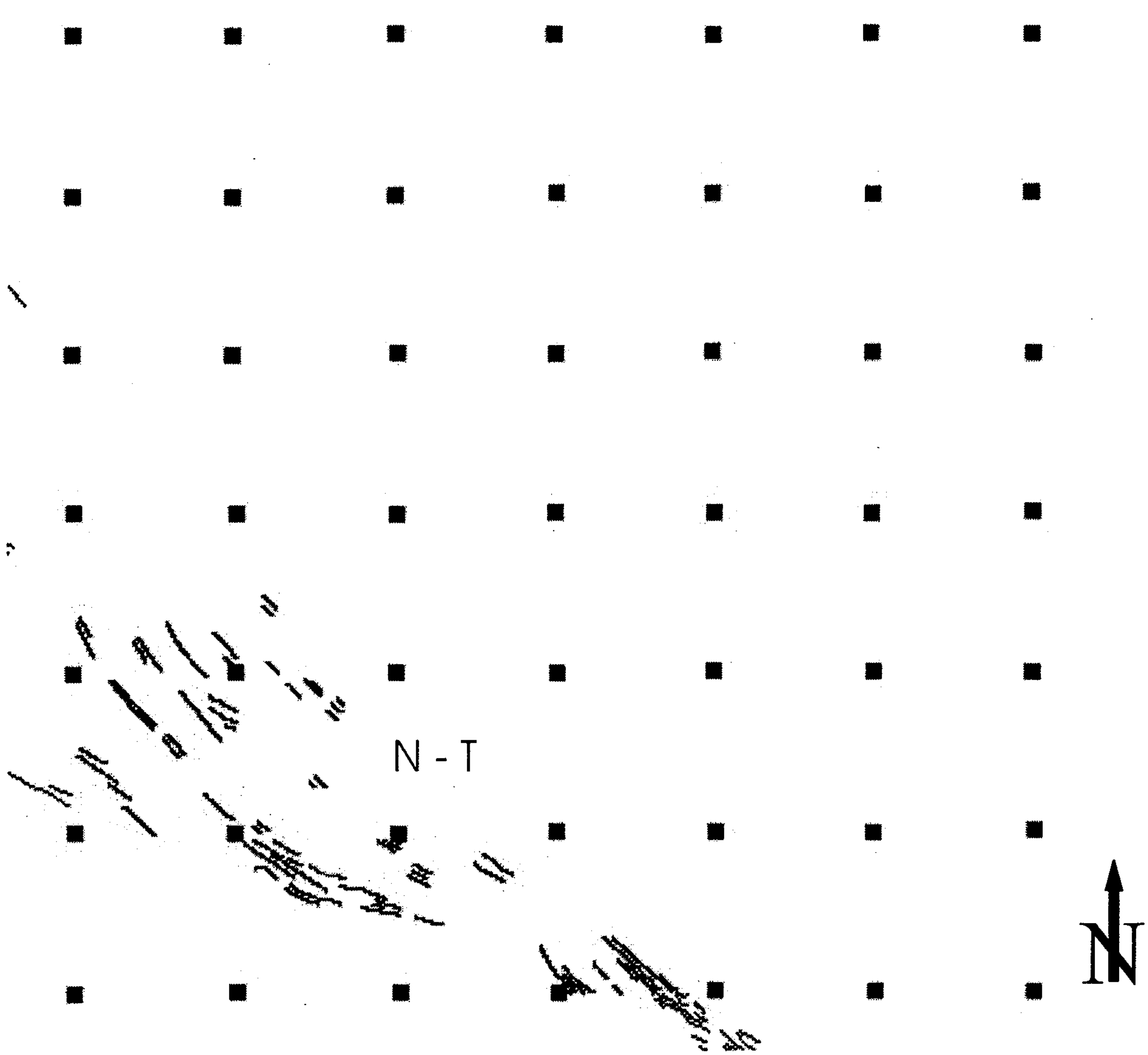


Figure 4-14. Shoreline features in Township 8, Range 9W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. All beach ridges are Norcross (N) – Tintah (T) stages (no clear boundary).

4.2.12 Township 8, Range 10W

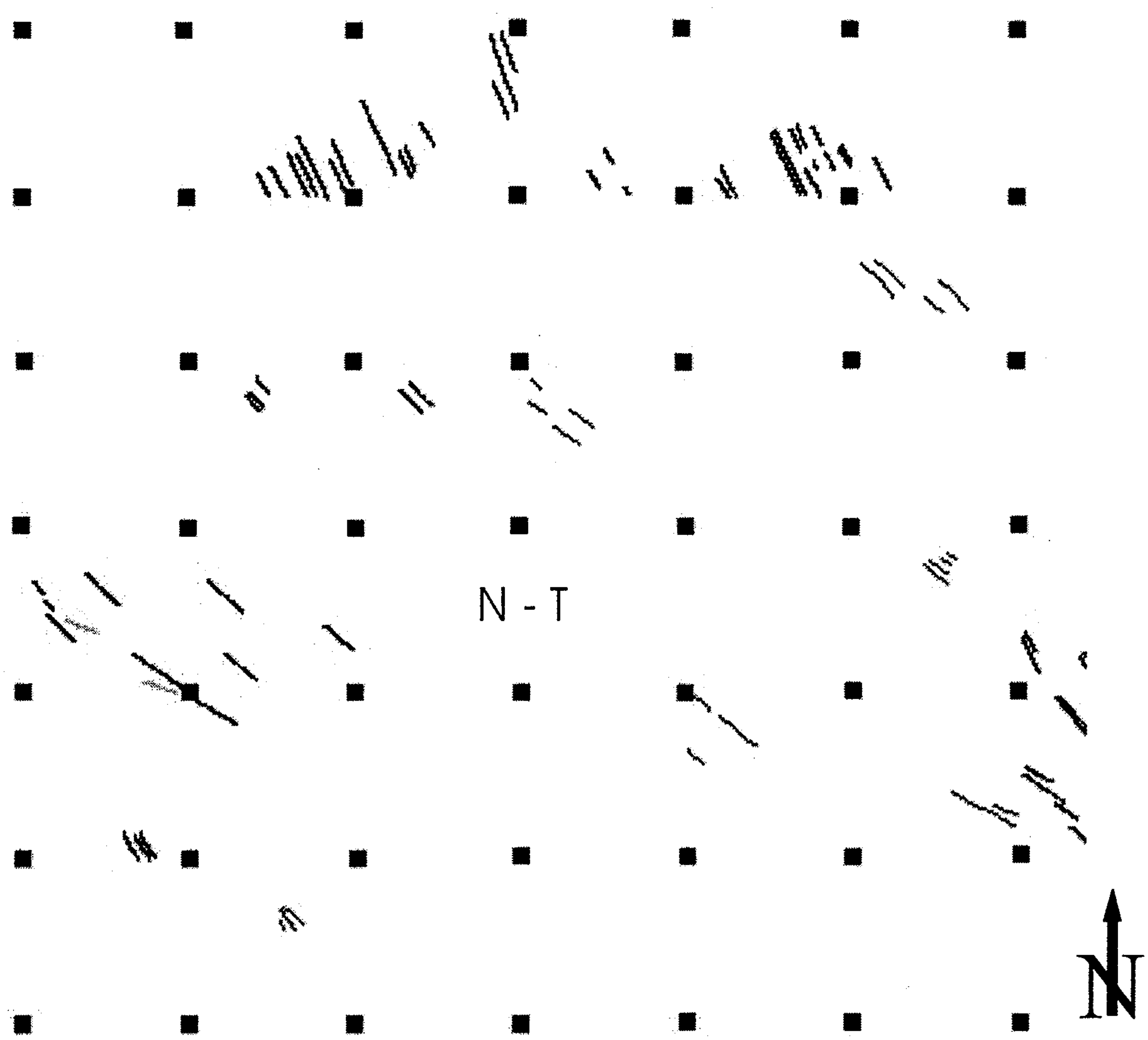


Figure 4-15. Shoreline features in Township 8, Range 10W. See Figure 4-3 for legend, and Figure 4-1 for relationships to other mapped beaches; square dots are 1 mile apart. All beach ridges are Norcross (N) – Tintah (T) stages (no clear boundary).

CHAPTER 5:

SHORELINE GEOLOGY

5.1 Introduction

Because this thesis deals with shoreline processes and geòlogy, it is appropriate to include a short discussion about relevant processes along the shorelines of large lakes. These will be used in interpreting the beaches of Lake Agassiz.

5.2 Fair-weather beaches

This section describes beaches that form under ordinary geologic and atmospheric conditions in temperate climates. Tideless beaches can be divided into several zones located in the shallow water of the lake, and may also have a backshore zone bordering the land (Davis, 1985; see Figure 5-1).

Beaches are often topped by dunes just landward of the main wave zone. When present, the backshore includes the nearly flat (slightly landward-dipping) berm, which is truncated at the more steeply dipping beachface that is part of the nearshore (Davis, 1985). The backshore zone may also include cross-bedded beach sands that dip landward overlying lagoonal silt, clay, and organics in the depression; sands from washover of the beach during storms are common in these lagoons (Reinson, 1992).

The nearshore extends from the beachface, which dips at between 1° and 30° depending on the beach material and wave conditions, to the lowest point where active subaqueous bars exist (Elliott, 1978; Davis, 1985). The nearshore grades into the offshore, where wave-action does not significantly rework sediments, so sediments are mainly silts and clays. The nearshore may contain one or more subaqueous sand bars (see Fig 5-1).

Sedimentologically, beaches consist of sand to gravel sized particles (depending on wave conditions, topography, and sediment sources; Komar, 1998), and are typically well- to very well-sorted (standard deviation is generally <0.35φ) and negatively skewed (i.e., having a mean particle size coarser than the modal particle size; Davis, 1985). The greatest grain size variation exists in the zone of wave-breaking where the greatest variation of energy conditions occurs; the largest grain sizes typically occur in the breaker zone because it is also the zone of maximum wave energy dissipation (Komar, 1998). Figure 5-2 shows a Lake Michigan beach profile with typical grain size parameter trends for a tideless beach, which illustrate this.

Bedforms differ along the beach depending on energy conditions. Waves typically carry sediments into the backshore zone only during storms. In the backbeach / lagoon zone, overwash beds dip landward at the angle of repose. In the area affected by swash and backwash in the nearshore, high-energy bedforms are typical, and may consist of antidunes, planar beds, and ripples (some symmetrical, others asymmetrical in cross section, sinusoidal in plan view, and evenly spaced between a few millimetres and several decimetres depending on wave size; Harms, 1969). Wind may rework the exposed beach surface during fair-weather periods, and ripples, dunes, and deflation surfaces are commonly found (Elliott, 1978).

In places, beaches may be extended by longshore drift into deeper water and cease to be backed by land. Lagoons lie between spits and the land; spits may extend themselves and rejoin the land, forming barrier beaches that completely enclose the lagoon. Offshore subaqueous bars are accumulations of sand, usually parallel to the shoreline, formed by wave action at the break point of waves, where sand moving landward intersects sand moving lakeward (King, 1972). Bars may form alone or as a series of several bars. Spits connected at both ends to land (or even almost so) have also been called bars (Evans, 1942). Barrier islands are narrow elongate shore-parallel islands that may form in several ways including offshore bar accumulation and emergence, and spit progradation (Reinson, 1992).

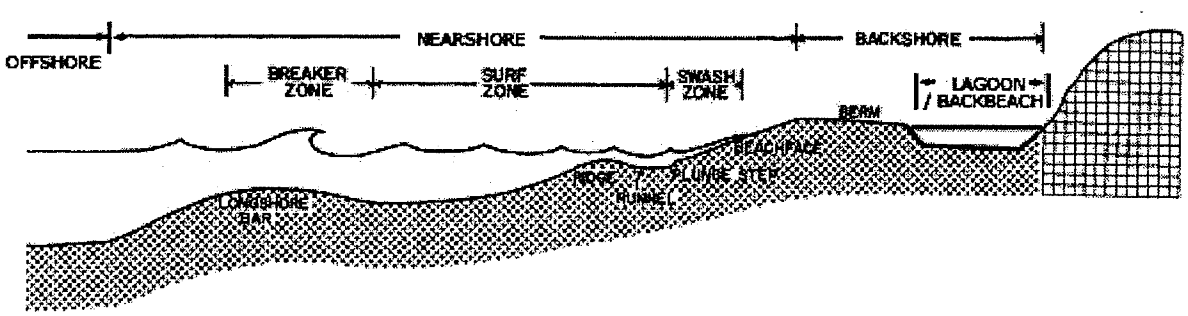


Figure 5-1. Generalized profile of a beach (after Davis, 1985).

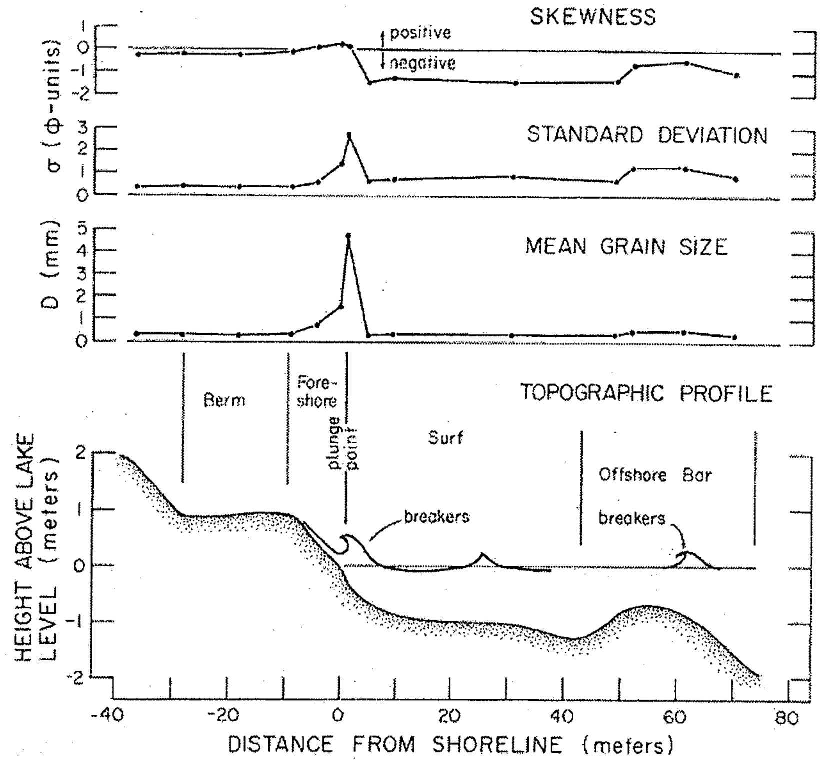


Figure 5-2. Grain size parameters of a Lake Michigan beach illustrating the effects of nearshore energy conditions and nearshore morphometry (Komar, 1998, p. 56).

5.3 Small-scale lake level changes

Glacial Lake Agassiz was in a constant state of flux. Lake level fluctuations occurred at several scales: inter-annually (within a given year), extra-annually (year to year; see Quinn, 2002), and episodically (e.g., Teller and Leverington, 2004). Inter-annual and extra-annual variations in lake levels were due to differences in the volume of water going to and coming from the lake from season to season and from year to year. Episodic changes were due to the opening and closing of outlets, and possibly to the drainage of smaller proglacial lakes to the west into Lake Agassiz that added significant volumes of water. Glacial Lakes Regina, Souris, and Hind are thought to have drained into Lake Agassiz catastrophically in a domino-fashion some time when Lake Agassiz stood at or above the Herman level (Kehew and Clayton, 1983; Kehew and Lord, 1986). The inflow of these lakes probably raised Lake Agassiz by no more than a metre: if we assume the area of Lake Agassiz was 134,000 km^2 (or 1.34×10^{11} m^2) at the Herman Stage, as calculated by Leverington et al. (2000), and that the combined volumes of glacial Lakes Regina, Souris, and Hind were 1.1×10^{11} m^3, as calculated by Kehew and Clayton (1983), then the rise in the level of Lake Agassiz from drainage of these lakes should have been $(1.1 \times 10^{11}\ m^3) / (1.34 \times 10^{11}\ m^2) = 0.82$ m, or slightly less than a metre. Seasonal and yearly variations in precipitation, runoff, groundwater flow, and evaporation are unlikely to have caused significant variations of lake level because inflow and outflow tend towards equilibrium, and these differences would have been subtle compared to the enormous volumes of overflow into and out of Lake Agassiz.

5.4 Storms and storm beaches

5.4.1 Storms

The main importance of storms to the beach environment is in the creation of large waves and strong currents in the nearshore, and the occurrence of storm surges (also called coastal swells; Nummendal, 1991; Seilacher and Aigner, 1991). Storms also cause movement of sediments into the beach or longshore zone from the surrounding landscape by increased stream runoff and erosion of high-relief features because of intense precipitation.

Nearshore waves may be several meters high. Dougherty et al. (2004) note that wave heights of 3 – 4 m occur during extra-tropical storms along the coast of New England. Wave heights of 6 m occurred during a particularly large storm in southern Maine on 5 – 6, 2001 (Hill et al., 2004). Wave height is a function of wind fetch, speed and duration (Nummedal, 1991). As wind fetch and duration increase, so does wave height. Because fetch across many directions of the Lake Agassiz would have been 200 – 400 km during early lake stages when beaches in this study area were formed, a 24-hour storm with wind speeds of 50 km/h over 400 km would have generated 4 m high waves (with a period of about 9.5 seconds); 64 km/h winds would have generated 5.5 m high wave heights in 24 hours (with a period of about 11 seconds; U.S. Army, 1966).

Storm surges refer to any storm-induced increases in water height (cf. non-storm-related events, e.g., tides). These may be initiated by atmospheric pressure gradients, wind-wave setup, and even precipitation and runoff (Sorensen, 1997; Pugh, 2004). Calculation of storm surges requires information on the temporal and lateral distribution of surface wind velocity, surface air pressure, velocity of the storm itself, as well as the geometry and bathymetry of the basin. Modern storm surges are difficult to model because of the difficulty of quantifying the many variables (Murty and Polavarapu, 1975); modelling storm surges from late glacial time could not be done with any accuracy because of the even greater range of uncertainty. However, some generalizations may be made about storm surges on lakes that will allow semi-quantitative estimates to be made about Lake Agassiz.

Atmospheric pressure gradients cause water to rise toward zones of low-pressure (the 'inverted barometer effect'). For every 0.03 atm drop in pressure, water rises by about 35 cm (Bretschneider, 1967). Thus, if pressures was to drop by 0.003 atm, as is common for modern thunderstorms (http://www.nssl.noaa.gov/edu/storm, cited on Oct. 25, 2005), one could expect a lake-level rise of only about 3.5 cm; pressure drops are much greater during tropical storms (e.g., hurricanes)–for a hurricane pressure drop of 0.08 atm, water would rise by about 98 cm.

Wind-wave setup refers to the effect of wind induced waves and currents 'piling up' water in the direction of wind movement, in an enclosed area, thus not allowing water to flow back as quickly as it is supplied to the shoreline area. Setup height may be approximated by the equation: $H_{SU} = 0.048\sqrt{H_W L_W}$, where H_{SU} = height of setup, H_W = root mean squared deepwater wave height, and L_W = deep water wavelength (Hanslow and Nielson, 1993). If we use a formula to calculate wavelength (Bascom, 1964) as $L = 5.12\ T^2$, where L = wavelength, and T = wave period, then assuming a wave period of 9.5 seconds (discussed above), we can assume a wavelength of $5.12\ (9.5)^2 = 462$ m; using this value with an assumed wave height of 4 m, calculated setup height becomes $0.048\sqrt{4 \times 462} = 2.1$ m (64 km/h winds would give wavelength and setup values of 620 m and 2.8 m, respectively).

If a storm with winds blowing over 24 hours were to occur over Lake Agassiz with a fetch of 400 km, water-wave setup would be about 2 – 3 m (calculated for 50 km/h and 64 km/h winds, respectively); pressure-induced water rises would probably only amount to 3 or 4 cm, but superposed on the increased mean water level would be waves 4 – 5 m in height. Other values could be calculated, changing wind fetch, duration, and speed, but the values calculated above serve to illustrate the potential height of storm impact that could be expected on Lake Agassiz.

The height of a storm surge is directly proportional to the rate of development of that particular storm (Murty and Polavarapu, 1975). Pugh (2004) notes that extra-tropical storms are usually large systems extending over hundreds of kilometres around a central zone of low-pressure, and may last for several days; storm surges may also occur over several hundred kilometres, but usually only last one day. Storm surges on the modern North American Great Lakes, which may be analogous in some ways to Lake Agassiz, are localized in a given year to a particular stormy season; in the case of the Great Lakes, the late autumn and early winter (Murty and Polavarapu, 1975).

Murty and Polavarapu (1975) cite observed storm surges at different stations from three major storms (in 1913, 1916, and 1940) between about 0.2 m and 1.4 m, which they found could be explained mainly by the large-scale changes in pressure from the storms. Murty et al. (1995) note that maximum storm surge on the great lakes is about 1.5 m.

Pugh (2004) notes that tropical storm surges (including those of hurricanes and typhoons) along oceanic coasts may be as high as 9 m, however extra-tropical surges (on oceanic coasts) are typically about 1 m. Estimating storm surges on Lake Agassiz based on data from tropical storm surges would yield overestimates, since extra-tropical storm surges are less intense (Pugh, 2004). Based on the examples and calculations discussed above, we can assume that storm surges did occur on Lake Agassiz, and that they probably reached heights of 2 – 3 m above normal lake levels, with waves as high as 4 – 5 m.

5.4.2 Storm beaches

A storm may have an erosive or constructive effect on a beach (King, 1972). Here, the term 'storm beach' is used to describe a beach deposit formed primarily during a storm event. Storm beaches may be preserved several metres above mean sea level (Orford, 1977). Using modern examples of storm beaches described by others, a conceptual model of storm beaches can be formed and compared to Lake Agassiz beaches. Elson (1967) has reviewed the theoretical conditions necessary to create storm beaches on Lake Agassiz; his conclusions, shown in Table 5-1, should be considered orders of magnitude, not precise values.

Fetch (km)	Wave height (m)	Beach height (m)	Wind velocity (km/h)	generation time (hours)	deep water limit (m)
40	1	1	23	4.5	4
80	1	1	29	7	7
161	2	2	39	11	12
241	2	3	43	14	16
322	3	4	48	17	21
402	3	5	51	19.5	24
483	4	5	55	22	28
563	5	6	56	24.5	31
644	5	7	59	26.5	35

Table 5-1. Some theoretical conditions of wave and beach formation on lakes during storms, with reasonable input-values for Lake Agassiz (after Elson, 1967).

King (1969) attributes 42 sequential beach ridges on Foley Island in the Canadian Arctic to 42 single storm events with recurrence intervals of about 30 years. These beaches consist of poorly sorted sand and limestone pebbles derived from bedrock. Beach are spaced laterally from 25 to 65 m apart, although some ridges are welded to older ones. The height of individual ridges ranges from 2 – 3 m.

