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SURFICIAL GEOLOGY OF THE TIGER HILLS REGION, MANITOBA, CANADA.

by

John Albert Elson

1955

A Dissertation presented to
the Faculty of the Graduate School
of Yale University in Candidacy for
the degree of Doctor of Philosophy.

Dedicated to all those who helped,
especially Lyn, Pat, June, Dorothy,
Pat, Steve, and Rocky; and to E.H.E.

SURFICIAL GEOLOGY OF THE TIGER HILLS REGION, MANITOBA
by John Albert Elson

Abstract

The Tiger Hills region (N. lat. 49°00' to 49°43', W. long. 98°00' to 100°00') lies between the basins of glacial Lake Souris and glacial Lake Agassiz and straddles the cuesta that separates the First and Second Prairie Steppes. It was glaciated at least twice during the Pleistocene Epoch. The surficial geology was mapped on the scale of 1 inch to 3 miles; areas to the west and north were mapped on the scale of 1 inch to 4 miles.

Washboard moraines, composed mainly of lodgment till, formed subglacially near the ice margin; their spacing and size depended on the subglacial supply of debris and on the amount of thrusting within the ice.

Striated boulder pavements form by selective subglacial erosion of till, and do not necessarily represent an interval of subaerial erosion. They may be the subglacial manifestation of a glacier-regimen fluctuation involving margin retreat and advance of substage magnitude.

The strandlines of Lake Agassiz I (altitudes about 1,050 to 1,265 feet) slope southward at about 1.5 feet per mile, but are nearly horizontal on the Assiniboine delta. It is inferred that isostatic adjustment of the crust followed deposition of the delta.

The last ice sheet flowed southeastward. During deglaciation it separated into a lobe that shrank rapidly northwestward and, in the Lake Agassiz basin, a southward-flowing lobe that readvanced slightly before final retreat. Withdrawal of the glacier northwestward resulted in the formation of glacial Lake Souris and its proglacial successor, Lake Hind, both of which drained through Pembina trench. Later ice recession northward from the Tiger Hills formed the Brandon glacial lake which discharged first through Pembina trench and then eastward through the Treherne spillway. The Lake Agassiz basin probably was drained through an outlet north of Lake Superior at this time. A late Cary (Mankato?) ice advance blocked this outlet and formed Lake Agassiz I, which filled to the Herman strandlines and discharged southward through the Minnesota River outlet. The Assiniboine delta and an alluvial fill in Pembina trench were deposited at this time. Lake Agassiz subsided as the southern outlet deepened until erosion halted at a bedrock sill. Lake Agassiz I drained when ice recession (Two Creeks interval) reopened the eastern outlet. Lake Agassiz II formed when the eastern outlet was again covered by advancing ice (Valders); Assiniboine valley was alluviated and a molluscan fauna entered the region. Lake Agassiz II probably lasted through Lake Algonquin time and was drained when final glacier recession opened eastern and then northern outlets, possibly during the Thermal Maximum.

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Chapter 1

INTRODUCTION

PRELIMINARY REMARKS

GENERAL STATEMENT

This dissertation is based on field work done by the writer while in the service of the Geological Survey of Canada. It comprises parts of two map projects, the Brandon map-area and the Virden map-area. In general, mapping of the surficial deposits was for publication on the scale of 1 inch to 4 miles. In the Tiger Hills region (Pl. 3), detail for a map on the scale of 1 inch to 3 miles was obtained.

The thesis area was originally about 875 square miles (Pl. 4), but this proved inadequate to deal with many of the problems, and it was subsequently expanded to about 4,550 square miles (Pl. 3). This was mapped during the summers of 1949 to 1951. Geological Survey assignments in adjacent areas in 1952, 1953 and 1954 bear directly on the problems in the Tiger Hills region, and some of this information is used. Thus, the data on which this thesis is based were derived from about 10,000 square miles, of which 4,550 square miles were examined in detail.

A triangular traverse about 1,500 miles long in southern Manitoba and southern Saskatchewan was made to collect pebbles for provenance research in 1950. About two weeks in 1951 and 1952 were spent observing the deposition of debris from glaciers in the Canadian Rocky Mountains.

SCOPE OF THE PROBLEM

The purpose of this thesis is to interpret the Pleistocene history of south-central and southwestern Manitoba, with special emphasis on the last (Wisconsin) glaciation. In the Tiger Hills region the shrinking late-Wisconsin Laurentide ice sheet split into two lobes, one flowing southeastward and the other southward. As these lobes melted, a series of glacial lakes, most important of which were Lake Agassiz, Lake Souris and the Brandon lake, were formed. The history of glacier recession is recorded by glacial, glaciofluvial, and glacial lake deposits; by spillways, and by terraces in the Pembina valley. Fluctuations in the level of Lake Agassiz are recorded by strandlines and by terraces in the Assiniboine valley. The structures of the Assiniboine and Pembina deltas in Lake Agassiz shed light on the origin of Lake Agassiz. Lesser problems studied include the modes of origin of washboard moraines and buried striated boulder pavements. Provenance studies, by pebble counting, gave negative results.

LOCATION AND ACCESS

The Tiger Hills Region is between latitudes 49°00' and 49°43' north, and longitudes 98°00' and 100°00' west. It includes Pembina Mountain (the Manitoba Escarpment) and extends along the International Boundary north of North Dakota as far west as Turtle Mountain (see index map on Pl. 3). The locations of adjacent areas studied are shown in index maps on Plates 5 and 7.

The system of ranges and sections used as a means of location is different from the system used in the United States. The ranges are numbered west from the Principal Meridian, which is 15 miles west of Winnipeg. Because there are six meridians in Canada from which ranges are numbered, it is necessary to use the designation "W. Prin." or "WPM" (west of the Principal Meridian). Townships are numbered north from the International Boundary. Numbering of the sections in a township, shown on Plates 1 and 3, differs from the American system in that section 1 is in the southeast corner of the township instead of the northeast. The standard abbreviated location form, "NW 27-6-15 W. Prin. (or WPM)," should be read "northeast quarter of section 27, township 6, range 15 west of the Principal Meridian."

The Tiger Hills region is crossed from east to west by two branch lines each of the Canadian Pacific and Canadian National Railways. North-south rail connections are poor. A network of all-weather hard-surfaced and gravelled highways and secondary roads connects all important towns. The grid of secondary roads and trails gives access by automobile to within a mile of almost any point, in good weather. Second-class hotel accommodation is available at the main towns, which include Wawanesa, Glenboro, Cypress River, Holland, Treherne, Carman, Somerset, Mariapolis, Ninette, Killarney, Cartwright, Crystal City, Pilot Mound, La Riviere, Manitou, and Morden. The population of these towns ranges from about 250 to 2,000 persons.

PREVIOUS WORK

Henry Youle Hind (1859) was first explorer in southwestern Manitoba to record geological observations, but his notes on the surficial deposits are brief. G.M. Dawson (1875) examined the area along the International Boundary and noted the surface geology, especially the lithologies of the stones in the drift. His careful pebble counts are still of value, although his theory of origin of the drift, by dropping from icebergs floating in a sea, has been discredited. Dawson's basic data are sound even though his interpretations are not acceptable.

The first areal study of the surface deposits was made for the Geological and Natural History Survey of Canada by Warren Upham (1890) in 1887. His reconnaissance map of southern Manitoba was published on the scale of about 1 inch to 21 miles. In his later work (1896) larger scale maps were used, but the data are the same. Upham had preconceived ideas with regard to the moraines he expected to find, and his maps err with respect to these and the boundaries of glacial Lake Souris.

W.A. Johnston (1934) published the first useful geological map of the surface deposits of southern Manitoba, on the scale of 1 inch to 8 miles. He wrote nothing on the Pleistocene history of the southwest part of the province, and was apparently satisfied with Upham's interpretation. Later, Johnston (1946) wrote on the deformed strandlines of Lake Agassiz and inferred a history of crustal warping from them (see Chapter 5 for further discussion).

E.C. Halstead and the writer collected data on groundwater conditions, and several ground-water reports of limited distribution contain this information, together with preliminary maps of the surficial geology, by the writer, on the scale 1 inch to 4 miles.

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The writer is indebted to the Geological Survey of Canada for the opportunity to study southwestern Manitoba. This organization has borne the full cost of field work and permitted academic digressions from projects that ordinarily require economic justification. Plate 3 was drafted by the Cartography Division, and the Photographic Division supplied many illustrations.

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Field operations were carried out with the able

assistance of J.E. Green, H.G. Ignatius, R.R. Roy, N.S. Toms and R.C. Anderson.

CLIMATE AND VEGETATION

Southwestern Manitoba has a continental climate, classified by Koeppen as humid microthermal with cool summers.

The mean annual temperature in the Tiger Hills region is about 47°F. and monthly means range from 0° in January to 67° in July. Mean monthly temperatures from April to October, inclusive, are above freezing. The mean daily range of temperature is about 22°.