Along the southwestern coast of James Bay, Ontario, which is an isostatically-rising region, modern shore-parallel beaches are predominantly formed by storms; these beaches range from about 0.3 m to 5 m in height; shore-parallel gravel beaches are thin (0.3 – 0.5 m), and beaches formed along wide headlands are particularly high (3 – 5 m; Martini et al., 1980; Martini, 1981). Generally these beaches have an anastomosing pattern in plan view, and consist of units of sand, gravel, and sandy gravel. These storm beaches have a steeply-dipping seaward slope, a gently-landward-dipping top and a very steep and short backbeach slope (Martini and Protz, 1978). Martini and Protz (1978) suggest that ridges with internal cross-bed sets and erosional-bounding surfaces may have been acted upon by more than one storm. Beaches form 'stair-steps' of progressively younger ridges toward the ocean, along the isostatically emerging coast, with little or no marshland between them. Along Hudson Bay regularly-spaced beach ridges occur up to 75 km inland of the modern coast, which Martini et al. (1980) contend is a function of periodic storm beach sedimentation superposed on continuous isostatic rebound throughout the Holocene.

Hall and Denton (1999) describe modern clast-supported storm beaches along the southern Scott coast of Antarctica composed of cobbles, boulders, and organic matter (shells, starfish, and kelp). These beaches are typically about 1.5 m in relief. Nearby raised beaches (isostatically rebounded up to 31 m above modern high-tide) consist mainly of clast-supported boulder-cobble diamictons with incorporated organic matter (shells, starfish, kelp, and seal remains), and are about 1.5 m in relief between ridges and swales. The authors suggest the raised beaches are storm beaches, based on the morphological and compositional similarity to modern storm beaches in the area.

Butler (1999) describes several raised beaches at McMurdo Sound, Antarctica, consisting of poorly-sorted sand- to cobble-sized sediments with sub-angular clasts. The modern beaches in that area contain sand and gravel with sub-rounded to rounded clasts. The raised beaches are about 1 – 5 m in relief; beach (shoreface) slopes vary considerably, from about 0.5° to 12°. Sediments in the raised beaches grade from clast supported at their bases to matrix supported in the upper 0.1 m; mean clast size generally increases with depth. Butler (1999) suggests that these beaches are storm beaches, based on the poor rounding and lack of consistent orientation of stones, and poor sorting of a wide range of sediment sizes. Butler (1999) further suggests that high magnitude storms have created the raised beach ridges along the isostatically-rebounding coast out of the zone of normal shoreline processes, which have now rebounded out of the reach of storm processes.

Sedimentologically, storm beds (tempestites) tend to have upward-grading grain sizes, reflecting initial erosion followed by successively weaker hydrologic depositional regimes during the waning storm (Seilacher, 1984). Storms are high-energy events—the dominant bedforms found in storm beaches are parallel lamination and swaley cross stratification (Walker and Plint, 1992).

In summary, storm beaches contain generally poorly sorted sediments (if a wide variety of grain sizes are available) reflecting the inability of the beach to equilibrate with wave conditions over a short period; this is in marked contrast to the typically excellent sorting of fair-weather beaches. They are often emplaced above the limit of normal shoreline processes because of higher water levels and wave uprush during storms. Bedforms within storm beaches may include planar lamination (indicative of a high-flow regime), and cross bedding; erosional surfaces may be present, especially where more than one storm event has modified a beach. The relief of a storm beach is typically on the order of less than a metre to a few metres; beach slope is highly variable and could be less than one degree to more than ten degrees.

5.5 Ice action and polar beaches

The term 'polar beaches' does not only apply to beaches within polar latitudes, but to all cold climate beaches that have been or are being affected by sea or lake ice, permafrost, or glaciers terminating in water (Nichols, 1961). There are several ways in which ice may impact on beaches and beach formation, both directly and indirectly. Overall the presence of abundant lake ice produces sediments that are immature (poorly sorted) and beaches that are less well developed morphologically than other beaches (King, 1969). Table 5-2 shows some characteristic features of polar beaches.

In terms of direct impact, frozen ground has the important effect of limiting the depths of sediment mobilization along a beach; since frozen sediments are really cemented sediments (i.e., rocks), frozen ground is significantly less erodable than unfrozen ground. When the unfrozen sediments above the frost table are removed by storms, thawing and erosion of the newly-exposed frozen ground is quite rapid; nonetheless, beach profile changes may be delayed because of the presence of this frozen ground (Taylor and McCann, 1983). Ground ice (wedges or lenses) may also cause rapid cliff retreat, since rapid thermal erosion of exposed ice may cause block slumping and flow slumping (solifluction) of sediments into the lake (Taylor and McCann, 1983; Emery and Kuhn, 1982).

Indirectly, lake ice shields beaches by diminishing wave energy at the shoreline; ice limits the formation of offshore waves and absorbs wave energy near the beach (Taylor and McCann, 1983). Sorting and rounding of grains are generally less than in beaches without ice impeded wave action. When a lake is completely ice covered (or only ice covered near the shore) wave energy (at the shore) is zero, so in ephemerally ice covered lakes, the annual duration of beach development is limited to ice-free periods. For example, in Hudson Bay, which in some ways may be analogous to Lake Agassiz, the fully ice-free season is only about 3 months (Natural Resources Canada, http://atlas.gc.ca/site/english/maps/environment/seaice/break-up/1, cited on Aug. 3, 2005). During freeze-up, ice first forms along the shoreline and develops progressively basin-ward, limiting wave energy at the shore; during break-up, ice recedes from the shoreline first and retreats progressively basin-ward, again leaving a 'moat' of water between the land and the offshore ice, limiting fetch and wave formation during this period. Ice also prolongs beach modifications when ice masses impede longshore transport along the beach. King (1969) notes that clay occurs in the nearshore zones of some modern beaches on Baffin Island, in northern Canada, because the limited wave energy is insufficient to wash it offshore.

Ice may also have a more direct role within the beach environment. Sediments may be introduced to a beach by ice rafting, which is usually not volumetrically significant, but may introduce sediments that are lithologically and texturally different from the surrounding sediments (Taylor and McCann, 1983). Unlike waves, floating ice can transport sediments of all size fractions. Ice may also act as a mechanism for moving sediments out of the beach zone, as autumn ice may incorporate beach sediment. Wind-generated movements of pack ice and icebergs can alter the beach by the mechanical action of ice scouring and pushing. Ice scouring and pushing are responsible for irregular topographic variations in beaches (including ice-push ridges), as well as reworking and mixing of nearby sediments, which may reduce the degree of sorting. Micro-topographic variations can also be caused by buried ice masses (winter ice or icebergs) that melt differentially, similar to kettle holes in periglacial environments. However, micro-topographic variations at the surface, whether caused by differential melt-out or ice scouring and pushing, tend to be quickly obliterated by wave action on active beaches or, if beyond the reach of waves, by subaerial processes over a longer time (as much as a few centuries; Taylor and McCann, 1983). In short, beaches associated with abundant lake ice are more likely to have disturbed bedding, poorer sorting, and large clasts because of disturbance by ice and ice rafting.

In places where coasts are ice-dominated most of the year, waves barely rework sediments at all, and beach materials reflect local sources; sorting is very poor, and sediments are affected significantly by terrestrial- and ice-processes, so bedding may be highly disturbed (Taylor and McCann, 1983). Infrequent storms tend to be the dominant agent of beach modification. Taylor and McCann (1983) raise the question as to what magnitude of storm could produce a significant beach and conclude, based on field observations of modern systems and observation of uplifted beach ridges, that a substantial amount of time (decades to centuries) is needed to accumulate sediment along a coast before storm reworking can create a sizable beach in polar-type conditions.

1)	Irregular topography due to ice block meltout and ice scouring
2)	Abrupt termination of beach ridges due to ice present during formation
3)	Presence of ice-rafted sediments
4)	Poorly rounded beach gravel due to limited wave energy and short wave-working season
5)	Poorly sorted sediments due to limited wave energy and short wave-working season

Table 5-2. Some relevant features of cold-climate beaches. Not all these features are present at every polar beach, but are common features of polar beaches; Taylor and McCann, 1983.

CHAPTER 6:

GROUND-PENETRATING RADAR SURVEY

6.1 Introduction

Ground-penetrating radar (GPR) is a non-invasive geophysical technique used to image shallow subsurface reflectors. GPR surveys were done at several localities in southern Manitoba in August 2004, with the help of Chris Hugenholtz from the University of Calgary. GPR lines were run on gravel roads, in ditches, and in farmer's fields. A total of 39 GPR lines were completed from 7 different sites, ranging from 29 m to 1072 m in length. The approximate locations for all GPR lines are shown in Figure 6-1; the end points of those GPR lines and the site-names of those lines are shown in Table 6-1. Table 6-2 shows the rationale for naming sites.

Interpreting GPR lines is similar in practice to interpreting seismic cross-sections. Radar facies is defined as 'the sum of all characteristics of a reflection pattern produced by a certain rock formation, or... by a sedimentary sequence.' (van Overmeeren, 1998, p. 4). Individual radar reflection surfaces are clustered into coherent groups (radar facies), which are interpreted, with all other facies in the sequence, in a geological framework.

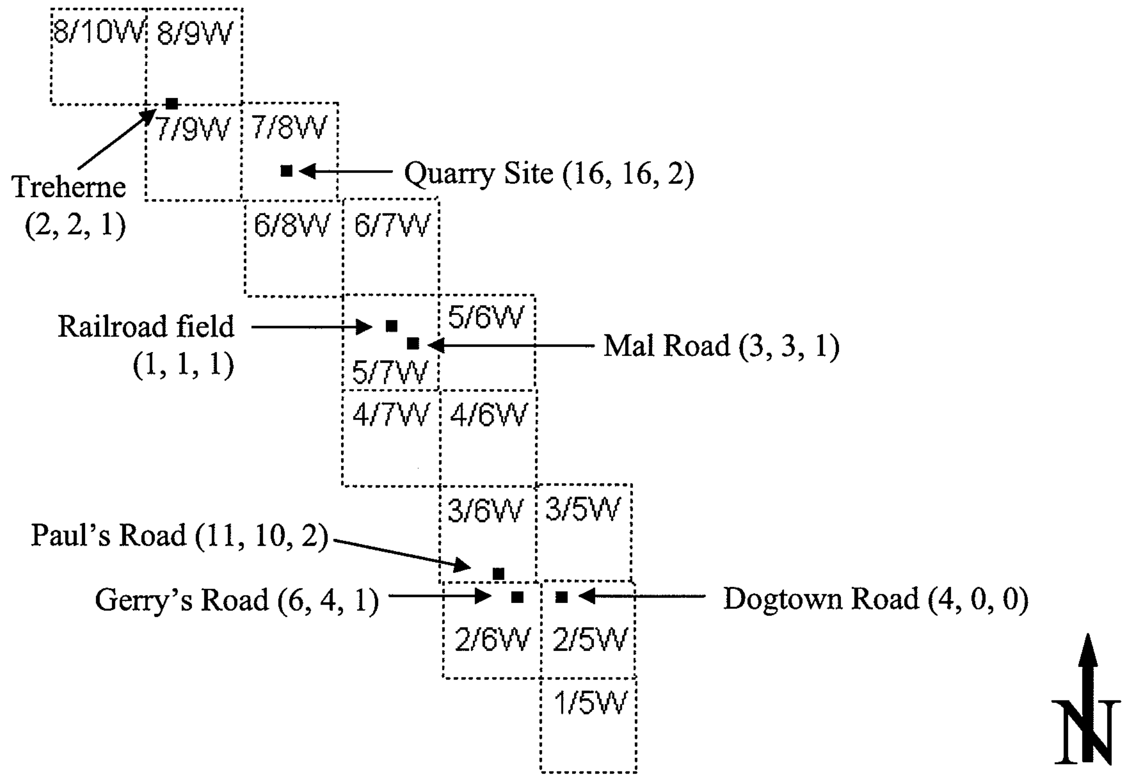


Figure 6-1. Locations of GPR sites within the study area, referred to below in Table 6-1. Numbers within squares (e.g., 1/5W) refer to townships in Manitoba (in this case, Township 1, Range 5 west of the principle meridian). Numbers in brackets refer to the number of GPR lines done each site, the number of lines that were processed and included in this thesis, and the number of those discussed in this chapter, respectively. For example (6, 4, 1) at Gerry's Road refers to six lines run at that site, four lines processed (all included in Appendix 3), and one line specifically discussed in this chapter.

Site Name	**Start (Easting)**	**Start (Northing)**	**End (Easting)**	**End (Northing)**	**GPR Lines**
Quarry, West Side	536722	5489807	536722	5489732	**MAN19a, MAN19b, MAN21, LINE12**
Quarry, Southwest Side Rd.	536654	5489389	536800	5489513	**MAN22, MAN23, LINE13**
Quarry, South Side #1	537210	5489435	537184	5489397	**MAN24, MAN29, LINE15**
Quarry, South Side #2	537160	5489387	537144	5489411	**MAN25, MAN30, LINE16**
Quarry, South Side #3	537276	5489466	537217	5489506	**MAN26, MAN28, LINE14**
Paul's Rd. #1	559379	5448120	558479	5448108	**MAN03, MAN04, LINE01, LINE 1a, LINE 1b**
Paul's Rd. #2	559379	5448120	559050	5448111	**MAN07**
Paul's Rd. #3	559303	5448113	559202	5448320	**LINE0, MAN08, MAN31**
Paul's Rd. #5	559217	5448333	559316	5448116	**MAN32**
Paul's Rd. #6	559380	5448222	559055	5448114	***MAN33***
Gerry's Rd. #1	561955	5445705	563157	5445734	**LINE6a, LINE6b**
Gerry's Rd. #2	562822	5445724	559975	5445689	***MAN09, MAN10***
Gerry's Rd. #3	561079	5445620	561196	5445336	**MAN11, LINE07**
Dog Town Rd. #1	565285	5445735	565723	5445743	***MAN12, LINE08***
Dog Town Rd. #2	565428	5445751	565608	5445755	***LINE09***
Dog Town Rd. #3	565504	5445749	565958	5445750	***MAN13***
Railway field	547870	5473474	547980	5473527	**MAN14**
Mal Rd. #1	550647	5471850	549575	5471840	**MAN16**
Mal Rd. #2	549575	5471840	549983	5471843	**MAN17, LINE10**
Treherne	525068	5496342	525726	5496350	**MAN18, LINE11, LINE11a, LINE11b**

Table 6-1. Names and coordinates of all GPR lines done for this study (C. Hugenholtz, pers. comm., 2004). Note that coordinates are in North American 1927 map datum. Lines in italics have not been processed and are not included in this thesis. Letters after line numbers (e.g., LINE 11a) indicate partial sections of those lines.

Site	Rationale for name
Quarry	In a gravel pit
Paul's Road	Named after farmer (site owner)
Gerry's Road	Named after local farmer
Dogtown road	Named after local farm (with many dogs)
Railway Field	Near a railway track
Mal road	Named after local dog (malamute breed)
Treherne	Near town of Treherne

Table 6-2. Rationales for site names.

6.2 Principles of ground-penetrating radar

A typical GPR system consists of a power supply, a transmitting antenna, a receiving antenna, a data storage drive, a waveform modulator, and a display screen. Figure 6-2 shows an operational flow chart for a typical GPR system. A beam of radio-frequency electromagnetic radiation (typically between 10 and 1000 MHz) is transmitted by the transmitting antenna into the ground, where it is reflected and refracted at the boundaries between media; some energy is absorbed by each of these media (Davis and Annan, 1989). Reflected signals are received by the receiving antenna, and processed to create a two or three dimensional view of the subsurface.

Reflections arise from the boundaries between media with different dielectric constants. The dielectric constant of a material is the ratio of the electric field storage capacity of that material to that of free space (Martinez and Byrnes, 2001). GPR response is also a function of magnetic permeability and electrical conductivity. Generally, good electrical conductors (e.g., metals, saline water) make poor dielectrics because of their inability to store electrical charges, which minimizes the effectiveness of GPR on these materials. The magnetic properties of most geological materials have a negligible effect on GPR signals. The magnetic, dielectric and electric properties of materials are frequency dependant, but the differences are negligible over the frequency range of GPR (Martinez and Byrnes, 2001).

Because of the high frequencies used in GPR, it is a comparatively shallow, high resolution method, used mostly for environmental investigations less than a metre to a few tens of metres deep; resolutions are on the order of centimetres to a few metres (Jol and Bristow, 2003). Like any electro-magnetic method, penetration depth and resolution are inversely related, so there is a trade-off between the two in any GPR survey.

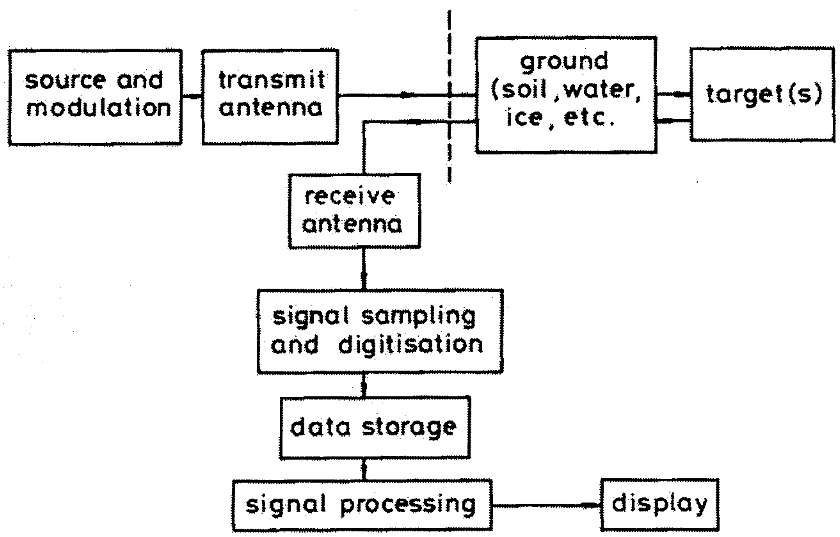


Figure 6-2. Flow chart of a typical GPR operation (Daniels et al., 1988, p. 280).

6.3 Field survey 2004

6.3.1 Systems

Three GPR systems were used in this study: a Pulse Ekko IV operating at 50 MHz, a Pulse Ekko IV operating at 100 MHz, and a Noggin operating at 250 MHz. The Pulse Ekko systems were identical, except for the antennae and the power supplies, which were changed manually to convert one system to the other. All systems are made by Sensors and Software, Inc. Table 6-3 shows the specifications for these systems.

Figures 6-3 and 6-4 are field photos showing the Pulse Ekko and Noggin systems, respectively.

The Pulse Ekko systems are operated by two users: one who drags the antennae, and another who follows behind and collects data on a laptop computer (see Fig. 6-3). The Pulse Ekko systems require the user to input the speed travelled, so care must be taken to travel at a constant speed for the entire run.

The Noggin system is a self contained GPR that is pushed by a user over the surface they wish to investigate (see Fig. 6-4); a real-time display is shown on an auxiliary display screen. This system keeps track of the distance travelled by measuring wheel rotations, so there is no need for a constant pace or speed estimates based on distance and time.

GPR system:	Pulse Ekko IV
Frequency:	50 MHz
Antenna spacing:	100 cm
Trace separation:	25 – 200 cm
Power:	1000 V
GPR system:	Pulse Ekko IV
Frequency:	100 MHz
Antenna spacing:	100 cm
Trace separation:	25 – 200 cm
Power:	400 V
GPR system:	Noggin
Frequency:	250 MHz
Antenna spacing:	27 cm
Trace separation:	5 cm
Power:	100 V

Table 6-3. Technical specifications for the GPR systems used in surveys done for this study.

Figure 6-3. The Pulse Ekko 100 MHz GPR system in use at the Paul's Road site.

Figure 6-4. The Noggin 250 MHz GPR system in use in SW Saskatchewan (C. Hugenholtz, pers. comm., 2005).

6.3.2 Post-acquisition filtering and manipulation

GPR data usually need to be filtered after collection, but preferably not on-site, so irreversible changes can be avoided. All post-acquisition data manipulation was done in Calgary by C. Hugenholtz. Lines from the Pulse Ekko system, which did not use an automatic odometer (as the Noggin unit did), were adjusted for distance and trace separation using UTM end-point coordinates (from handheld GPS). Trace-stacking was done to reduce random noise and enhance coherent reflectors. Dewow filtering was applied to remove long-period noise, that is shifts in the baseline of a given trace. An automatic gain function was implemented to each trace to amplify the signal exponentially with depth, because signals are attenuated exponentially with depth.

Topographic corrections were made, where necessary, to correct for changes in elevation. Topographic control was provided by a total-station survey done in the summer of 2004. A total station is a surveying system that integrates a theodolite (which measures the horizontal and vertical angles to a point), an electronic range-finder, and a computer (for data storage and geometric calculations; L. Sheng, pers. comm., 2004). The instrument is operated by two people: one holding a reflective prism that the total station measures the angles and distance to, and the other operating the total station. Geographic coordinates and elevation values are entered into the total station before measurements are made so that all data are given in their true geographic coordinates and elevations.

6.3.3 Results

6.3.3.1 Introduction

A total of 39 GPR lines were run at seven different sites, however not all GPR lines are included in this thesis because some were not considered to be worth processing, as they did not show any useful stratigraphic features. Including all GPR lines in this chapter would be redundant, so a representative example from each GPR site (which included one or more GPR lines) was chosen to be discussed below. Only the Dogtown Road site is not included here because it has no processed GPR lines.

The GPR lines shown in the following sections are first shown as 'raw responses' without any interpretation of reflector geometries (of bedding) given, and then with the interpreted strata boundaries drawn on digitally by myself over the raw response, which is dimmed in order to accentuate the drawn-on interpretations. GPR lines are complicated by multiple reflections, diffractions, and reflectors that may not actually represent subsurface bedding (e.g., the water table, soil profiles). For these reasons, interpretation of reflector geometries is somewhat subjective—it should be kept in mind that a raw GPR line represents the true radar response of the ground, whereas interpreted reflector geometries are my own interpretations of bedding patterns, based on raw response data.

6.3.3.2 Paul's Road (LINE01a and MAN32)

The 'Paul's Road' site is located in a private farmyard in the NE quadrant of Section 3, Township 3, Range 6W; the road itself is an E – W half-section gravel road in this section that runs oblique, but almost perpendicular, to the strike of a series of Herman beaches. The approximate location of this site is shown in Fig. 6-1; coordinates of the GPR lines along this road are given in Table 6-1. This site has some of the best expressed beaches in the study area. Figure 6-5 shows the endpoints of GPR line 'LINE01a' in aerial view, which was run on the gravel road. Figures 6-6, and 6-7 show the interpreted and uninterpreted views of 'LINE01a'.

Figure 6-5. Aerial photograph showing the start and end points (white dots with black centres; right central part of photo) of GPR line 'LINE01a', shown in Figures 6-6 and 6-7. Field of view is about 1 mile by 1 mile.

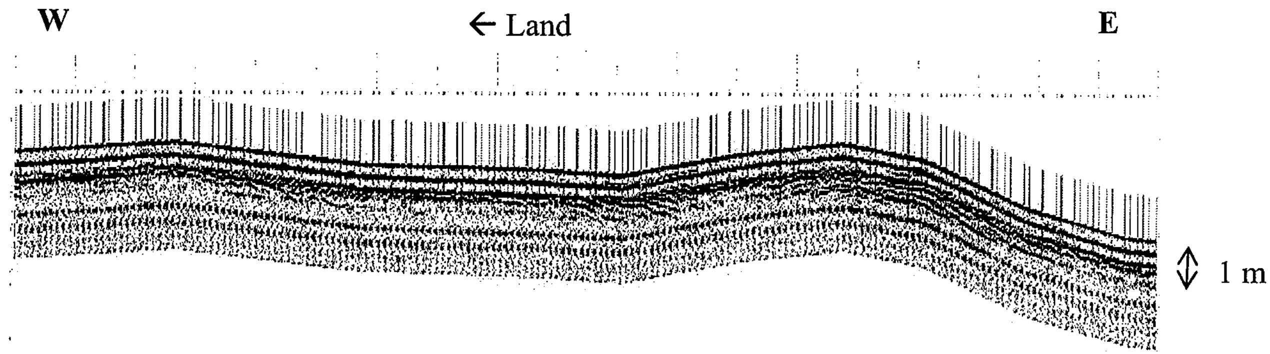


Figure 6-6. GPR line 'LINE 01a'; 250 MHz. Raw response. Total length is 190 m. This line is a small portion of 'LINE01' (the easternmost 230 m, minus the easternmost 40 m); the whole line being too large to fit on a single page (see Appendix 3). The two small ridges are Herman beaches.

Figure 6-7. GPR line 'LINE 01a'; 250 MHz. Interpreted bedding contacts are drawn over the raw response seen in Figure 6-6. Total length is 190 m.

This line shows two beach ridges. The dominant reflectors are lakeward-dipping reflectors (about parallel to the ground surface) on the lakeward sides of the ridges that become horizontal at the tops of the ridges, probably representing swash-backwash sedimentation in the nearshore. Just landward of the eastern ridge (and partially within the eastern ridge), reflectors are dipping lakeward at about the same angle as those on the lakeward side of the eastern ridge. This indicates these beds must not have been exposed to waves long enough for reworking to have occurred at the shoreline, or that they represent nearshore sediments of another ridge that has been bevelled off. Landward of the easternmost ridge there seems to be a package of short landward-dipping reflectors (dipping at about 11° to 16°), which onlap (at a non-horizontal angle) onto lakeward-dipping reflectors of the ridge to the west. These beds probably represent backbeach sedimentation during a storm event. Horizontal parallel reflectors separate the two ridges.

A GPR line (MAN32) was run parallel to a well-developed Herman beach at Paul's Road to investigate a longitudinal radar cross section of a beach (also see MAN11 and LINE07 in Appendix 3, which were run parallel to a Norcross beach at Gerry's Road, but are not discussed in that section because of the similarity to MAN32). Figure 6-8 shows the position of MAN32 in aerial view. The raw response of MAN32 is shown in Figure 6-9; the interpreted reflector geometries are shown in Figure 6-10.

Figure 6-8. Aerial photograph showing the start and end points (white dots with black centres; right central part of photo) of GPR line 'MAN32', shown in Figures 6-9 and 6-10. Field of view is about 1 mile by 1 mile.

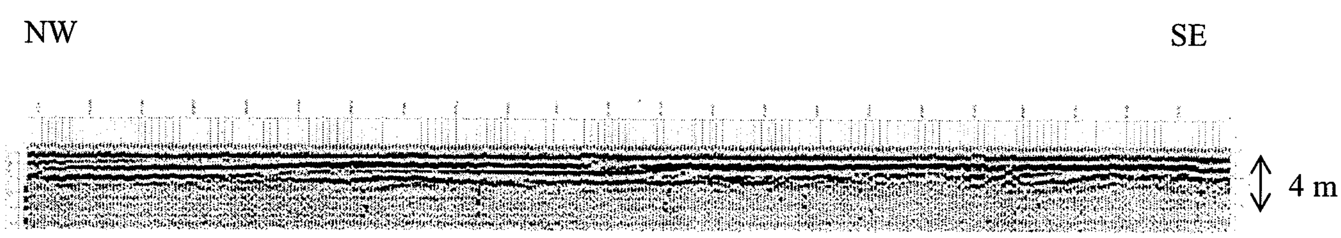


Figure 6-9. GPR line 'MAN32'; 100 MHz. Raw response. Total length is 233 m.

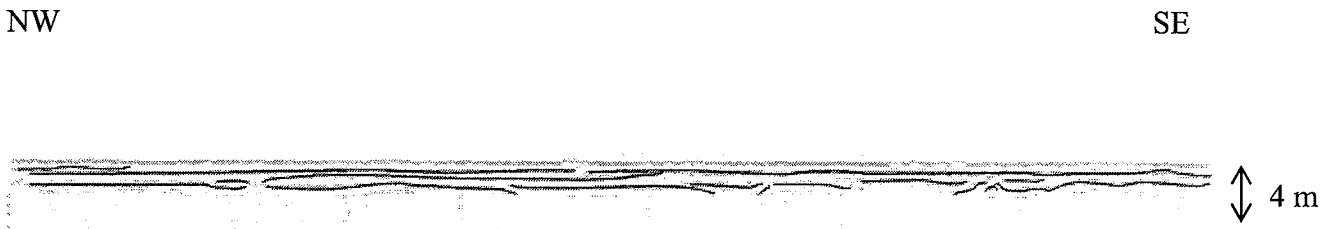


Figure 6-10. GPR line 'MAN32'; 100 MHz. Interpreted bedding contacts are drawn over the raw response seen in Figure 6-9. Total length is 233 m.

This line shows the expected response for a line run parallel to a beach ridge: predominantly parallel nearly-horizontal reflectors. A few short localized dipping reflectors occur within the profile, and may represent small lateral variations in the beach, such as stream cuts.

6.3.3.3 Gerry's Road (LINE06a)

The 'Gerry's Road' site is a long (2 mile) E – W gravel section-road between sections 26 & 35, and 25 & 36 of Township 2, Range 6W. GPR lines were run on the road, in the ditch, and in adjacent fields. The road crosses several beach ridges of the Herman to Tintah stages of Lake Agassiz. Figure 6-11 is an aerial photo that shows the endpoints of LINE06a, which crosses a beach of the Norcross stage. LINE06a is shown as a raw response in Figure 6-12, and with interpretations drawn on in Figure 6-13.

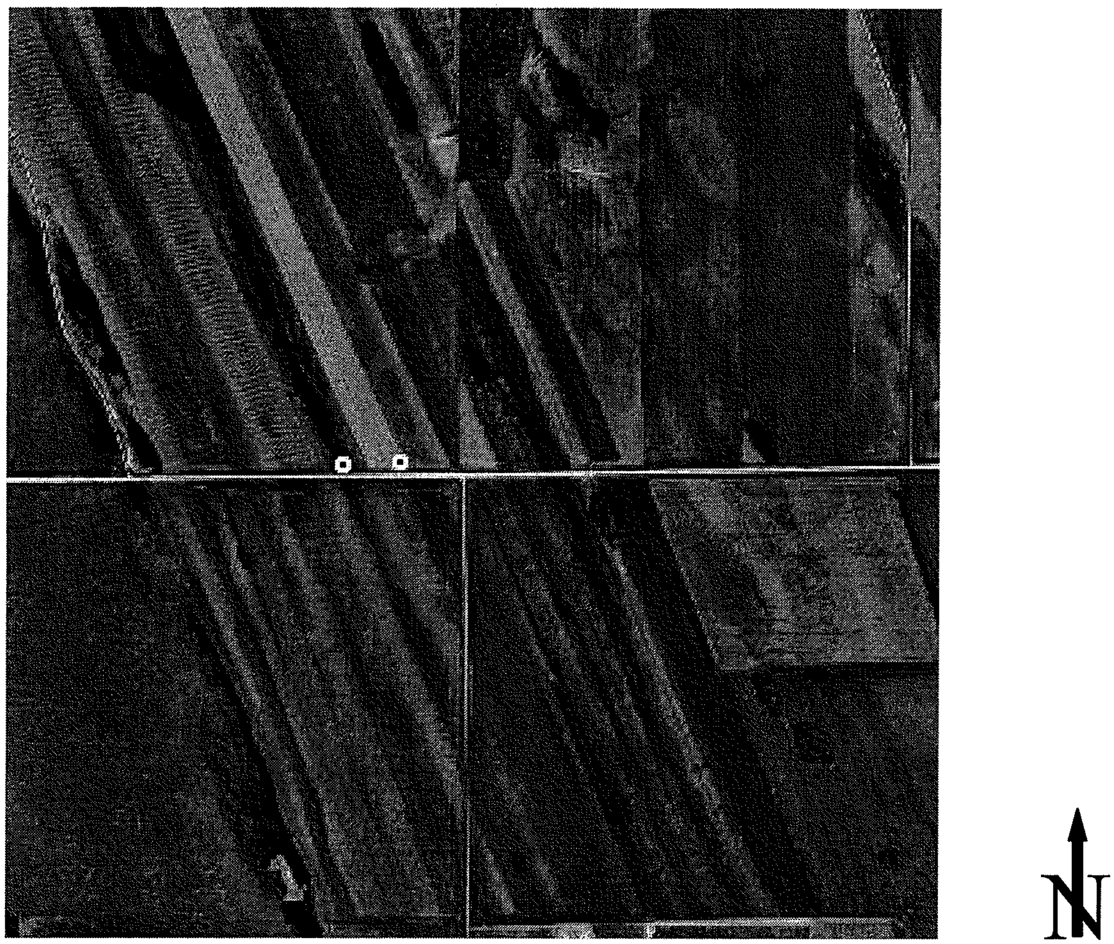


Figure 6-11. Aerial photograph showing the start and end points (white dots with black centres; right central part of photo) of GPR line 'LINE06a', shown in Figures 6-12 and 6-13. Field of view is about 1 mile by 1 mile.

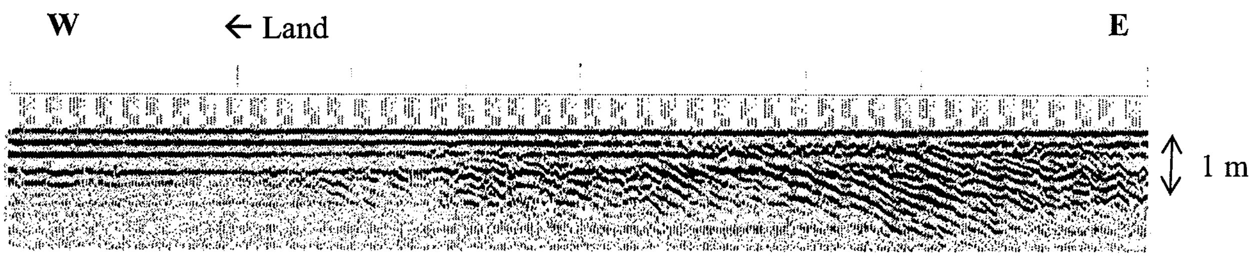


Figure 6-12. GPR line 'LINE 6a'; 250 MHz. Raw response. Total length is 100 m. This line is a small portion of 'LINE6' (between 450 m and 550 m). These shoreline features are of the Norcross stage. Profile has not been topographically corrected, because survey was done in the roadside ditch, with little natural relief.

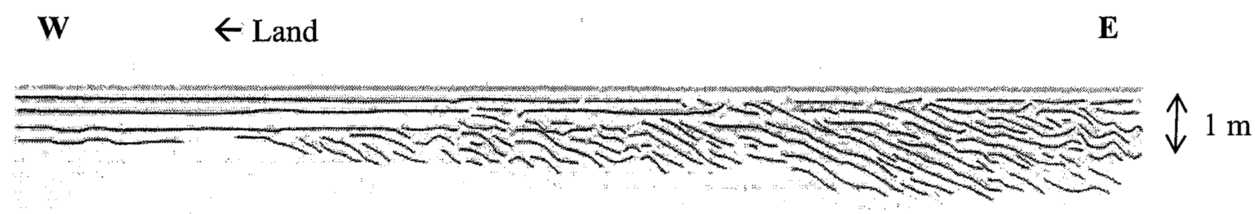


Figure 6-13. GPR line 'LINE 6a'; 250 MHz. Interpreted bedding contacts are drawn over the raw response seen in Figure 6-12. Total length is 100 m.

The dominant reflectors in Figure 6-13 are lakeward-dipping reflectors, particularly in the eastern part of the line, probably representing extensive swash-backwash sedimentation in the nearshore. In the western part of the line, the lakeward-dipping reflectors are mostly confined to the lower part of the profile. Horizontal parallel reflectors occur atop and landward of lakeward-dipping reflectors. Some landward-dipping reflectors occur in the eastern part of the profile, however these are mainly very short and connected to longer, lakeward-dipping reflectors. Other than line LINE06a & b, and two lines parallel to a beach ridge (LINE07, MAN11), the other lines at the Gerry's Road site were not processed.

6.3.3.4 Railway Field (MAN14)

The Railway Field site is located in a small clearing at the intersection of two gravel section roads, at the SW corner of Section 27, Township 5, Range 7W (see Fig. 6-1); the coordinates of GPR line MAN14 (the only line run at Railway Field) are shown in Table 6-1. MAN14 was run perpendicular to the strike of a Tintah beach ridge. Figure 6-14 shows the position of MAN14; the raw response is shown in Figure 6-15; Figure 6-16 shows the interpreted reflector geometries drawn on over the raw response.

Figure 6-14. Aerial photograph showing the start and end points (white dots with black centres; lower left part of photo) of GPR line 'MAN14', shown in Figures 6-15, and 6-16. Field of view is about 0.25 miles by 0.25 miles.

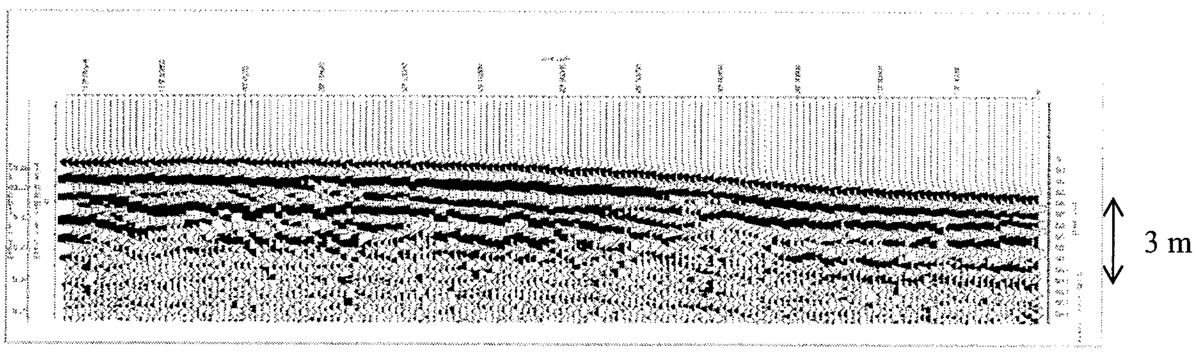


Figure 6-15. GPR line 'MAN14'; 100 MHz. Raw response. Total length is 122 m.

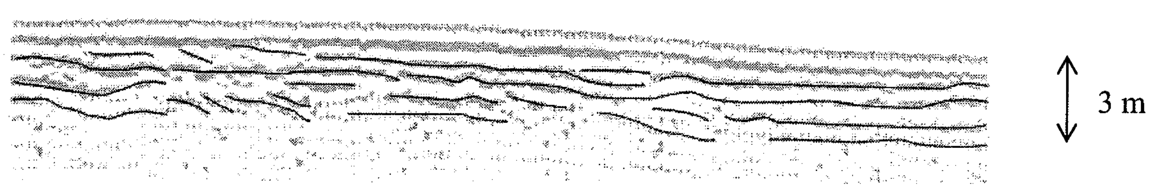


Figure 6-16. GPR line 'MAN14'; 100 MHz. interpreted bedding contacts are drawn over the raw response seen in Figure 6-15. Total length is 122 m.

This line consists of parallel nearly horizontal reflectors in the northeastern part and gently lakeward-dipping reflectors, about parallel to the ground surface, in the southwestern and in the lower central parts of the line, which seem to have horizontal reflectors overlying them. These reflectors probably represent sedimentation along the shoreface.

6.3.3.5 Mal Road (MAN17)

Mal Road is located along a gravel section road (between Sections 14 and 23 of Township 5, Range 7W; see Fig. 6-1) on the flat area between the Tintah and Campbell scarps; the coordinates of GPR lines run at Mal Road are shown in Table 6-1. Figure 6-17 shows the position of GPR line 'MAN17', discussed below, in aerial view. A very thick (~ 24 m) package of quartz sand overlying till was encountered by augering about 660 m to the east of the eastern end of this GPR line (auger site KMAg17, see Appendix 2). Another auger (KMAg16) about 2 km to the west of KMAg17 did not encounter any clean sand (only poorly sorted units of clay, diamicton, and gravel), indicating the sand body is localized to within a few kilometres at the most. Unfortunately GPR did not penetrate nearly deep enough (only about 3 m) to show the shape of this sand body, or its internal characteristics. The raw-response of MAN17 is shown in Figure 6-18; interpreted reflector geometries are shown in Figure 6-19.

Figure 6-17. Aerial photograph showing the start and end points (white dots with black centres; lower left part of photo) of GPR line 'MAN17', shown in Figures 6-18, and 6-19. Field of view is about 1 mile by 1 mile. The Upper Campbell scarp can be seen to the left of the gravel pit in the upper right corner of photo.

W ← Land E

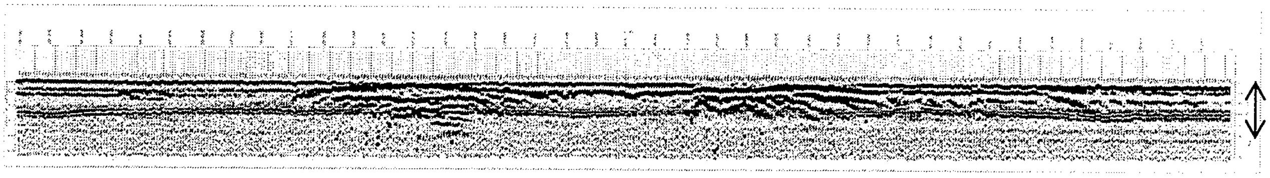


Figure 6-18. GPR line 'MAN17'; 100 MHz. Raw response. Total length is 247 m.

W ← Land E

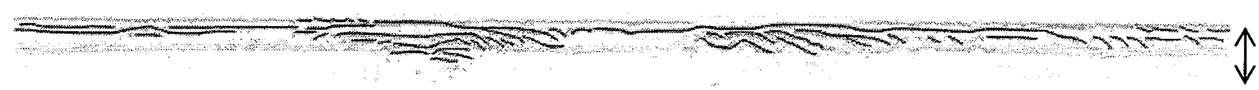


Figure 6-19. GPR line 'MAN17'; 100 MHz. Interpreted reflector geometries are drawn over the raw response seen in Figure 6-18. Total length is 247 m.

GPR line 'MAN18' only shows reflectors about 2 m deep, so it seems likely that although a larger sand body probably does underlie this GPR line (which was dated at nearly 35 ^{14}C ka and likely predates any shoreline sediments in the area; see Section 4.2.4), the upper few metres probably have been reworked by shoreline processes. Interestingly this area is a flat region with little geomorphic evidence of beach development; it is about 25 m below the Tintah scarp, and may have resulted from the bevelling of subaqueous bars of the Tintah stage. Figure 6-19 shows two groups of dipping reflectors (one that occupies most of the eastern part of the profile and one that occupies a smaller section of the western part of the profile); separated by horizontal parallel reflectors. The reflectors at the peaks of the ridges are about horizontal, and become gently dipping along the sides of the ridges (lakeward in both cases, as well as landward in the western ridge).

6.3.3.6 Quarry Site (MAN23 and LINE14)

The Quarry site is located in a large gravel pit about 9 miles east, and 4 miles south of the town of Treherne in Section 9, Township 7, Range 8W (see Fig. 6-1); the coordinates of the GPR lines at this site are given in Table 6-1. Figure 6-20, shows the position of line 'MAN23', discussed below, in aerial view. Line 'MAN23' was run perpendicular to the strike of several Herman beach ridges; raw-response is shown in Figure 6-21; interpreted reflector geometries are shown in Figure 6-22.

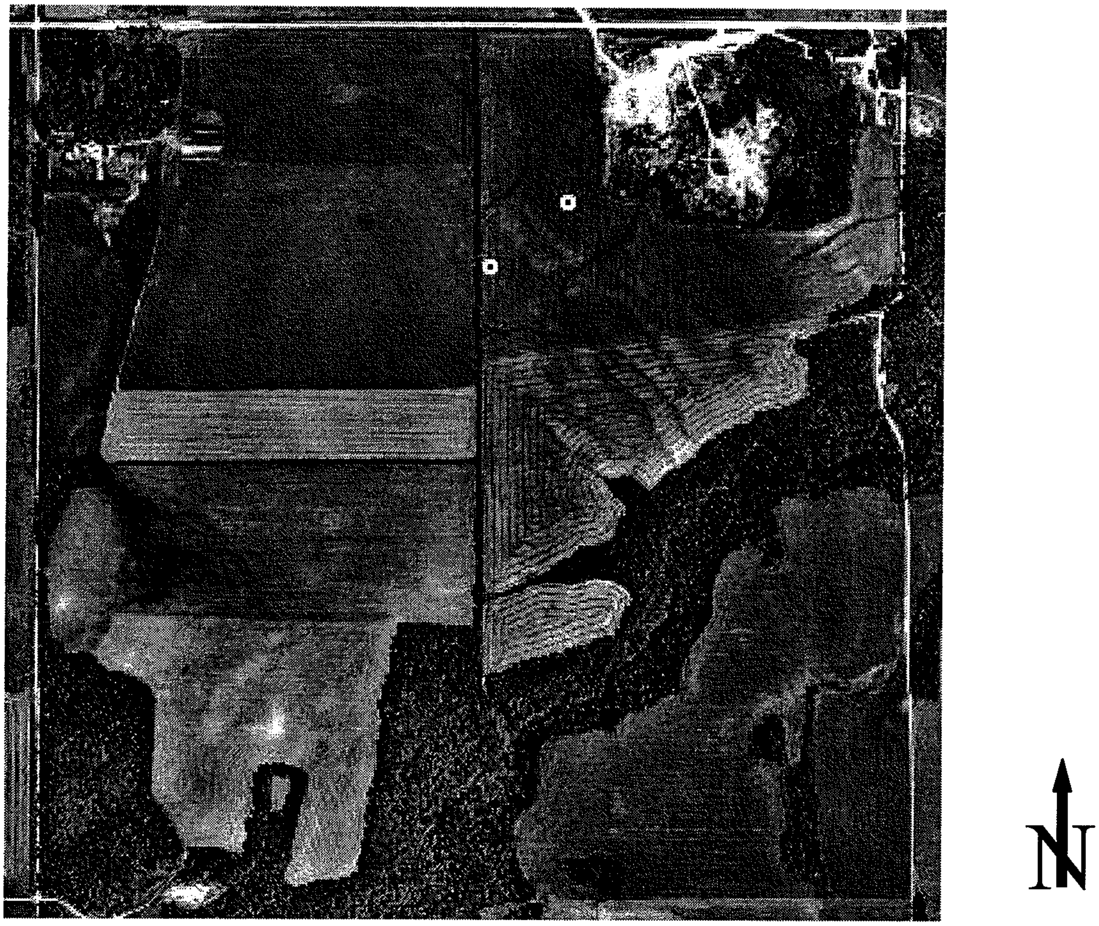


Figure 6-20. Aerial photograph showing the start and end points (white dots with black centres; upper right part of photo) of GPR line 'MAN23', shown in Figures 6-21, and 6-22. Field of view is about 1 mile by 1 mile. Parallel tonal contrasts represent beach ridges.

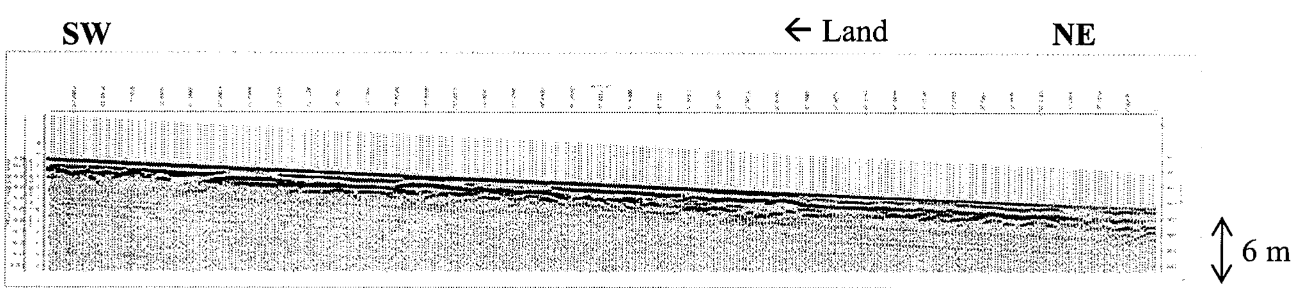


Figure 6-21. GPR line 'MAN23'; 100 MHz. Raw response. Total length is 192 m. all beaches are Herman stage.

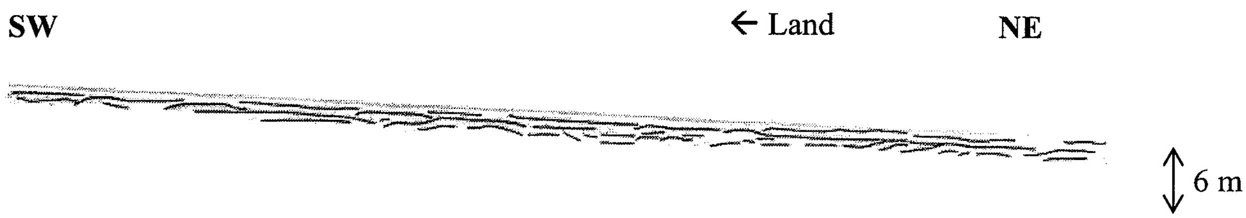


Figure 6-22. GPR line 'MAN23'; 100 MHz. Interpreted reflector geometries are drawn over the raw response seen in Figure 6-21. Total length is 192 m.

Note the gently landward-dipping reflectors in the SW part of Figure 6-22 that are overlain by parallel horizontal reflectors (which may be the soil profile). In the upper part of Figure 6-21, the reflectors are mostly parallel and horizontal, and are probably strata from swash-backwash sedimentation in the nearshore. In the NE part of the line, some short landward-dipping reflectors occur and may represent backbeach sedimentation.

Other lines run at the Quarry site are interpreted to show ice-marginal glaciofluvial sediments that predate beach development (McMillan, 2005); observations in the gravel pit have shown these sediments are at least 10 m thick. Figure 6-23 shows the position of one of these lines (LINE14) running parallel to the strike of beaches in the area (which can be seen in Figures 6-19 and 6-22 to be developed over the glaciofluvial sediments being excavated in the gravel pit). The raw response of LINE14 is shown in Figure 6-23; Figure 6-24 shows this line with interpreted reflection geometries drawn over the raw response.

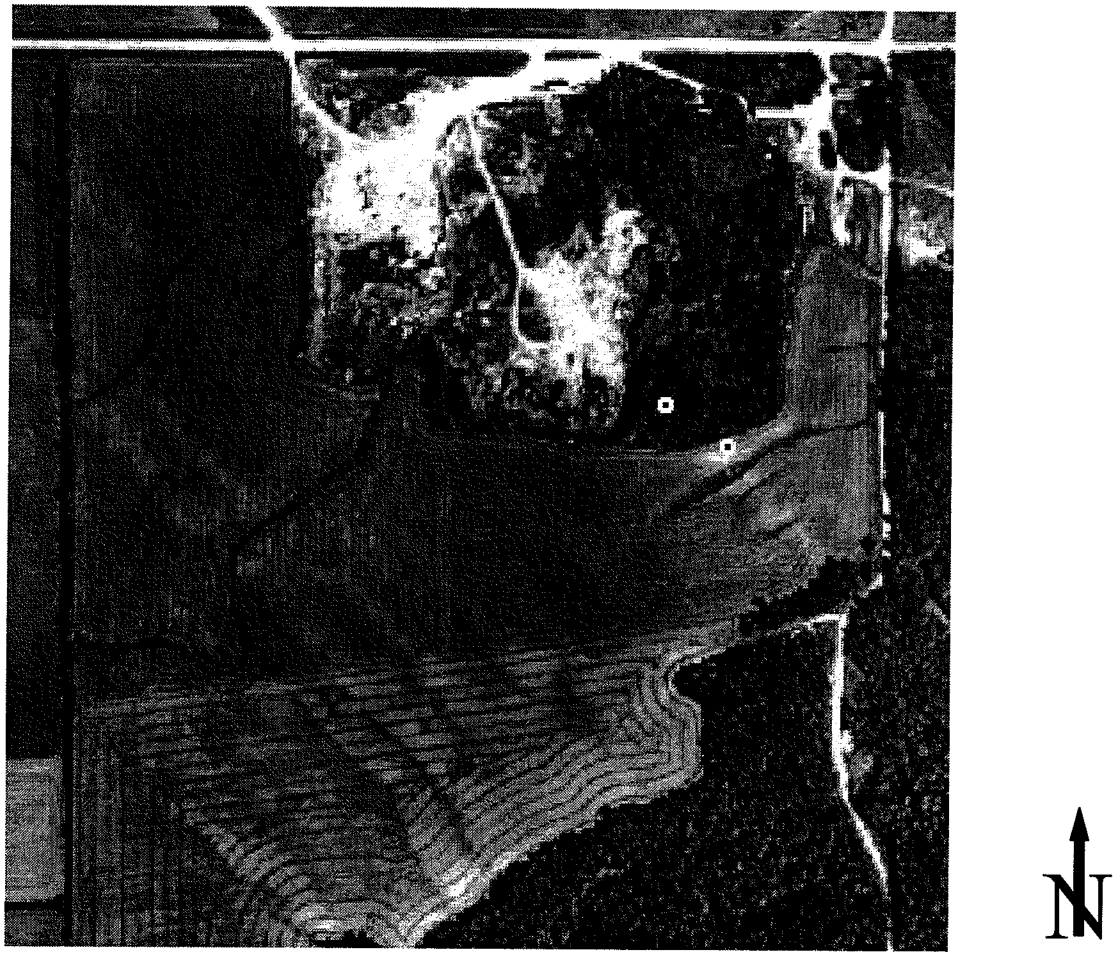


Figure 6-23. Aerial photograph showing the start and end points (white dots with black centres; right central part of photo) of GPR line 'LINE14', shown in Figures 6-24, and 6-25. Field of view is about 0.25 miles by 0.25 miles. The gravel pit has changed since this photo was taken in 1998; this line was run within the modern active pit

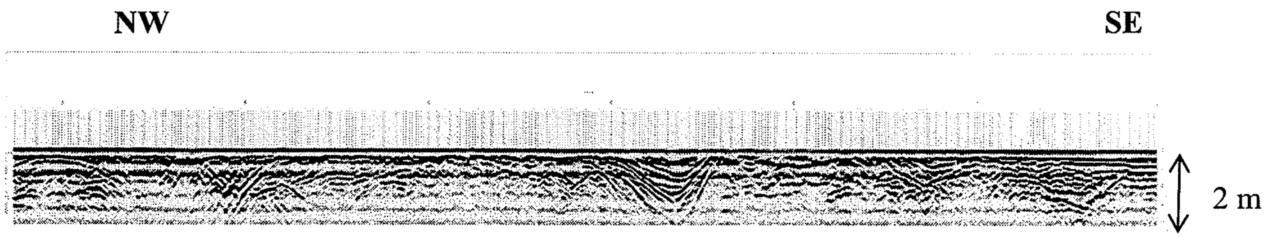


Figure 6-24. GPR line 'LINE14'; 250 MHz. Raw-response. Total length is 63 m.

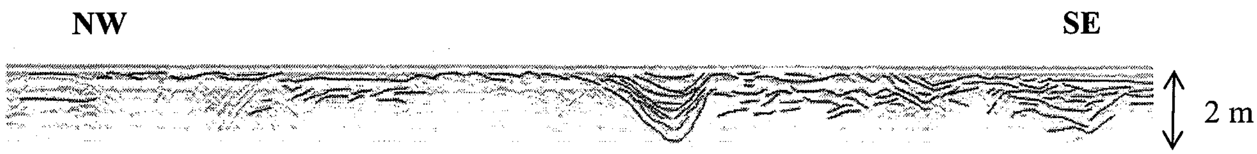


Figure 6-25. GPR line 'LINE14'; 250 MHz. Interpreted reflector geometries are drawn over the raw response seen in Figure 6-24. Total length is 63 m.

This GPR line shows many reflectors with no consistent orientations. A large cut and fill structure in the central part is very prominent. There are one or two similar, although not as well-developed structures in the southeast part. This GPR line is different from the other GPR lines run parallel to beach ridges, which generally show horizontal parallel reflectors, with little variation (see MAN11, LINE7, and MAN32 in Appendix 3; MAN32 is discussed in Section 6.3.3.2). The GPR lines done at this site, as well as the overall thickness and sedimentology of these sediments (see McMillan, 2005), indicate that the thick accumulation of sediments are not part of the Agassiz shoreline complex. Rather, they are interpreted to be glaciofluvial deposits, possibly deposited between the glacier and the Manitoba Escarpment, that predate beach sedimentation in the area. Subsequently, these deposits may have been bevelled by wave action associated with the formation of the nearby Herman beaches.

6.3.3.7 Treherne (MAN18)

The Treherne Site is located about two miles east of the town of Treherne, along the section road between Section 32, Township 7, Range 9W, and Section 5, Township 8, Range 9W (see Fig. 6-1); the coordinates of the GPR lines at this site are given in Table 6-1. Figure 6-26 shows the positions of the start and end points of MAN18, which crosses beaches of the Herman stage. Raw-response is of MAN18 shown in Figure 6-27 and interpreted reflector geometries are shown in Figure 6-28.

Figure 6-26. Aerial photograph showing the start and end points (white dots with black centres; right central part of photo) of GPR line 'MAN18', shown in Figures 6-26, and 6-27. Field of view is about 1 mile by 1 mile.

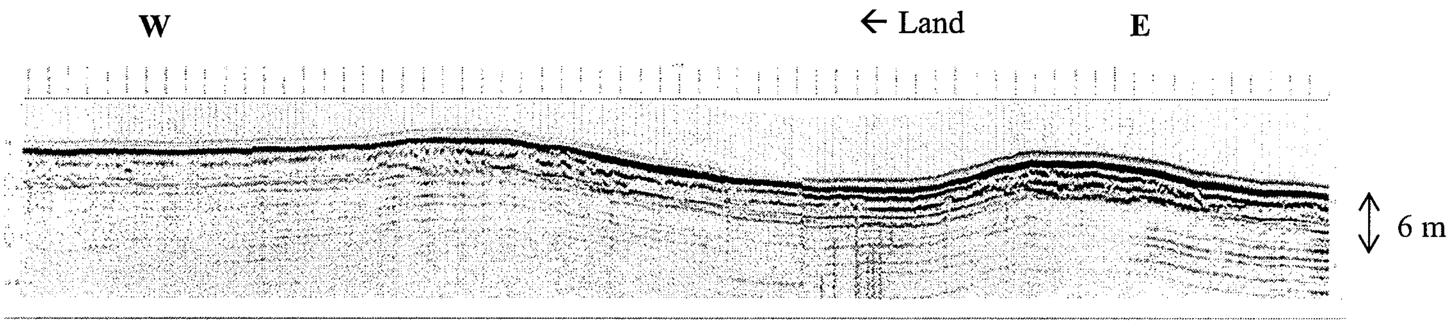


Figure 6-27. GPR line 'MAN18'; 100 MHz. Raw-response. Total length is 662 m.

Figure 6-28. GPR line 'MAN18'; 100 MHz. Interpreted reflector geometries are drawn over the raw response seen in Figure 6-27. Total length is 662 m.

Note the gentle lakeward-dipping reflectors occurring lakeward of the ridges (about parallel to the ground surface). In the eastern ridge, these reflectors are fairly long and continuous. However, along the shoreface of the western ridge there are some steeper reflectors; a few short lakeward-dipping reflectors can be seen landward of the western ridge. On the landward side of the ridges, reflectors that are parallel to each other and to the ground surface are prominent. These reflectors indicate shoreface swash-backwash sedimentation.

CHAPTER 7:

STRATIGRAPHY, SEDIMENTS, AND GEOMORPHOLOGY OF AGASSIZ SHORLINES

7.1 Introduction

This chapter discusses the sediments and geomorphology of beaches and scarps in the study area. Several sources of data were used to examine the sediments and geomorphology of Agassiz shoreline features. Power augering was done for this study in a few selected areas. Water well data were available for all townships, as were provincial soils maps; in some townships government aggregate reports were available. Provincial water-well data as well as descriptions of stratigraphies from new auger holes are included in Appendix 2. An interpretation of Lake Agassiz history based on the data discussed in this chapter is given in Chapter 8.

As noted in Chapter 4, each named lake stage (e.g., Herman) contains several beach ridges (and possibly scarps). Lake stages will not be treated as discrete elevations, but as elevationally constrained areas (keeping in mind the effects of differential isostatic rebound). Each sub-area is shown in map view, labelled with letters to approximately indicate named beach sets; these letters are the first letters of each lake stage (pH = pre-Herman, H = Herman, N = Norcross, T = Tintah, and C = Campbell).

Because of the large study area of this thesis, the mapped area has been divided into four sub-areas (shown in Fig. 7-1). These sub-areas are based on large-scale plan-view morphologies of shoreline features, and named after cultural features in those areas. The sub-areas and bases for sub-division are as follows:

- *Sub-area 1) Canada – USA border*: This is the southernmost extent of the study area, and is differentiated from sub-area 2 to the north because the beach sets in this area are more widely spaced and, in general, poorly distinguished from one another than in sub-area 2.
- *Sub-area 2) Morden – Miami*: This sub-area is differentiated from sub-area 1 to the south because the beach sets in this sub-area are better defined than in sub-area 1; it is differentiated from sub-area 3, to the northwest, because it mainly contains beaches, whereas sub-area 3 is dominated by scarps.
- *Sub-area 3) Tobacco Creek – Snow Valley*: This sub-area is dominated by scarps; it is differentiated from the sub-area 2 to its south and sub-area 4 to its north by the fact that those sub-areas contain mainly beaches.
- *Sub-area 4) Treherne*: This sub-area is the northernmost extent of the study area; it is differentiated from sub-area 3 to its south because it contains mainly beaches, whereas sub-area 3 contains mainly scarps.

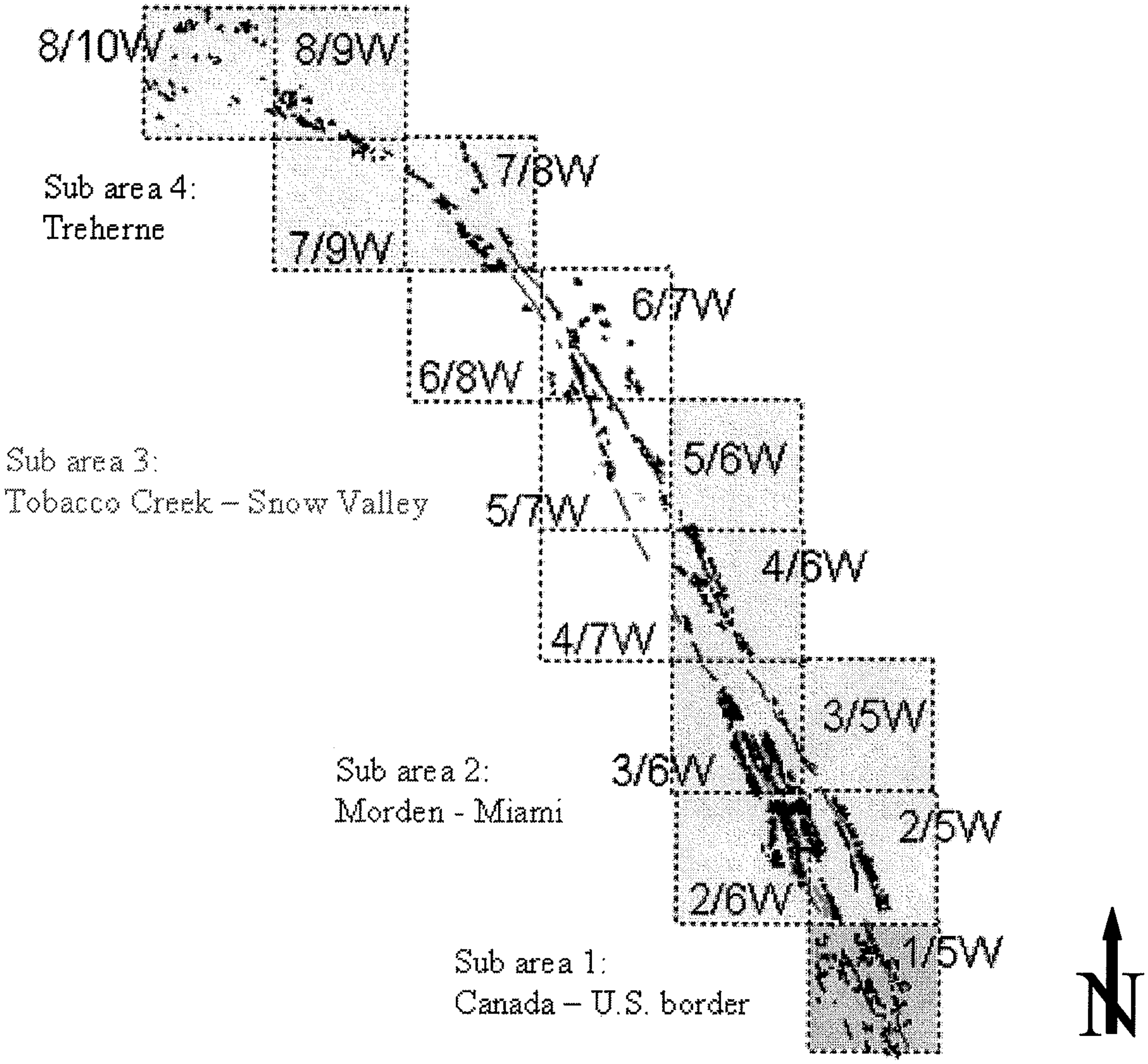


Figure 7-1. Sub-areas of the study area. Numbers (e.g., 1/5W) refer to townships (e.g., Township 1, Range 5W). Scale is ~ 1 : 508,000.

7.2 Sediments, stratigraphy, and morphology of the sub-areas

7.2.1 Sub-area 1: Canada – USA Border

This sub-area consists of Sections in Township 1, Range 5W (see Figs. 7-1 and 7-2). GPR and power-augering were not done. The Manitoba aggregate report for the RM of Stanley (Young, 1993) includes this area.

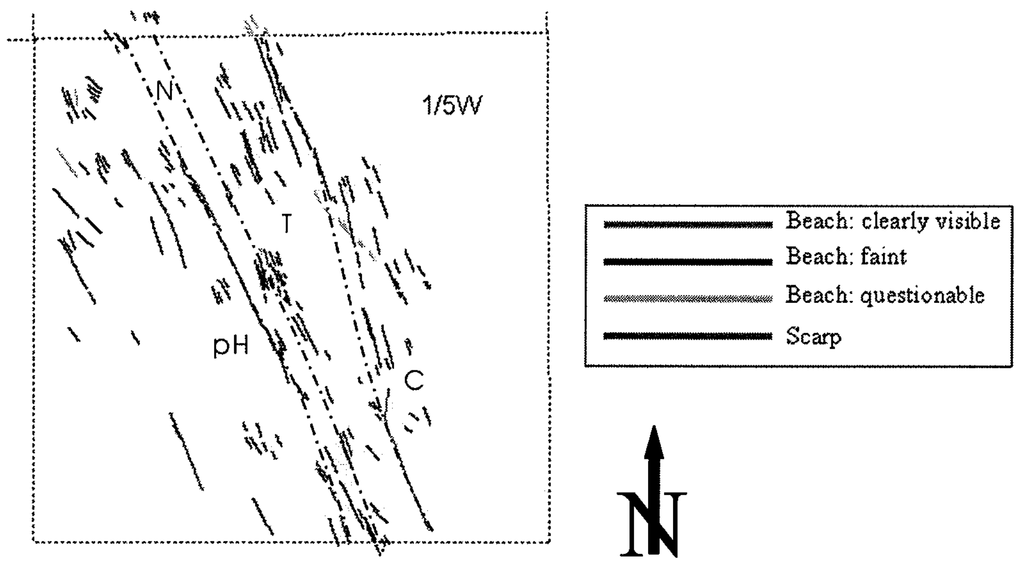


Figure 7-2. Map view of Canada – USA border sub-area. Letters refer to lake stages: pH – pre-Herman, N – Norcross, T – Tintah, C – Campbell. Dash-dot black lines identify approximate boundaries between beach zones.

This sub-area consists of beaches and scarps, striking NNW-SSE; all beach ridges are faint on aerial photos, topographically low relief (< 2 m), and not distinguished individually on soils maps (Michalyna et al., 1988). Based mainly on subtle differences in photo tone and projected elevations for Lake Agassiz beaches, pre-Herman, Norcross, Tintah, and Campbell stages are present. Water-well records indicate that near-surface sand and gravel deposits are about 1 – 2.7 m thick (see Appendix 2); scarps are about 18 to 50 m high. Most beach ridges are continuous for less than a km; scarps are less than one km to several km in length. Boundaries between different named beach groups (e.g., Norcross, Tintah) are not well defined in plan view. This area has been mapped as mostly till by Matile and Keller (2004), perhaps because shoreline beach accumulations are quite thin, narrow, and faintly shown on air photos. Water well and aggregate reports make numerous references to clay underlying sand and gravel, but this may refer to till, shale or clay, since these clayey materials may all be treated similarly in engineering applications.

Pre-Herman beaches were identified well above the upper elevation of the Herman beach, extrapolated from the southern part of sub-area 2, about four miles to the north; these beaches occur between 405 – 447 m in this sub-area. No stratigraphic information is available for these beaches, but they probably consist of sand and gravel, like most of the other beaches in the study area. Herman beaches are absent in this area, probably because they have been removed by wave action related to the formation of the Norcross beach; the elevations where the Herman beaches should occur are along the slope of the Norcross scarp (see Fig. 7-3). The Norcross stage is mainly represented by a scarp in this sub-area. Norcross beaches (343 – 353 m) in this sub-area consist of 1 to 4 m of silty fine sand- to gravel-sized sediments (Young, 1993). Tintah beaches are low narrow ridges that occur between about 333 and 343 m in this sub-area. Generally, water well and aggregate report data indicate the Tintah beaches consist of about 0.6 to 2 m of sand and gravel (Young, 1993). The Upper and Lower Campbell beaches (308 – 333 m) cannot easily be distinguished from one another in this sub-area. The Campbell beach set consists of beaches and a short Upper Campbell scarp in this sub-area; the scarp cuts obliquely across older (higher elevation) beaches (see Fig. 7-2). Water well data and aggregate reports indicate Campbell beaches below the scarp consist of about 1 to 5 m of sand and gravel. Figure 7-3 shows a schematic WSW – ENE (perpendicular to beaches) cross section of this area.

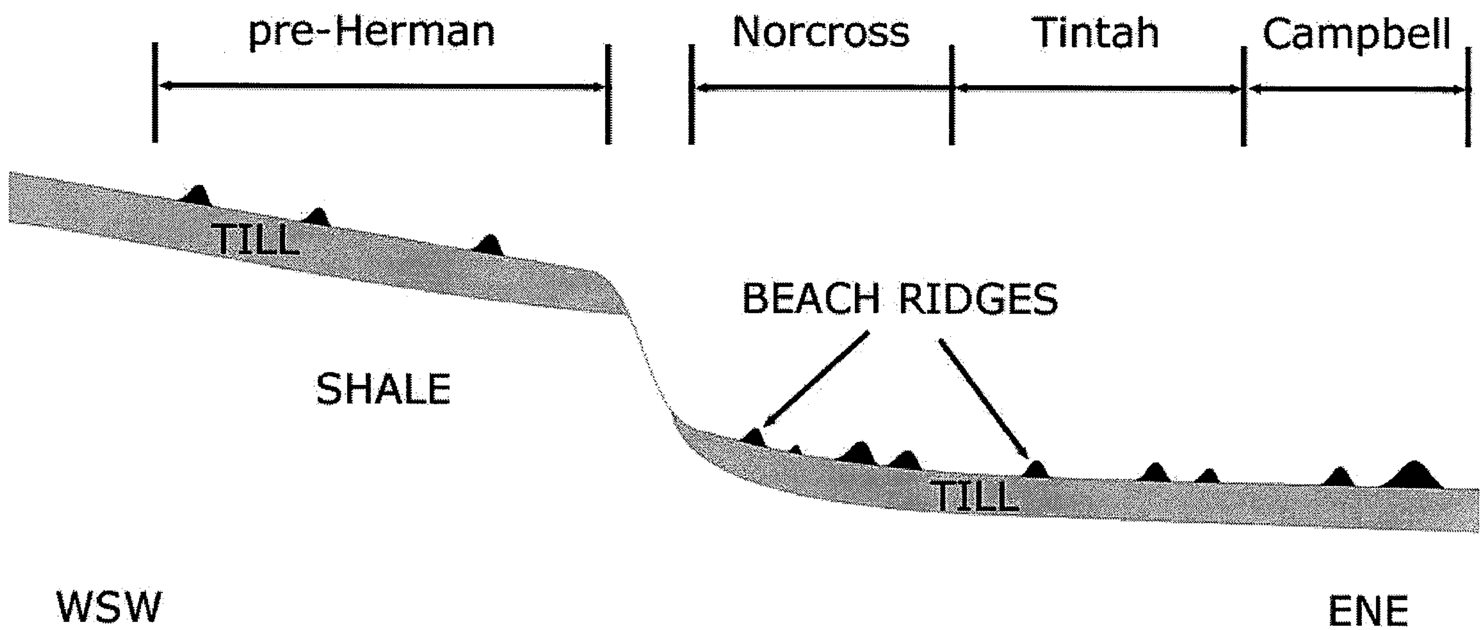


Figure 7-3. Schematic WSW-ENE cross section (perpendicular to beaches) of sub-area 1. Note that the Upper Campbell and Lower Campbell beaches are not easily distinguished in this sub-area, and are grouped together; also note that an Upper Campbell scarp occurs in part of this sub-area (not shown on this diagram). Not to scale.

7.2.2 Sub-area 2: Morden – Miami

This sub-area consists of sections in Township 2, Ranges 5W & 6W; Township 3, Ranges 5W & 6W; Township 4, Range 6W; and Township 5, Range 6W (see Figs. 7-1 and 7-4), and is perhaps the most interesting in the study area because of its well defined beaches, and clear separation between named beach sets; it is also the sub-area with the most data collected for this project. This sub-area contains data from the aggregate report for the RM of Stanley (Young, 1993), auger holes, and GPR lines.

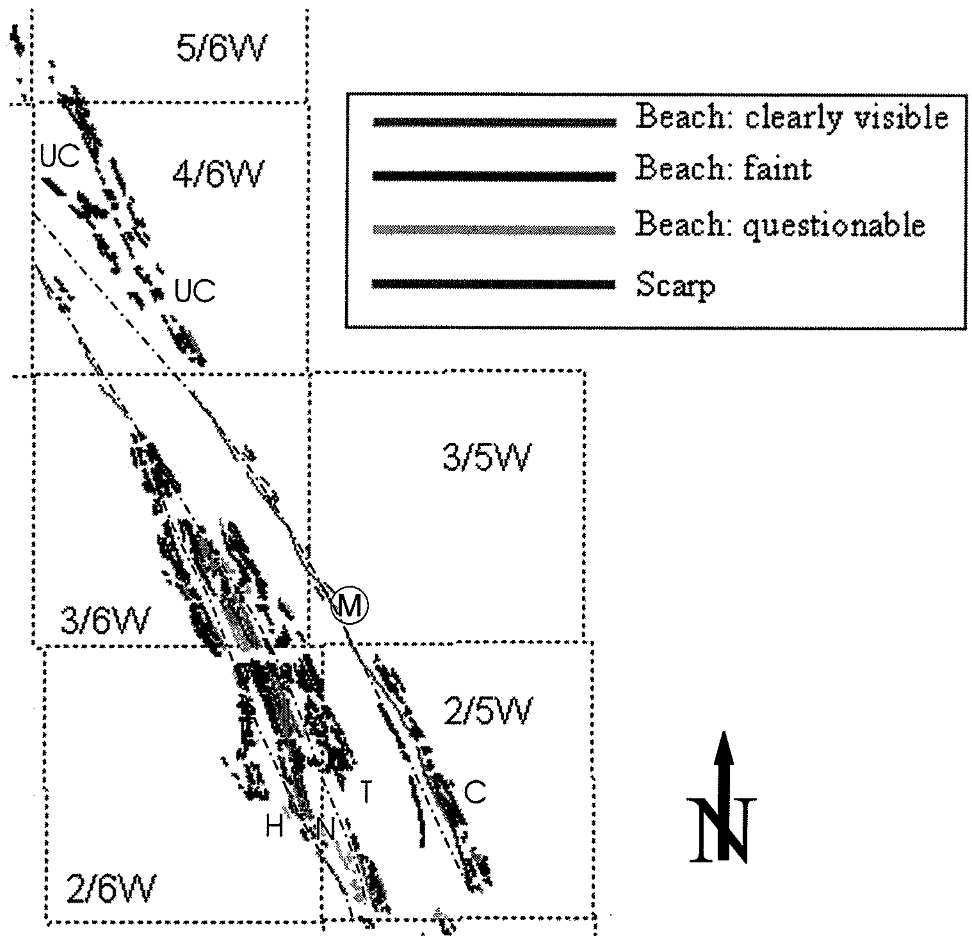


Figure 7-4. Map view of Morden-Miami sub-area. Letters refer to named lake stages: H – Herman, N – Norcross, T – Tintah, UC – Upper Campbell, C - Campbell (refers to both the Upper and Lower Campbell, where these beaches are not easily distinguished). Dash-dot black lines identify approximate boundaries between beach zones. Circled 'M' indicates town of Morden.

Most beach ridges in this area are mapped as 'faint', however many of the ridges are mapped as clear (more than in any other sub-area). This sub-area consists mostly of beaches, but Norcross, Tintah, Upper Campbell, and Lower Campbell scarps are also present. By far the most prominent scarp in this sub-area is the Upper Campbell. Generally the Herman, Norcross, and Tintah beach sets are fairly close together (1 km or less); the Tintah and Campbell beaches are 1.5 to 3 km apart.

The non-shoreline (pre-beach) Quaternary sediments in this sub area have previously been mapped as deltaic / offshore sediments (Elson, 1959), which Matile and Keller (2004) later refined by mapping as glaciofluvial / subaqueous outwash deposits. Soils maps from this sub-area (Michalyna et al., 1988) also describe non-beach soils as having been formed in glaciofluvial deposits. The poorly sorted sand and gravel deposits not associated with individual beach ridges in this sub-area could be shoreline sediments, however (J. Teller, pers. comm., 2005). Fieldwork (hand augering and digging with shovels) for this study revealed concentrations of cobbles and boulders in many of the low-lying areas between beach ridges of the Herman and Norcross stages; in other areas, < 1 m of clayey to sandy silt was found to occur between beach ridges of the Herman, Norcross, and Tintah stages, in places atop gravel-lags. Gravel lags probably occur between Tintah beaches (Elson, 1959), but were not observed in this study. These thin units of clayey to sandy silt may have been deposited in backbeach lagoons or by storm overwash.

The uppermost beaches in this sub-area have been defined by Upham (1895) as being Herman stage (~ 373 – 383 m). These beaches consist of sand and gravel, and are underlain by till. Elson (1959) and Michalyna et al. (1988) indicate a lag of wave-worked boulders, gravel, and sand landward of the Herman beaches in this sub-area; this may be equivalent to the pre-Herman beaches mapped in sub-area 1. Individual Herman beaches range from about 2.5 to 4 m in thickness (before till is encountered). Herman beach sediments generally consist of poorly sorted sand, usually containing silt, granules, and pebbles. Augering has revealed that individual beaches do not consist of a single massive unit, but of several units ranging in thickness from about 0.1 m to 2 m; GPR profiles of Herman beaches done at the Paul's Road site (see Figs. 6-6 and 6-7, and Appendix 3) generally show bedding about parallel to the ground surface, and short landward dipping beds in places (see Fig. 6-7). Some sand units are well sorted, but no well sorted units of any other grain size were found. A backhoe test pit dug between two Herman beach ridges was found by Young (1993) to be 1 m of silty sand over till (exposure # BB256, Young, 1993, p. 25).

Between the Herman and Norcross beach sets, the soils are mainly Carvey and Capell series (Michalyna et al., 1988), which are developed in (what are described as) moderately to rapidly permeable silty and sandy lacustrine sediments over sandy glaciofluvial deposits; the lacustrine veneer is 25 – 100 cm thick.

Sediments in the Norcross beaches in this sub-area occur between about 360 – 368 m, and are similar to those in the Herman beaches – poorly sorted gravelly sand to sandy coarse gravel. Units 0.3 – 1.5 m in thickness make up beach ridges that are between 2.4 and 3.3 m thick. Like the Herman beaches, sediments are generally poorly sorted sand and gravel, with some clean sand units. A shallow (< 2 m) pit between Norcross beaches (perhaps between the Norcross and Tintah beach sets) was noted near Morden (SW corner of the SE quadrant of sec. 11, Township. 3, Range 6W, 356 m ASL) containing extremely high concentrations (hundreds) of boulders; most boulders were igneous rocks, however abundant carbonate cobbles were observed. The Norcross and Tintah beach sets are not easily distinguished in this sub-area. Between the Norcross and Tintah beaches, the soils are mapped as Croyon and Capell series (Michalyna et al., 1988), which are, like the soils between the Herman and Norcross beaches, developed in (what are described as) moderately to rapidly permeable silty sandy lacustrine sediments overlying 25 – 100 cm of sandy glaciofluvial deposits (which may actually be shoreline deposits).

Tintah beaches occur between ~343 – 353 in this sub-area, and were found by augering to typically be about 3 m thick, and consist of 0.3 – 0.9 m thick units of poorly sorted to very poorly sorted sand, with clay- to gravel-sized sediments present in parts. Between the Tintah and Campbell beach sets, the soils are mostly Roseisle series, with Guerra, Glencross, and Nanton series present as well. All of these soils are supposedly developed in lacustrine sediments (clay to fine sand; 25 – 100 cm thick) overlying water worked till, typically with a thin (<10 cm) gravel lag at the contact between lacustrine sediments and till (Michalyna et al., 1988; Elson, 1959). Auger holes (KMAg 7, 8, 9, and 15; see Appendix 2) revealed diamicton between the Tintah and Campbell beach sets, with some sandier beds (0.2 – 0.3 m thick), but no apparent gravel lag. Short (~ 1 m) hand-auger holes between these beach sets yielded silt underlain by gravelly silt.

The distinction between the Upper and Lower Campbell levels (~318 and 310 m elevation, respectively, in this sub-area) is poor throughout much of the study area, however in some places, the Upper Campbell level is represented by a large scarp (about 9 m high), and the Lower Campbell level is represented by a smaller scarp (about 3 m high; this Lower Campbell scarp is not present throughout the entire Morden-Miami sub-area; see Fig 7-4). These scarps are separated from one another by a flat area about 350 m wide. The flat-area between the Upper and Lower Campbell scarps was augered at one site (auger site KMAg10; see Appendix 2), and found to contain about 2 m of pebbly to clean sand over till. Water well records indicate that the Campbell beaches consist of sand and gravel, overlying till. Figure 7-5 shows a schematic cross section, perpendicular to beaches, of sub-area 2.

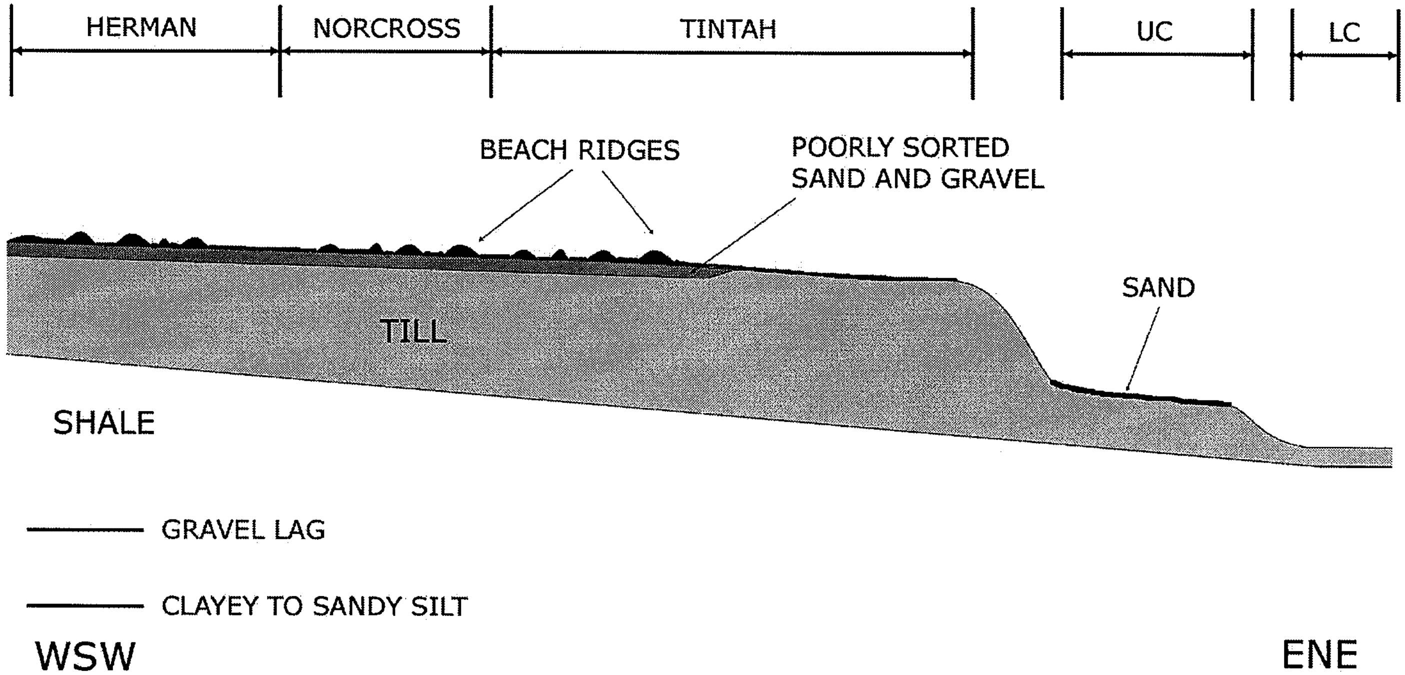


Figure 7-5. WSW – ENE schematic cross section of sub-area 2. UC – Upper Campbell, LC – Lower Campbell. Not to scale.

7.2.4 Sub-area 3: Tobacco Creek – Snow Valley

This sub-area includes sections in Townships 4, 5, & 6, Range 7W, and Township 6, Range 8W (see Figs. 7-2 and 7-6). This sub-area includes auger sites, GPR lines, and aggregate report data from the RM of Lorne (Young, 1991).

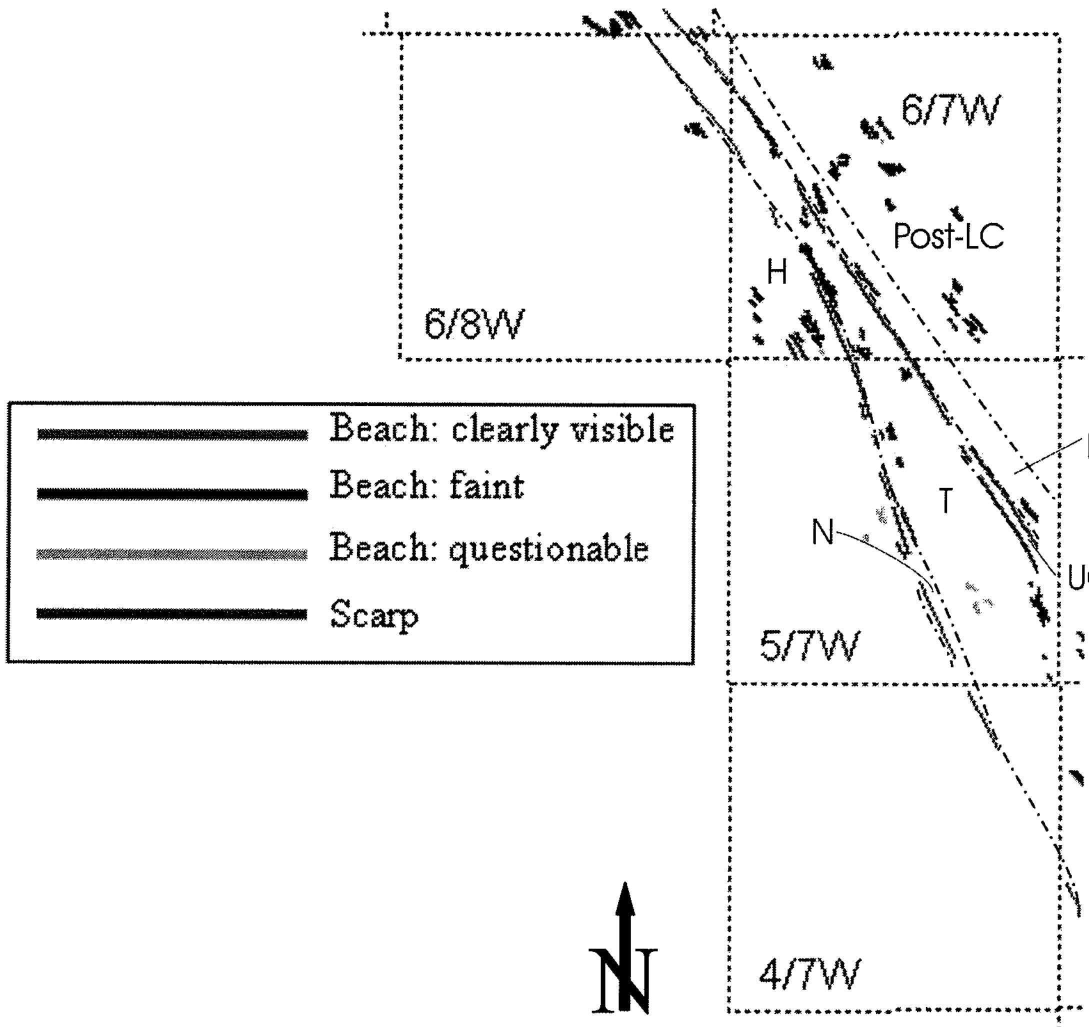


Figure 7-6. Map view of Tobacco Creek – Snow Valley sub-area. Letters refer to named lake stages: H – Herman, T – Tintah, LC – Lower Campbell, Post-LC – post-Lower Campbell; also see Figure 7-8 for detailed (interpreted) lake stage names of the scarps. Dash-dot black lines identify approximate boundaries between beach zones.

Generally, Lake Agassiz shorelines are represented by scarps in this sub-area, rather than beach ridges. There are far more scarps in this sub-area than in any of the other sub-areas. Scarp elevations are only relevant at the base of the scarp; some scarps that appear to be corelatable based on the elevations of their crests may not be. I have attempted to correlate the scarps on the basis of their basal elevations; this tentative correlation is shown in Figure 7-8. It should be noted that the Upper Campbell scarp may have coalesced with the Lower Campbell scarp in parts of this area. Based on this correlation, there appear to be scarps of the Norcross, Tintah, and Upper plus Lower Campbell stages present within this sub-area (as well as one short scarp that seems to be between the Tintah and Upper Campbell levels elevationally). The Norcross, Tintah, and Tintah-Campbell-intermediate scarps are quite close together (on the order of a few hundred metres), whereas the Tintah and Upper Campbell scarps are quite widely (but not uniformly) spaced about 1 – 3.5 km apart; where both exist, the Upper and Lower Campbell scarps are closely spaced as well (a few hundred metres apart).

Small patches of beaches are present throughout this sub-area. Beaches of the Herman, Tintah, and Campbell stages are present (post-Lower Campbell beaches have also been mapped in this area, although they are not part of the objectives of this thesis); no Norcross beaches seem to be present. Generally, beaches occur as short (a few km or less) ridges in small isolated groups.

Herman beaches (380 – 400 m) occur in a small area above the Tintah scarp in Township 6, Range 7W, and as a few short ridges above the Norcross scarp in Township 5, Range 7W (see Fig. 7-7). No stratigraphic information is available for these beaches, but they probably consist of sand and gravel like most of the other beaches in this study area.

Based on soils maps (Ellis and Shafer, 1943), surface sediments above the Norcross scarp (~ 375 m at its base) consist mainly of till; one auger hole above the Norcross scarp (but not through a Herman beach) went through about 2 m of pebbly sand over clay (KMAg18; see Appendix 2). A single auger hole drilled between the Tintah and Norcross scarps (not through a beach) went through about 0.75 m of very poorly sorted sandy gravel over clay (KMAg19; see Appendix 2). The soils between the Tintah and Norcross scarps are highly variable, however the most common soil type is Roseisle series (Michalyna et al., 1988; particularly near the Campbell scarp) which is described as a fine sandy to clayey soil developed on lacustrine and deltaic deposits 25 to 100 cm thick, with a gravelly lag base, overlying till (see Fig. 7-2).

The elevation of the base of the Tintah scarp is about 363 m in this sub-area. Soils maps show surface sediments in this area to be mainly nearshore sand and gravel with scattered areas of till (Ellis and Shafer, 1943); soils maps do not show individual beach ridges. Between the Tintah and Campbell scarps stratigraphy seems to be quite variable. Water well records indicate that sediments consist of up to 20 m of alternating units of sand and clay overlying till, which overlies shale.

Where the Upper Campbell and Lower Campbell scarps are discernable (basal elevations of ~ 320 and 315 m, respectively), the soil between them is predominantly Agassiz series (Michalyna et al., 1988), which is defined as a sandy soil developed on beach deposits, which may be nearshore shallow-water blanket accumulations.

Stratigraphy in this area is very complex, and data control from water well records is poor. Interestingly, there seems to be till in some areas (e.g., Township 6, Range 7W), but not in others (e.g., Township 5, Range 7W). This may reflect the true stratigraphy of the area, or it could be the result of poor data quality. Most likely, the subsurface stratigraphy reflects the bevelled deposits of Agassiz and pre-Agassiz events, which are now overlain by a thin veneer of nearshore sand related to Campbell or lower levels. No cross section for this sub-area is included because data are too limited and do not permit stratigraphy to be accurately known.

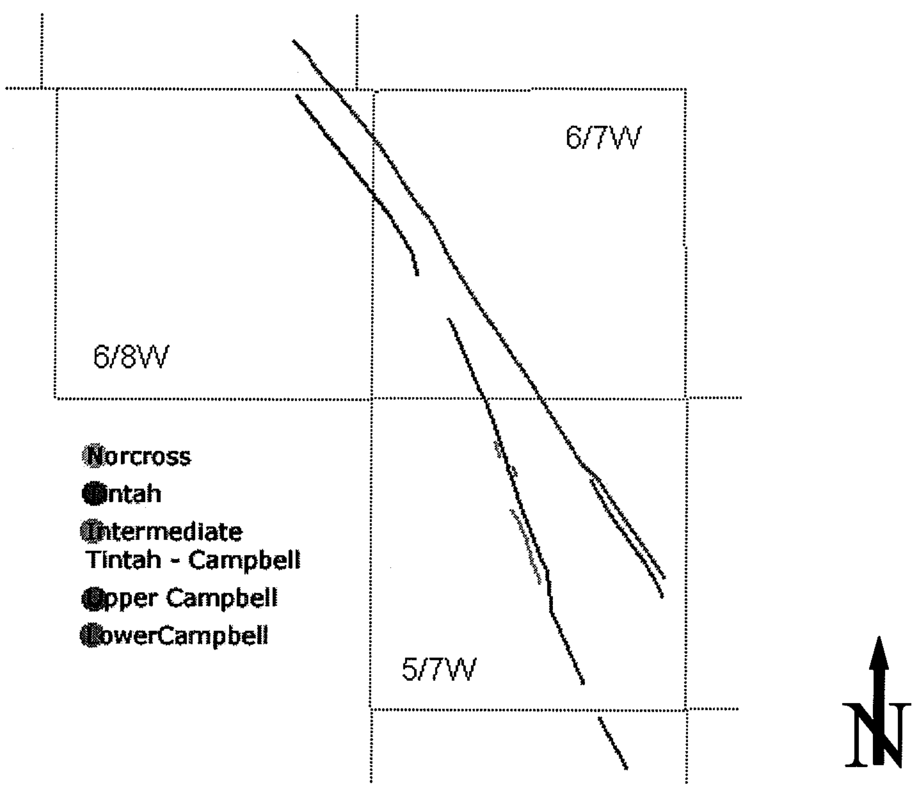


Figure 7-7. Apparent correlation of scarps within sub-area 3.

7.2.5 Sub-area 4: Treherne

This area consists of sections in Township 7, Ranges 8W & 9W & 10W, and Township, 8 Range 10W (see Figs. 7-2 and 7-11). This sub-area contains several auger sites, and aggregate report data from the RM of Lorne (Young, 1991).

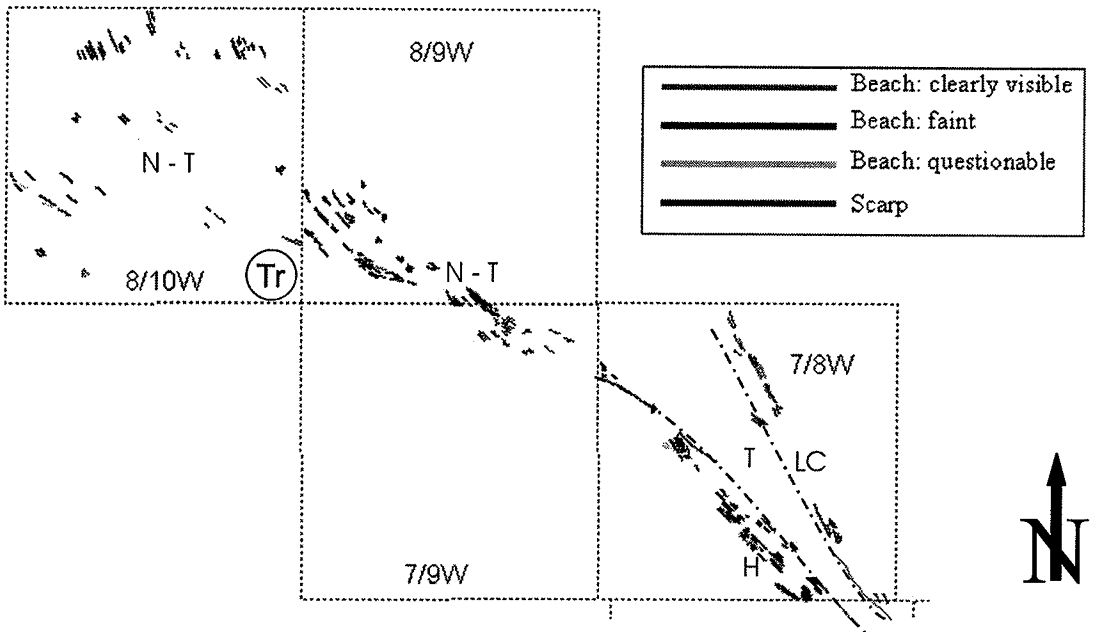


Figure 7-8. Map view of Treherne sub-area. Letters refer to named lake stages: H – Herman, N – Norcross, T – Tintah, LC – Lower Campbell. Dash-dot black lines identify approximate boundaries between beach zones. Circled 'Tr' indicates town of Treherne.

This sub-area contains mostly beaches that are indistinct on aerial photos, soils maps, and on the ground. They range from Herman to Lower Campbell. However, based on projected elevation for the Upper Campbell, no Upper Campbell beaches seem to occur in this sub-area, perhaps because of low available sediment supply. Overall, beach development is very localized, and individual beach ridges are short (less than 1 km long). Toward the northern part of the sub-area (Townships 8, Range 9W, and 8 Range

10W) beaches 'fan out' (see Fig. 7-8). These 'fanned out' beaches retain their NW-SE strike direction, and remain about parallel to one another.

Herman beaches (~379 – 388 m) were augered in the northern part of this sub-area (auger sites KMAg23 & KMAg24; see Appendix 2); auger holes do not correlate to mapped ridges, but were drilled on what appeared to be ridges on the ground, based on land relief. Herman beaches were found to consist of about 2.7 – 3.9 m of silty sand, overlying 5 – 6 m of clay or silt, overlying till. In Township 7, Range 8W, Herman beaches are associated with what is interpreted as an underlying ice-marginal glaciofluvial deposit (see Figs. 6-23 and 6-24; McMillan, 2005), and were observed at the top of a large gravel pit in these mostly glaciofluvial sediments, where they are represented as very low ridges (see Fig. 6-22) and a continuous ~ 1 m thick deposit of sandy gravel veneer with a lag base. Thickness are probably greater where ridges are developed, perhaps being as much as 4 m thick, but probably no more, based on the thicknesses of other Herman beaches in the study area. Soil records from this sub-area indicate soils developed in Herman beaches are Vandal and Trinton series (Langman, 1988), which are developed in 25 – 100 cm of sandy lacustrine deposits over glaciofluvial deposits.

There is no clear distinction between Norcross and Tintah beach sets in most of this sub-area; collectively they range in elevation from about 356 – 378 m, with individual beaches increasing in elevation to the north because of differential isostatic rebound. Based on other beaches of these stages in the study area, these beaches probably consist of sand and gravel. Scattered water well records indicate 2 to 9 m of sand and gravel overlie clay or shale in this area. Depth to bedrock is, in places, as much as 45 m. A schematic cross section through Township 8, Range 10W is shown in Figure 7-9.

Scattered water well data indicate that Lower Campbell beaches (not shown on Fig. 7-9) consist of 11 to 14 feet of sand and gravel over clay in this sub-area (see Appendix 2). The Lower Campbell beaches are predominantly Agassiz and Stockton series soils (Langman, 1988), which are developed in sandy lacustrine deposits.

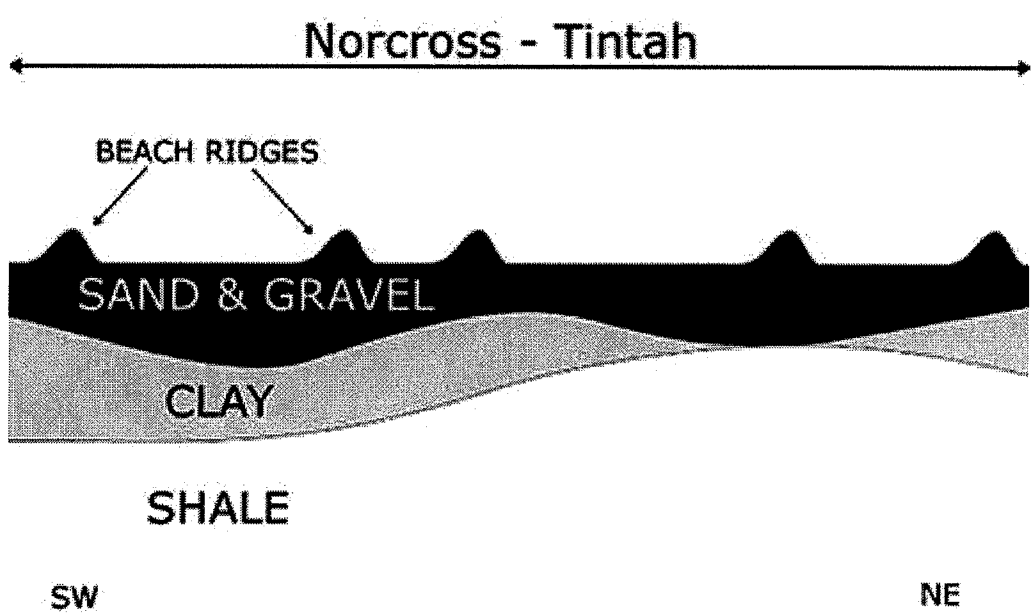


Figure 7-9. Schematic SW – NE cross section of Township 8, Range 10W in sub-area 4. Not to scale.

7.3 Named beach levels

7.3.1 Introduction

This section is a brief synthesis of previous sections, which concisely discusses the sedimentology and geomorphology of all beaches in each named lake stage considered in this study. Overall, beaches consist of units ranging from clean sand to gravelly diamicton; the beaches themselves do not have a consistent grading (i.e., coarsening or fining upwards). Generally, beaches of the Herman to Tintah stages are discontinuous and sedimentologically immature, whereas the Upper Campbell beach is much more continuous and mature.

7.3.2 Pre-Herman stages

Pre-Herman beach ridges have been identified in the southernmost part of the mapped area, near the Canada - USA border, where they lie 22 – 74 m above the level of the Herman beaches east of the Manitoba Escarpment. These beaches are short (generally less than 1 km), and fairly widely spaced. The beach ridges are low in relief (< 2 m) and narrow (a few tens of metres), and probably consist of sand and gravel. There are two small erosional scarps that have been mapped as pre-Herman in this region. Pre-Herman beaches probably do not extend much beyond Township 1, Range 5W. Their absence to the north may be explained by: (1) the presence of the LIS to the north at the time water levels were this high; or (2) subsequent erosion, as water levels of younger stages eroded the lake margin into these higher beaches. In addition, Elson (1959) shows a wave-worked lag base of boulders, sand, and gravel overlying till just west (landward) of the

Herman beaches, near Morden, that may be correlative with the more distant pre-Herman beaches to the south.

7.3.3 Herman stage

The Herman beaches are only developed in a few places in the study area (see Figs. 7-4, 7-6, and 7-8). They are well developed near Morden, in a small localized area in Township 6, Range 7W, and in another localized area in Township 7, Range 8W. Throughout much of the study area, wave action along the Tintah scarp appears to have removed any Herman stage shoreline features that may have existed.

Near Morden, the set of Herman beaches is well developed and distinct from the Norcross beach set. Sedimentologically, these Herman beaches consist of poorly sorted sand and gravel, in places approaching diamicton, overlying till. Between Herman beaches, sediments consist of gravel lag deposits, or fine grained clayey to sandy silt. Herman beaches 2.5 – 4 m thick are noted from augering, and previously published data (Young, 1993; also see Appendix 2), although relief is generally only a few metres; individual ridges are a few tens of metres wide. The sediments between the Herman and Norcross beach sets were mapped by Elson (1959) as wave-worked lag deposits of boulders, gravel, and sand; however, soil reports indicate that the near-surface sediments are sand and silt, and do not mention a lag base. There are no mapped Herman scarps in the entire study area—the Herman is the only named lake level that does not include a scarp; this could be because water was not at the Herman level long enough to create a scarp, or because wave-action was not strong enough to create one, perhaps because of dampening of wave energy by nearshore ice.

7.3.4 Norcross stage

The Norcross shorelines of Lake Agassiz are extensive in this study area (see Figs. 7-2, 7-4, 7-6, and 7-8). Scarps of the Norcross stage occur near the Canada–USA border, and in Township 5, Range 7W. Norcross beaches are particularly well developed near Morden and near Treherne. Near Morden, they contain similar sediments as Herman beaches, being poorly sorted accumulations of sand and gravel over till; these beaches are separated by gravel lags and/or silts. Near Treherne Norcross beaches overlie clay or shale. Norcross beaches between ~ 1.5 – 3.3 m thick near Morden, and ~ 2.7 – 4.5 m thick near Treherne are noted from augering and previously published data (Young, 1993; also see Appendix 2). Relief of Norcross beaches is generally a few metres.

The Norcross and Tintah beach sets are not easily distinguished from one another in most of the study area, even near Morden, indicating that they may actually be arbitrarily defined parts of a continuum of beach ridges.

7.3.5 Tintah stage

Features of the Tintah stage are quite extensive throughout the study area (see Figs. 7-2, 7-4, 7-6, and 7-8); an extensive Tintah scarp extends from Township 4, Range 6W at its southern end to Township 6, Range 8W at its northern end. The Tintah beaches are well developed from the Canada – USA border to the northern end of the beach complex near Morden. Auger cores of these beaches indicate that they are generally 2.4- to 3-m-thick ridges of poorly sorted sand, containing clay- to gravel-sized sediments, which like the Norcross beaches, overlie till in some places (near Morden) and clay and shale in other places (near Treherne). Tintah beaches are a few metres in relief, and a few tens of metres wide. Aggregate reports indicate that near the Canada – USA border the Tintah beaches are 0.6- to 2-m-thick accumulations of poorly sorted sand and gravel, and generally overlie clay or shale.

The Tintah beach set is easily distinguished from the younger Upper Campbell beaches. The vertical gap between the Tintah and Upper Campbell beach sets (18 m from the top of the Upper Campbell scarp, or 25 m from the bottom of the Upper Campbell scarp) is significantly larger than that between the Herman and Norcross beach sets (7 m) or between the Norcross and Tintah beach sets (7 m; values quoted for beaches near Morden). There seems to be a gravelly lag at the surface between Tintah and Campbell beaches in much of the study area (Michalyna et al., 1988; Elson, 1959).

7.3.6 Campbell stages

The Upper Campbell and Lower Campbell beach levels are difficult to differentiate from each other in much of the study area, and are 'merged' in places into a single Campbell scarp (or beach). The Campbell is the best developed shoreline in the basin. It is the most continuous shoreline in this study area, and is represented by beach ridges and/or scarps. The Upper Campbell beach is generally accepted as having formed by transgression during the Emerson phase; the Lower Campbell beach likely formed less than 200 years later by transgression following the abandonment of the Upper Campbell level (e.g., Teller, 2001). In places in the study area, multiple Campbell beach ridges (>2) are mapped; however, they are generally faintly visible on aerial photos, and narrow (a few tens of metres), low relief (< 2 m) features, none of which were individually augered for this project–thus most of these ridges may be offshore bars. No individual Upper Campbell or Lower Campbell ridges were augered for this project, however, water well data (see Appendix 2) and aggregate reports (Young, 1993) indicate that these beaches may be up to 6 m thick; within the study area mapped Campbell beach ridges are a few hundred metres wide and less 2 – 3 m in relief. West of the large Campbell scarp 16 – 24 m of sand and silt were augered (auger holes KMAg17, KMAg20; see Appendix 2). However, these thick accumulations must be pre-Campbell sediments, as they occur above the Campbell scarp and have no relief to indicate beaches. The plateau between the Upper Campbell and Lower Campbell scarps was augered near Morden (auger hole KMAg10; see Appendix 2), and was found to contain about 1.8 m of sand and gravel over till.

7.4 Dating of Lake Agassiz beaches

7.4.1 Introduction

As noted in Chapter 1, dating control of Lake Agassiz beaches is generally poor; only a few of the dates used to establish the chronology of Lake Agassiz in southern Manitoba are from beaches. Most of the dates in the Agassiz basin are radiocarbon dates, however datable material is rare, especially in beaches themselves. No beaches in this study area have been directly dated.

Some radiocarbon dates from upper Lake Agassiz beaches do exist, however. A lagoon behind the Upper Campbell beach about 20 km to the north of the study area, in the Rossendale area of Manitoba, has been radiocarbon dated by Teller (1989) at about 9.5 – 9.6 ^{14}C ka. Similar Upper Campbell lagoons have been dated in southeastern Manitoba by Teller et al. (2000) and in west-central Manitoba by Mann (1999), at 9.3 – 9.4 ^{14}C ka. Boyd (in press) has presented dates of about 10 ^{14}C ka from wood and spruce needles near the base of the organic-rich sequence at the Rossendale site, which he argues represent a brief occupation of the Upper Campbell level during the earliest part of the Emerson phase, before its occupation later in the Emerson phase.

Until Teller (1989) established that previously reported dates (on aquatic moss) from the Rossendale site were contaminated by older carbon, it was believed by many geologists (e.g., Elson, 1967; Prest, 1970) that the Upper Campbell beach was deposited about 12 ^{14}C ka; this had important ramifications for the deglacial chronology of the southwestern margin of the LIS.

A date of 11.7 ^{14}C ka has been published by Elson (1967) for wood below a Herman beach in northwestern Minnesota, establishing a maximum age for that beach ridge (although no error margin is given, this date is almost certainly plus or minus a few hundred years). A radiocarbon date of 13,500 ± 220 ^{14}C yrs has been reported for shells in fluvial sediments associated with the Herman level in North Dakota (Ashworth and Cvancara, 1983), however this date is likely too old because of the hard-water effect (ingestion of old carbon by an aqueous organism). Ice was still in Iowa 13.5 ^{14}C ka (Clayton and Moran, 1982), so it is extremely unlikely that Lake Agassiz could have formed in North Dakota even by 13.3 ^{14}C ka (the youngest possible value for this date, given the uncertainty).

Sediments of the Moorhead low-water phase have also been dated by several authors; published dates range from about 11.0 – 9.9 ^{14}C ka (Yansa and Ashworth, 2005; Fisher, 2003; Bajc et al., 2000; Morlan, 2000; Broecker, 1989).

Relative dating methods, such as age estimates based on pebble roundness and rates of sedimentation have been attempted, but have not been very successful, especially in a quantitative way (Elson, 1971; also see Klassen, 1984). Because of the absence of organic sediments associated with beaches within the study area, optically-stimulated luminescence (OSL) dating of quartz and feldspar grains may be promising, and sampling for OSL dating was done for this study to evaluate its usability for dating Lake Agassiz beaches. Unfortunately results were not available at the time of writing. A previous attempt at OSL dating of Lake Agassiz beaches in southeastern Manitoba yielded ages that were too old, and some were even inconsistent with the known sequence of deposition (J. Teller, pers. comm., 2005).

7.4.2 Radiocarbon sample

One radiocarbon sample (bulk sediment; organic rich silt) was collected from an auger core (auger site KMAg17; see Appendix 2) between the Tintah and Campbell scarps along the 'Mal Road' GPR line (location: 550611 E 5472076 N, 7.3 m depth). It gave an age of 34,880 ± 710 ^{14}C BP (lab no. #AA60944)–far older than any Lake Agassiz beaches. This sample was a bulk sediment sample, and could have been contaminated with older organics. Alternatively, it may indicate that the sandy sequence in this area was deposited prior to the last glacial advance into the area.

Chapter 8:

INTERPRETATIONS AND CONCLUSIONS

8.1 Introduction

This chapter summarizes important information from previous chapters and presents an interpretation of the sedimentology and history of Lake Agassiz, based on the study of shoreline sediments in the study area. The focus is on sediments deposited during the Herman, Norcross, and Tintah beach stages.

8.2 Mode of beach formation

Herman, Norcross, and Tintah beaches are generally thin accumulations of well- to very poorly-sorted sand and gravel overlying till. The Campbell beaches are generally thicker than pre-Campbell beaches, are better sorted, and contain better rounded pebbles (Elson, 1971). GPR and auger holes indicate that pre-Campbell ridges are consistently thin (3 m or less), compared to the Campbell beaches, which are thicker.

GPR surveys of Herman, Norcross, and Tintah beach ridges indicate that most sediment accumulation was along the shoreface of the ridge, as indicated by horizontal to lakeward-dipping reflectors on the tops and lakeward sides of ridges. Shorter landward-dipping reflectors on the landward sides of ridges, some of which climb on top of older lakeward-dipping reflectors, seem to indicate backbeach deposition.

As each named beach set (e.g., Herman) consists of multiple ridges, accumulation in this study area was probably episodic. If shoreline accumulation had been continuous, a uniformly-thick blanket of sediment would have been deposited as the lake level dropped (Teller, 2001). Alternatively, 'jittery' isostatic rebound (slow rates of rebound interrupted by faster rates) could cause differential shoreline accumulation, resulting in the deposition (and preservation) of beach ridges during periods of slow rebound; however there is no reason to suppose (nor has anyone suggested) that 'jittery' rebound could occur.

Based on their poor-sorting, low-relief, and erratic lateral continuity, it is suggested that storms were the dominant beach forming events for the Herman, Norcross, and Tintah beaches. Most augered beaches contain several distinct units, so more than one storm may have acted on a particular ridge. The combination of high water during storms and subsequent isostatic rebound resulted in the beaches being stranded above the limit of normal wave action, and eventually above the limit of storm-wave action, as has been suggested by other authors (Martini and Protz, 1978; Butler, 1999) working in different isostatically rebounding coasts. Some beaches contain mainly sand, whereas others contain clay- to gravel-sized sediments; in places bouldery gravel deposits occur between ridges. Where beaches are mainly sand, it is likely that there was an absence of coarser sizes in the source. Boulder-cobble-pebble accumulations probably represent lags of winnowed material, perhaps derived from underlying till, that were not reworked during a storm into a beach ridge.

It is also suggested that these beaches formed in a polar-style environment (with only a few ice-free months per year). Polar beaches are generally low-energy environments because of the presence of offshore and onshore ice retarding the rate of longshore drift during much of the year—this is reflected by immature sediments and irregular shorelines. Taylor and McCann (1983) suggest that decades to centuries are required to accumulate coastal sediments in the nearshore before a storm can create a distinct ridge in a polar-style environment.

Shoreline features of the Upper Campbell stage are much better developed sedimentologically than those of pre-Campbell stages, and beaches are larger (thicker, wider); wave cut scarps are more common and are longer. Pebble roundness is significantly greater in Campbell beaches than Herman, Norcross, and Tintah beaches (Elson, 1971). Because of their relative sedimentological maturity, although beds of poorly sorted material are observed in some pits, it is suggested that the Campbell beaches probably formed mainly in fair-weather conditions. Since climate was probably warmer by the Campbell stage, it is likely that these beaches formed during a longer ice-free season with a longer ice-free period and larger areas not covered by ice at other times.

8.3 Paleohydrology

Several questions about the paleohydrology of Agassiz remain unanswered; these questions largely revolve around whether the shorelines of different stages were formed during transgression or regression, how many transgressions and regressions occurred during the formation of the upper beaches of Lake Agassiz, and in fact, whether there are basic differences in mode of formation between different beach sets.

As has been pointed out by several authors (e.g., Fenton et al, 1983) the Herman, Norcross, and Tintah stages each have multiple shorelines associated with them, not a single corelatable ridge or scarp. Teller and Thorleifson's (1983; see Figure 8-1) model of shoreline distribution, while geographically accurate, is flawed in that it represents each lake stage as a single shoreline. To properly model shoreline distribution, lake stages should not be treated as single lines on a plot of distance vs. elevation, but rather as shoreline zones, each with a variable number of beaches and scarps, as shown conceptually in Figure 8-2. I do not propose discarding the current system of named beaches as it is both well-established and useful.

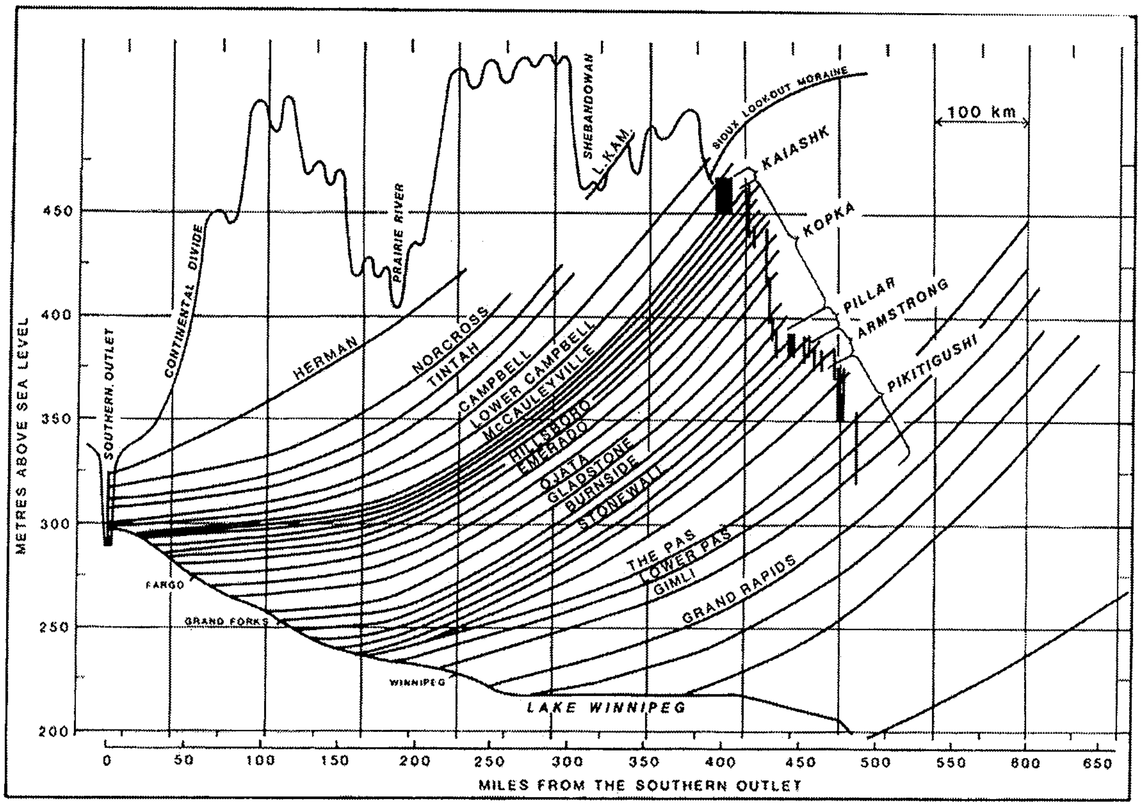


Figure 8-1. Agassiz paleobeach distribution. Note that each beach set is defined by a line. After Teller and Thorleifson, 1983, p. 265.

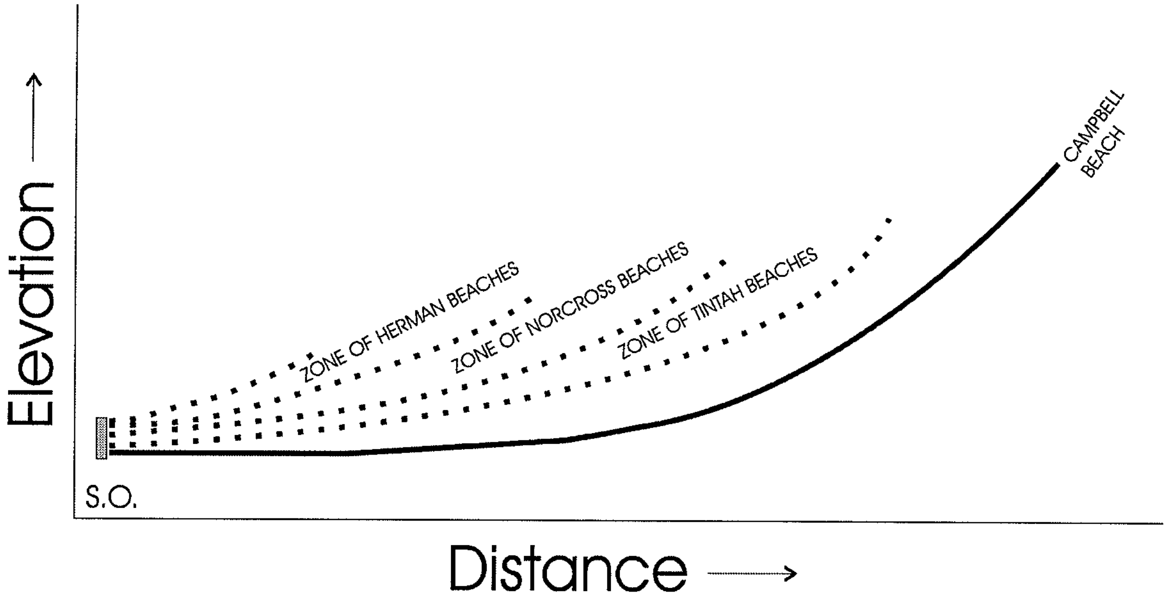


Figure 8-2. Proposed conceptual model of Agassiz paleobeach distribution. Note that beach sets are bounded by lines, not defined as lines.

Herman, Norcross, and Tintah beaches are fairly similar to each other, consisting of low and narrow ridges of about 1 to 5 m of well- to poorly-sorted sand, containing clay- to gravel-sized sediments in some parts; in places, the composition of Herman, Norcross, and Tintah beaches approaches diamicton. Inter-beach sediments include gravel-lag deposits, and clayey to sandy silts. Gravel lags probably represent storm and non-storm wave-working of till during regression that winnowed finer sediments; silty inter-beach sediments probably represent storm-overwash deposits. Sections through some beaches show they contain several units, and GPR confirms that all beaches are stratified.

Teller (2001) notes that beaches formed under normal fair-weather wave conditions cannot be preserved along regressing coastlines; instead, a thin veneer of nearshore sediments without any topographic expression of beach morphology is deposited as the shoreline moves lakeward. For this reason, Teller (2001) proposes that the Norcross and Tintah beaches formed by transgressions of lower lake levels to the southern outlet, due to differential isostatic uplift. However, given the interpretation that the Herman, Norcross, and Tintah beaches formed by storms, there is no reason to conclude that these beaches formed by abandonment following transgressions. When Lake Agassiz drained through the southern outlet, the northern part of the lake (which was rising the most rapidly) regressed because of differential isostatic rebound (Teller, 2001); water levels dropped throughout the entire lake due to downcutting of the southern outlet (although the southern outlet may have been fully eroded by the end of the Lockhart phase, before the formation of the Upper Campbell beach; Fisher, 2003). Therefore, the beaches defined as the Herman, Norcross, and Tintah by Upham (1895) probably do not represent the last stages of transgressions or stillstands, but rather storm events or variable erosion rates of the southern outlet, along an otherwise regressing coastline. In either case, the terms "Herman", "Norcross", and "Tintah" are somewhat artificial, and only reflect three 'clusters' of beaches formed during the early stages of Lake Agassiz. The definition that does exist between these beach sets may be the result of periods of increased storminess, as suggested by Fenton et al. (1983). Alternately, if the southern outlet was being eroded at different rates over time, beaches would tend be associated with times of slower erosion, when lake level was more-nearly stationary for a longer time (J. Teller, pers. comm., 2005). If these beaches did form in sequence during the early stages of the lake, then the Herman, Norcross, and Tintah beaches must have formed between about 11.0 ^{14}C ka and 10.8 ^{14}C ka, as suggested by earlier researchers, and more recently by Fisher (2003).

The Upper Campbell beach is interpreted to have formed under mainly fair-weather conditions, and must have formed during transgression, because of its size and the preceding history of the lake as noted by Teller (2001). The vertical gap in elevation between the Tintah and Upper Campbell beach sets is much larger than between other beach sets. Given the interpretation that the Herman, Norcross, and Tintah beaches all formed about 11.0 – 10.8 ^{14}C ka (during the Lockhart phase), and given that the date of the Upper Campbell level has been established to be 9.3 – 9.4 ^{14}C ka (during the Emerson phase; e.g., Teller et al., 2000, Mann, 1999), then the relatively large and featureless region between the Tintah and Upper Campbell beach sets must represent an area that was not inundated after the onset of the Moorhead low-water phase. Steady regression may have continued for some time after the deposition of the last Tintah storm beach, but prior to the initiation of the Moorhead phase (J. Teller, pers. comm., 2005). The Upper Campbell beach must have formed at the end of a transgression of Lake Agassiz during the Emerson phase.

Outflow from Lake Agassiz is interpreted to have been through the southern outlet during the Lockhart phase, 11.7 – 10.8 (e.g., Fenton et al., 1983; Fisher, 2003), through the eastern outlets during the Moorhead phase 10.8 – 9.9 ^{14}C ka (e.g., Teller and Thorleifson, 1983), and through the northwestern outlet during the Emerson phase, 9.9 – 9.4 ^{14}C ka (e.g., Fisher and Smith, 1994). One exception noted by Thorleifson (1996) and Teller (2001) is the short period just before the Emerson phase when ice readvanced across the northwestern outlet, closing that overflow route and forcing Lake Agassiz to overflow briefly to the south or east. Another exception is at the end of the Emerson phase, when the Upper Campbell beach reached its maximum transgressive point and Lake Agassiz spilled briefly through the southern outlet again (e.g., Teller, 2001).

8.4 Dating control of beaches

The chronology of Lake Agassiz fluctuations and beach formation has not been fully resolved, and the timing of certain events remains controversial (e.g., Teller et al., 2005; Fisher, 2003). The debate over the timing of beach formation is intrinsically linked with the debate over the timing of outlet use and lake fluctuations, which is superposed on the larger debate over the chronology of the last deglaciation—insights from any of these debates have implications for the others. A major reason that the chronology of lake level fluctuations in the Agassiz basin is so poorly constrained is because there are few radiocarbon dates from beaches themselves; additionally, several radiocarbon plateaus occur at times of Agassiz' existence (Teller, 2001; Teller and Leverington, 2004), limiting the precision of age interpretations. Of the named sets of beaches considered in this study, only the Campbell beaches have been reliably dated directly; organic material has not been found in Norcross or Tintah beaches. No beaches in the study-area of this project have been dated directly, and the fact that no organic material was found in low areas landward of Herman, Norcross, or Tintah beaches may be because these beaches all formed by storms, and thus did not have long-lasting lagoons associated with them, where organics could grow and accumulate. Vegetation was not sparse around Lake Agassiz; vegetation reconstructions of the last deglaciation indicate that within the present study area, boreal forest, boreal parkland, and possibly grassland ecosystems each occurred along the western margin of Lake Agassiz at different times during the Lockhart to Emerson phases of the lake (Dyke, 2005; see http://rcvcc.nrcan.gc.ca/j27/1_1_e.php, cited on Nov. 30, 2005). It has been suggested by Ashworth and Cvancara (1983) that tundra or tundra-like vegetation may have occurred along exposed beach ridges adjacent to the lake.

The dates on which the chronology of Lake Agassiz is based all come from a few locations in the Agassiz basin, and from sites outside the basin (Teller and Leverington, 2004; Licciardi et al., 1999). Within the basin, the following events have generally been accepted:

1) Formation of Herman beaches: 11.0 – 10.8 ^{14}C ka
2) Moorhead low-water phase: 10.8 – 9.9 ^{14}C ka
3) Formation of Upper Campbell beach: 9.4 – 9.3 ^{14}C ka
4) Final drainage of Lake Agassiz into the Tyrrell Sea: 7.7 ^{14}C ka.

The Herman beaches are the highest and oldest extensive beaches in the Lake Agassiz basin, extending from the southern outlet to at least Riding Mountain in Manitoba (Upham, 1895), although individual Herman beach ridges cannot be correlated across the study area, let alone from North Dakota to Riding Mountain. The deposition of the Herman beach ridges was probably time-transgressive with the northward retreat of the LIS (i.e., the Herman beaches first developed in the North Dakota and Minnesota, then in Manitoba). In Manitoba these beaches formed after retreat from a glacial readvance that reached northern North Dakota and Minnesota ~ 11.2 ^{14}C ka, but before the beginning of the low-water Moorhead phase ~ 10.8 ^{14}C ka (Fenton et al., 1983; Teller and Thorleifson, 1983). A few hundred years are probably required for ice to have retreated past the northernmost Herman beaches in Manitoba, from North Dakota and

Minnesota after 11.2 ^{14}C ka; therefore the Herman beaches in Manitoba are probably no older than about 11.0 ^{14}C ka.

Wood from below a Herman beach in northwestern Minnesota has been dated at 11,740 ^{14}C yrs (Elson, 1967). This date does not constrain the youngest possible age of the beach, but means it can be no older than ~ 11.7 ^{14}C ka. Ashworth and Cvancara (1983) describe several sites with vertebrate and invertebrate fossils within or beneath Herman beaches in North Dakota and Minnesota. Only one site, about 75 km southwest of Fargo, is dated; this site contains molluscs from fluvial sediments associated with the cutting of the Sheyenne Delta below the Herman level, which are dated at 13.5 ^{14}C ka ± 220. Since this is a shell date, it may be too old because of the hard-water effect (ingestion of old carbon by the organism), and should not be considered reliable.

Lake Agassiz became significantly shallower at the beginning of the Moorhead phase; in places (e.g., North Dakota and Minnesota) the lakebed became subaerially exposed, and colonized by spruce and marsh-plants (Fenton et al., 1983). Sediments of the Moorhead low-water phase have been radiocarbon-dated at about 10.8 – 9.9 ^{14}C ka by several researchers. Fluvial, alluvial, pedogenic, deltaic, shoreline, small pond, and offshore sediments have all been dated. Table 8-1 shows published radiocarbon dates for the Moorhead phase (earliest and latest date, for each reference).

Dates (^{14}C yrs)	Material(s) dated	Reference
10,870 (±170) – 10,398 (±75)	Wood	Fisher (2003)
10,960 (±300) – 10,050 (±300)	Wood	Broecker et al. (1989)
10,810 (±240) – 9920 (±110)	Wood, charcoal, plant detritus, peat	Bajc et al. (2000)
10,230 (±80) – 9920 (±60)	Wood, leaves	Yansa and Ashworth (2005)
10,900 (±100) – 9940 (±80)	Wood, plant detritus, moss	Morlan et al. (2000)*

Table 8-1. Published dates for Moorhead phase sediments. (*Also reports several older dates that have been discredited by Teller (1989)).

The Upper Campbell beach has been dated by Teller et al. (2000) and Mann (1999) at 9.4 – 9.3 ^{14}C ka. Earlier radiocarbon dates, from the Rossendale site in southern Manitoba, placed the Upper Campbell beach at ~ 12 ^{14}C ka (e.g., Elson, 1967; Klassen, 1984), however, Teller (1989), showed these dates to be unreliable because they were from mosses influenced by the hard-water effect. Teller (1989) presented new wood dates of ~ 9.6 ^{14}C ka, and established that the Upper Campbell beach was deposited during the Emerson phase, after a rise from the Moorhead low-water phase; the date of the Upper Campbell beach was later refined by further dating to 9.4 – 9.3 ^{14}C ka (Teller et al., 2000; Mann, 1999). It should be noted that some researchers believe that the Upper Campbell beach formed slightly earlier, some time between ~ 9.7 and 9.4 ^{14}C ka, based on dates from younger beaches in the basin (G. Matile, pers. comm., 2005).

Barber et al. (1999) discuss the final drainage of Lake Agassiz into Hudson Bay, and review published radiocarbon dates. These authors conclude, based on the marine radiocarbon reservoir of Hudson Bay and regional geologic data, that Lake Agassiz drained into Hudson Bay about 7.7 ^{14}C ka, which Klassen (1983) and Dredge (1983) concluded long before this.

Between the Herman and Campbell stages, a precise chronology has not been established, although interpretations by Teller (2001), Thorleifson (1996), and Fisher (2003) have been advanced (see Section 2.3.2). Thorleifson (1996) and Teller (2001) conclude that the Tintah and Norcross beaches were formed during the Emerson phase, *after* the Moorhead lower-water phase. These authors argue that differential isostatic rebound caused the lake to rise to the Norcross level (abandoning the eastern outlets for the southern outlet) some time between 10.2 and 9.9 ^{14}C ka, followed by a drop in lake level due to the opening of the northwestern outlet, and then by a glacial readvance at about 10.0 ^{14}C ka that dammed the northwestern outlet and caused a rise to the Tintah level. Others argue that the Norcross and Tintah beaches were formed by 'stair-step' dropdowns of lake level soon after the Herman beaches, between about 10.9 and 10.8 ^{14}C ka, before the Moorhead low-water phase (Elson, 1967; Fenton et al., 1983; Fisher, 2003).

Although no absolute dates from beaches have been obtained during this project, the interpretation that Herman, Norcross, and Tintah beaches formed by storms along a regressive coast does argue against the view of Teller (2001) that the Norcross and Tintah beaches must reflect younger lake levels related to lake transgressions. For this reason it seems reasonable to conclude that the Norcross and Tintah beaches could have formed within a few hundred years after the formation of the Herman beaches. It is therefore suggested that the Herman, Norcross, and Tintah beaches all formed during the Lockhart phase, between ~ 11.0 – 10.8 ka.

It may be informative to compare the elevations and assumed ages of beaches in this study area with some estimates of the initial rate of differential isostatic rebound. The elevations of beach sets near Morden are approximately 375 – 383 m for Herman beaches, 353 – 360 for Norcross beaches, and 343 – 353 for Tintah beaches, as measured from topographic maps with 2 – 3 m contour intervals; the zones between these elevations have noticeably fewer beach ridges (although not necessarily none). Differences in beach elevation at the southern outlet due to differential isostatic rebound are nil (see Fig. 8-1; Teller and Thorleifson, 1983; Teller, 2001), however differences in beach elevations due to differential isostatic rebound become appreciable northward of the southern outlet—so beach elevation differences at the southern outlet can be assumed to be solely due to outlet downcutting. The elevational difference between the Herman and Tintah beaches at the southern outlet is about 12 m (323 m at the Herman beach minus 311 m at the Tintah beach; Matsch, 1983). Subtracting 12 m from the elevational difference between the Herman and Tintah beach sets near Morden (40 m) yields a value of 28 m that cannot be explained by outlet downcutting. The rate of uplift of the Lake Agassiz basin during the early Holocene is not known; assuming an average uplift value of 6 m per century ~ 11 ^{14}C ka, then the time needed to regress 28 m would be (2800 cm / 6 cm * yr^{-1}) = 467 years (for comparison, uplift rates of 4 and 11 metres per century would require uplift times of 700 and 255 years, respectively). Initial (first 1000 years) post-glacial uplift rates of 4 – 11 m have been reported for sites in the Arctic Canada (Taylor and McCann, 1983), so these assumed values are probably not unreasonable, although the faster uplift values of 10 or 11 m per century do agree better with the interpretation that these beaches formed within a few hundred years of each other. There was no radiocarbon plateau between 12.0 – 10.4 ^{14}C ka (Lowell and Teller, 1995), so radiocarbon dates of 11.0 – 10.8 ^{14}C ka should correspond to about 200 calendar years.

8.5 Summary of conclusions

Herman, Norcross, and Tintah beaches are generally thin (1 – 5 m) accumulations of well- to poorly- sorted sand and gravel, with clay and silt present in parts. Inter-beach areas consist of either fine grained sediments (silt and fine sand), or coarse gravel-cobble-boulder lags. Each of these beach sets contains multiple ridges, which are considered to have formed episodically by storms during a regressing stage of the lake. The Upper Campbell beach is generally a thick well-sorted beach, and has been dated by others at 9.3 – 9.4 ^{14}C ka. This beach is interpreted to have formed during mainly fair-weather conditions at the end of a transgression during the Emerson phase.

Dating control of Agassiz beaches is generally poor; no useful organic material was found during the course of this study. OSL samples were collected, but no results were available at the time of writing; however, based on the conclusion that the Herman, Norcross, and Tintah beaches were deposited by storms, the time frame for their collective deposition was only a few hundred years, between about 11.0 – 10.8 ^{14}C ka. If rebound was 11 m per century (11 cm per year) 11 ^{14}C ka, then regression of about 28 m from the Herman beaches to the Tintah beaches (that cannot be explained by outlet downcutting) would have occurred in ~ 255 years.

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APPENDICIES

Each Appendix contains a brief introduction; all Appendices are included on the CD in the back cover of this thesis. Each Appendix also contains an electronic version of the introductions below (.doc format).

INTRODUCTION TO APPENDIX 1

This Appendix contains electronic versions of maps from this thesis (CD in back cover). Maps are in two folders, one containing ArcView versions of map themes (folder 'GIS map features'), the containing images in .JPG format (folder 'Maps, by township (JPGs)'). JPG maps are included for users who do not have ArcView, who are unfamiliar with the program, or who want to quickly access a given map. The folder 'Maps, by township (JPGs)' contains two folders: the first folder contains images of each township showing names and boundaries of beach zones (folder 'With names'; similar to maps of townships shown in Chapter 4); the second folder contains images of each township, without names or boundaries of beach zones (folder 'With no names'). The legend for all maps in this Appendix is the same as in Chapter 4, and is also shown below (Figure A2-1). This Appendix also contains a file (detailed digitizing procedures.doc) describing detailed digitizing procedures used in converting hard-copy maps to digital format.

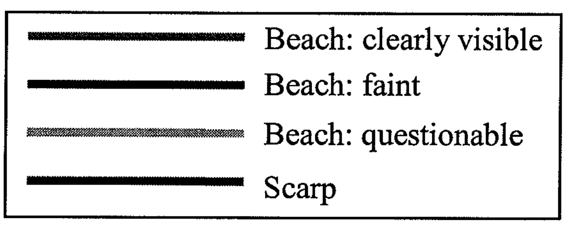

Figure A1-1. Legend for maps of shoreline features. Lines indicate features too thin to outlined individually; larger beach ridges were outlined individually.

INTRODUCTION TO APPENDIX 2

This Appendix contains the stratigraphic descriptions of power-auger holes that were drilled for this study by Paddock Drilling Co. on July 28 and July 29, 2004; these are included as individual text files named by their corresponding codes. Table A2-1 shows the UTM (NAD-83) coordinates of these auger holes (included on CD in back cover as 'Auger hole coordinates.XLS'). Geographic locations of these auger holes are shown in Figures A2-1 – A2-7, which are also included on the CD (folder 'Auger hole locations').This Appendix also contains a folder with water well data from the townships and sections in this study area, obtained from the Manitoba Water Resources Branch in Winnipeg (folder 'Water well data (MB Water Resources Branch)').

SITE	EASTING	NORTHING
KMAg1	561039	5445904
KMAg2	561569	5445921
KMAg3	562263	5445909
KMAg4	562628	5445944
KMAg5	563242	5445767
KMAg6	563376	5445764
KMAg7	564414	5445946
KMAg8	564923	5445932
KMAg9	565335	5445948
KMAg10	565874	5445784
KMAg11	560142	5445827
KMAg12	559263	5448336
KMAg13	558747	5448328
KMAg14	558303	5448319
KMAg15	554834	5458956
KMAg16	548443	5472056
KMAg17	550611	5472076
KMAg18	547955	5471646
KMAg19	548002	5471965
KMAg20	549491	5474820
KMAg21	529956	5496573
KMAg22	528205	5496581
KMAg23	525557	5496562
KMAg24	521361	5496539

Table A2-1. Auger hole coordinates, in NAD-83 format.

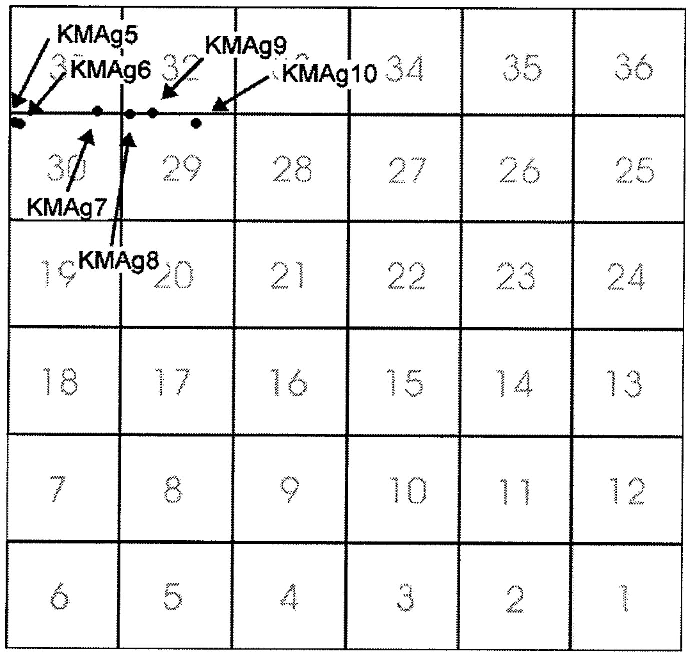

Figure A2-1. Locations of power-auger holes in Township 2 Range 5W. Grey numbers (1-36) refer to section numbers within this township.

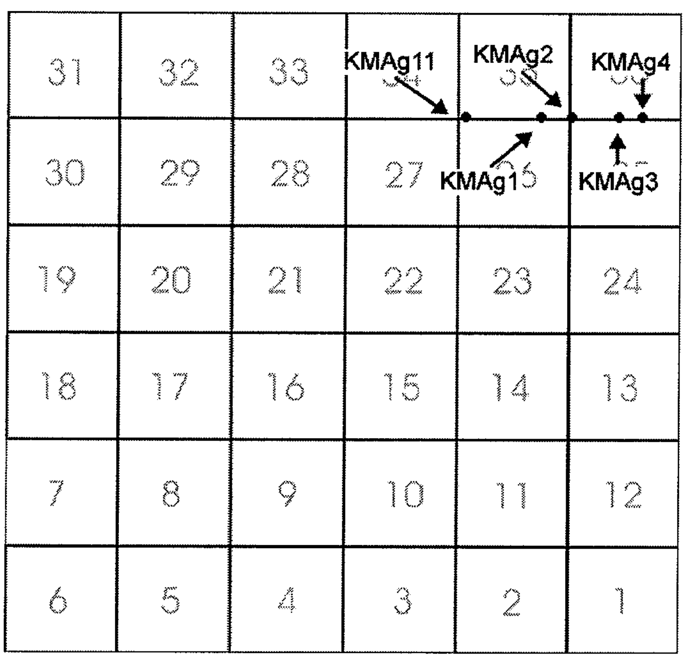

Figure A2-2. Locations of power-auger holes in Township 2 Range 6W. Grey numbers (1-36) refer to section numbers within this township.

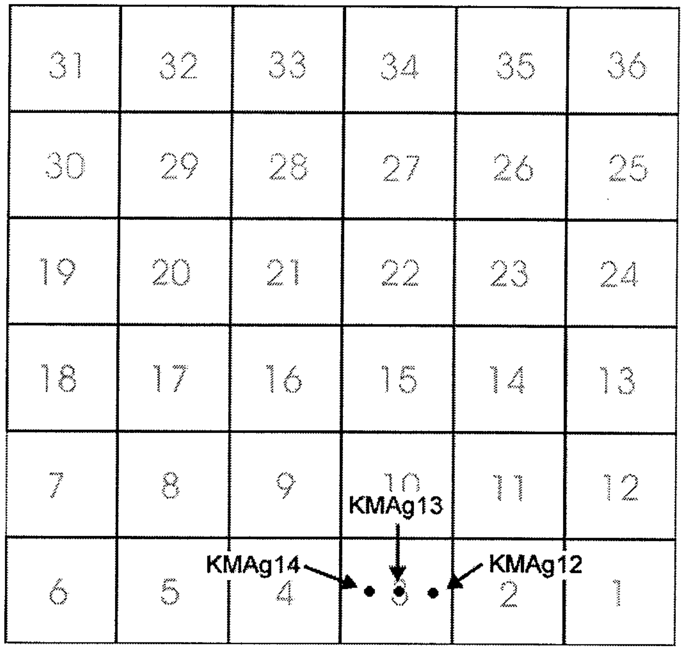

Figure A2-3. Locations of power-auger holes in Township 3 Range 6W. Grey numbers (1-36) refer to section numbers within this township.

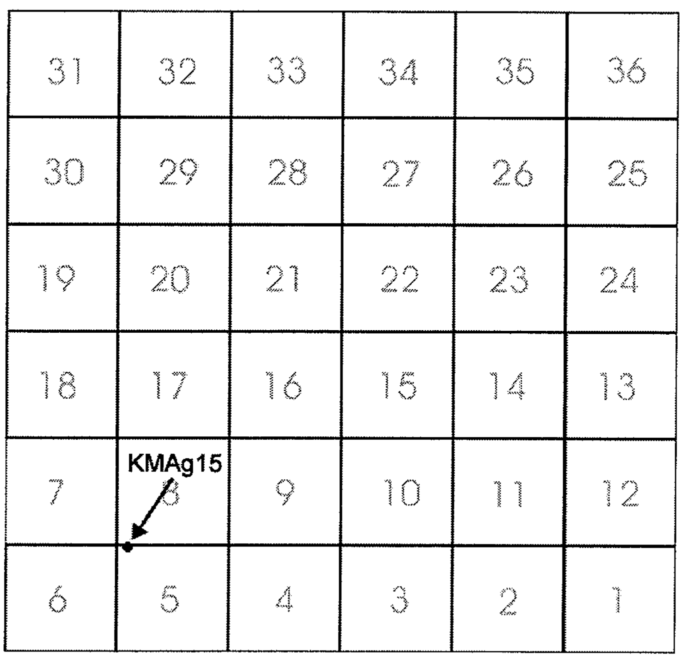

Figure A2-4. Locations of power-auger holes in Township 4 Range 6W. Grey numbers (1-36) refer to section numbers within this township.

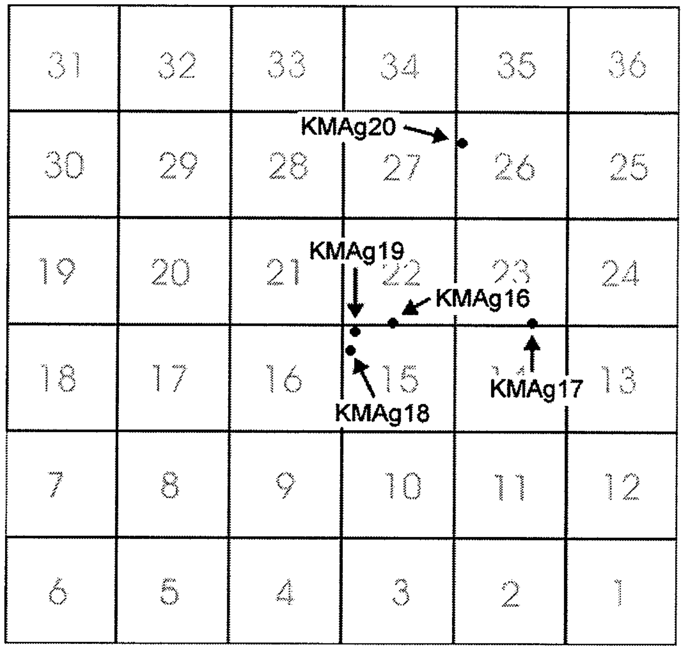

Figure A2-5. Locations of power-auger holes in Township 5 Range 7W. Grey numbers (1-36) refer to section numbers within this township.

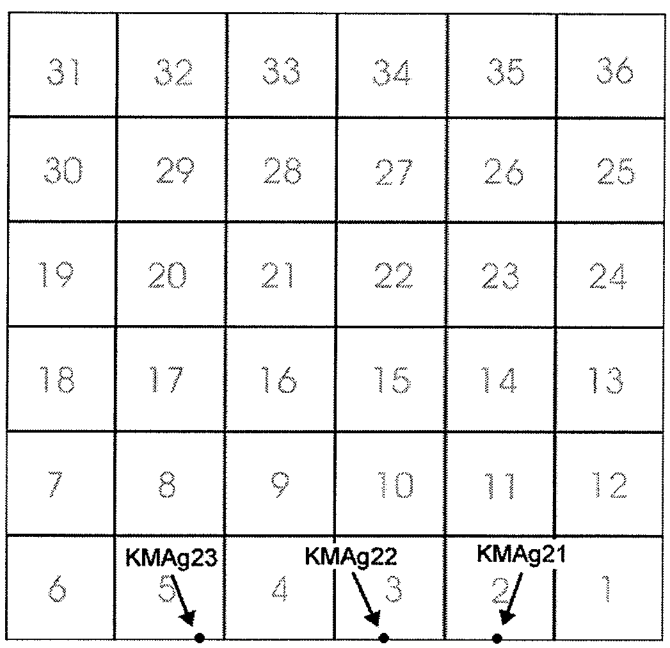

Figure A2-6. Locations of power-auger holes in Township 8 Range 9W. Grey numbers (1-36) refer to section numbers within this township.

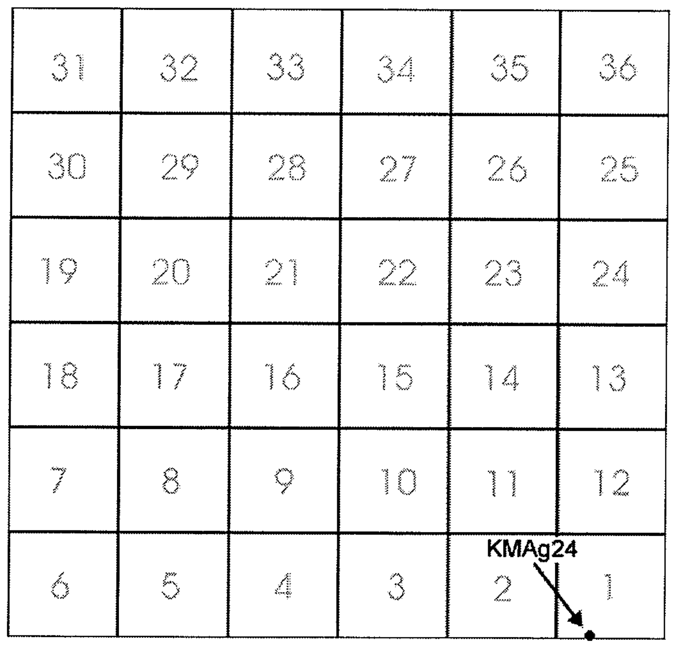

Figure A2-7. Locations of power-auger holes in Township 8 Range 10W. Grey numbers (1-36) refer to section numbers within this township.

INTRODUCTION TO APPENDIX 3

This Appendix contains Ground Penetrating Radar (GPR) lines in both the original .PCX file format (folder 'PCX files'), and in .JPG format (folder 'JPG files'). PCX files are readable in CorelDraw. JPGs are of lower image quality, but are included for convenience for users who do not have CorelDraw installed on their computers. Header files are included in a separate folder, and include information on the systems used as well as the length of each GPR line. Some lines were not processed and therefore not included in this thesis, as indicated in Chapter 6. UTM (NAD83) coordinates are included as .DBF files (folder 'GPR endpoints'), which are readable in Microsoft Excel. Geographic locations of GPR lines are shown in Figure A3-1 (also see Table 6-1).

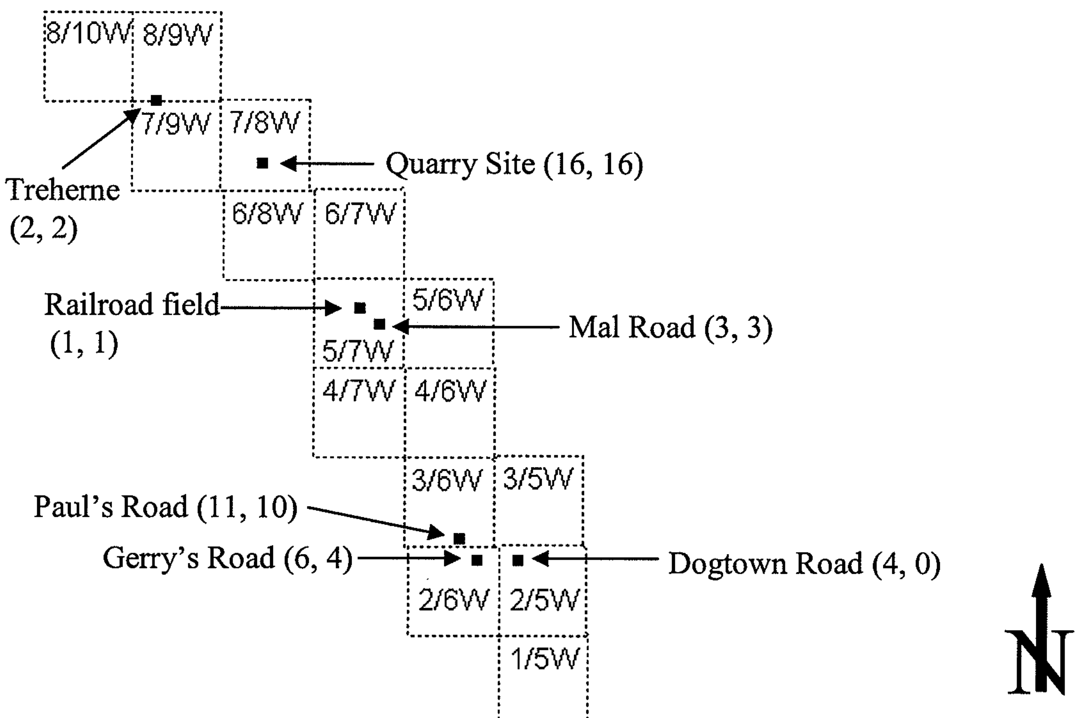

Figure A3-1. Locations of GPR sites within the study area. Numbers within squares (e.g., 1/5W) refer to townships in Manitoba (i.e., Township 1, Range 5 west of the principle meridian). Numbers in brackets refer to the number of GPR lines done at each site, and the number that were processed and included in this thesis, respectively. For example, (6, 4) at Gerry's Road refers to six lines run at that site, four of which were processed.

INTRODUCTION TO APPENDIX 3

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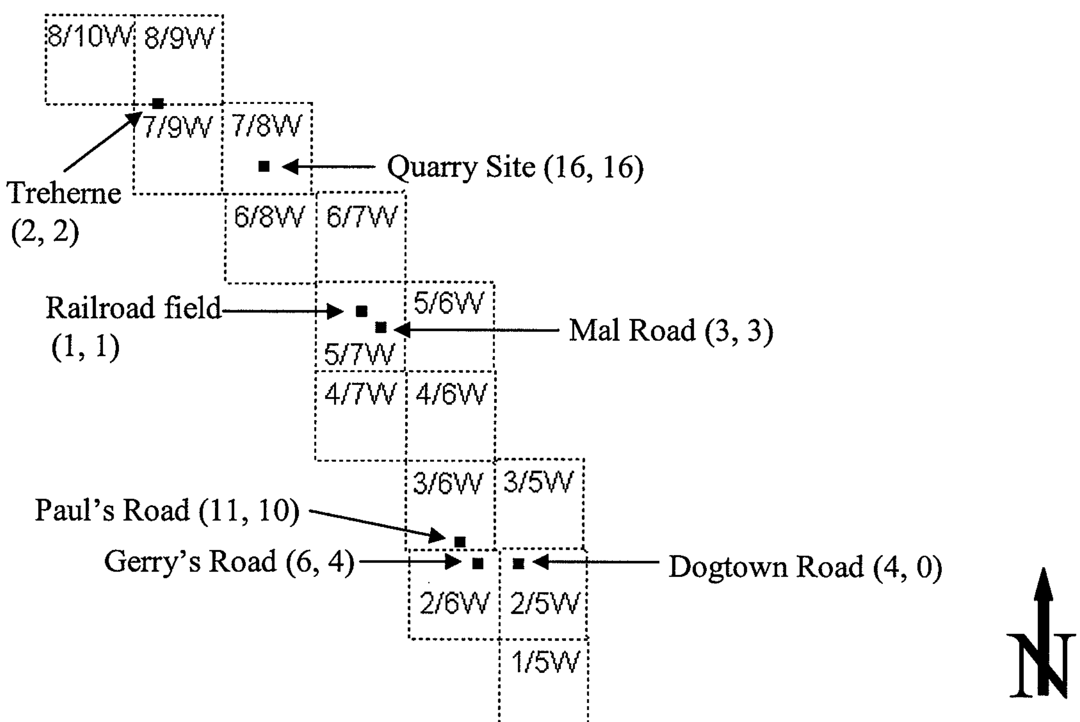

Figure A3-1. Locations of GPR sites within the study area. Numbers within squares (e.g., 1/5W) refer to townships in Manitoba (i.e., Township 1, Range 5 west of the principle meridian). Numbers in brackets refer to the number of GPR lines done at each site, and the number that were processed and included in this thesis, respectively. For example, (6, 4) at Gerry's Road refers to six lines run at that site, four of which were processed.