The annual precipitation in the Tiger Hills region varies from 12 to 26 inches (Ellis and Shafer, 1943) with a 56-year mean of 18.35 inches. More than a third falls in June, July and August, and the winter months are relatively dry. Rainfall is characterized by convectional storms through the summer months and year-around cyclonic storms of about 3 days duration.

The Tiger Hills region is mainly a prairie parkland with forest on high ground (Turtle Mountain, Pembina Mountain and the Tiger Hills) and steep slopes. In the west, the north-facing slopes are woodland and south-facing slopes are grassland. The woodland areas are mainly oak and poplar. Aspen groves surround numerous lakelets and intermittent ponds in the plains, which are otherwise grassland. The plants of the region are listed by Ellis and Shafer (1943, Appendix IV).

The predominant soils of the region are Chernozems, with other soils transitional to Brownearths and Podzols (degrading Chernozems). The last are thought to indicate an invasion of grassland by woodland.

The principal industry in the Tiger Hills region is grain farming.

SURFACE FEATURES

INTRODUCTION

The Tiger Hills region (map-area) refers to the area shown in Plate 3. The words Tiger Hills used alone refer to the central subdivision of the Tiger Hills region, described on pages 19 to 25. The Tiger Hills region lies astride, but mostly west of, a 700-foot east-facing cuesta known as the Manitoba Escarpment. This cuesta forms the west side of the glacial Lake Agassiz basin, and separates the uniform surface of the lake basin in the east from the undulating to rolling upland to the west. The eastern lowland is termed the First Prairie Steppe (Alcock, 1951) or Manitoba Lowland (Alcock, 1951 and Ellis, 1951); Dowling (1915) called it the First Division of the Great Plains. The western part of the Tiger Hills region is part of a larger physiographic unit termed by Dowling the Second Division of the Great Plains, by Ellis the Western Uplands ((of Manitoba)), and by Alcock the Second Prairie Steppe.

The physiographic classification of this part of the North American continent has undergone little, if any, evolution. Most of the publications are restatements of older classifications, using different terminology. They are summarized in Table 1-1. In making this table it was assumed that physiographers who restricted their writing to the United States would extend their subdivisions into contiguous parts of Canada.

Table 1-1. Physiographic divisions of the Tiger Hills region

Authority	Physiographic Province (of N.A.)	Subdivisions applicable to Tiger Hills region
Powell, 1896	Prairie plains	Ice plains (vs. water plains in southern U.S.A.)
Dowling, 1915	Great plains	First and second divisions
Fenneman, 1926	Central lowland	Western lake section
Atwood, 1940	Central plains	Northwest glaciated division
Alcock, 1951 and earlier	Interior plains	First prairie steppe or Manitoba lowland; Second Prairie steppe
Ellis, 1953	(Restricted to political province of Manitoba)	Manitoba lowland and Western uplands; subdivided into smaller landscape areas.

Ellis's Western uplands are the Eastern lowlands of the Province of Saskatchewan and because physiographic terms transcend political boundaries, his units were discarded by the writer in favour of Alcock's First-and Second prairie steppe.

In an area as small as the Tiger Hills region the boundary line between two physiographic units must be more specific than in the case of the broader classifications above. The Manitoba Escarpment face in the Tiger Hills region is as wide as 4 miles. The escarpment is the dividing line between the First and Second prairie steppes. To refine this, the writer arbitrarily placed the boundary at the Campbell scarp, which in this area corresponds to the 1050-foot contour (Fig. 1-2). This separates the main body of glacial and glacio-fluvial deposits in the west from the younger lake and alluvial deposits in the east.

Subdividing the Tiger Hills region into smaller units is necessary for purposes of description. Ellis has already done this but several of the type localities for his units lie outside the map-area, hence, his names would convey nothing to the reader. Also his subdivisions (landscape areas) are based on soils and ecology (forest versus grassland) rather than surface features; the writer's units are based on geomorphology alone.

The highest and smallest subdivision of the Tiger Hills region is a part of Turtle Mountain in the extreme southwest part of the area (Fig. 1-1). It is characterized by a rolling, relatively high-relief, random knob-and-kettle topography with numerous small lakes. Most of the southwest quarter of the map-area is occupied by the Killarney plain, an undulating to rolling area with a lobate system of moraine ridges. The Purves plain, about the same size as the Killarney plain, lies east of it and is smoothly undulating in conformity with the bedrock surface. The Tiger

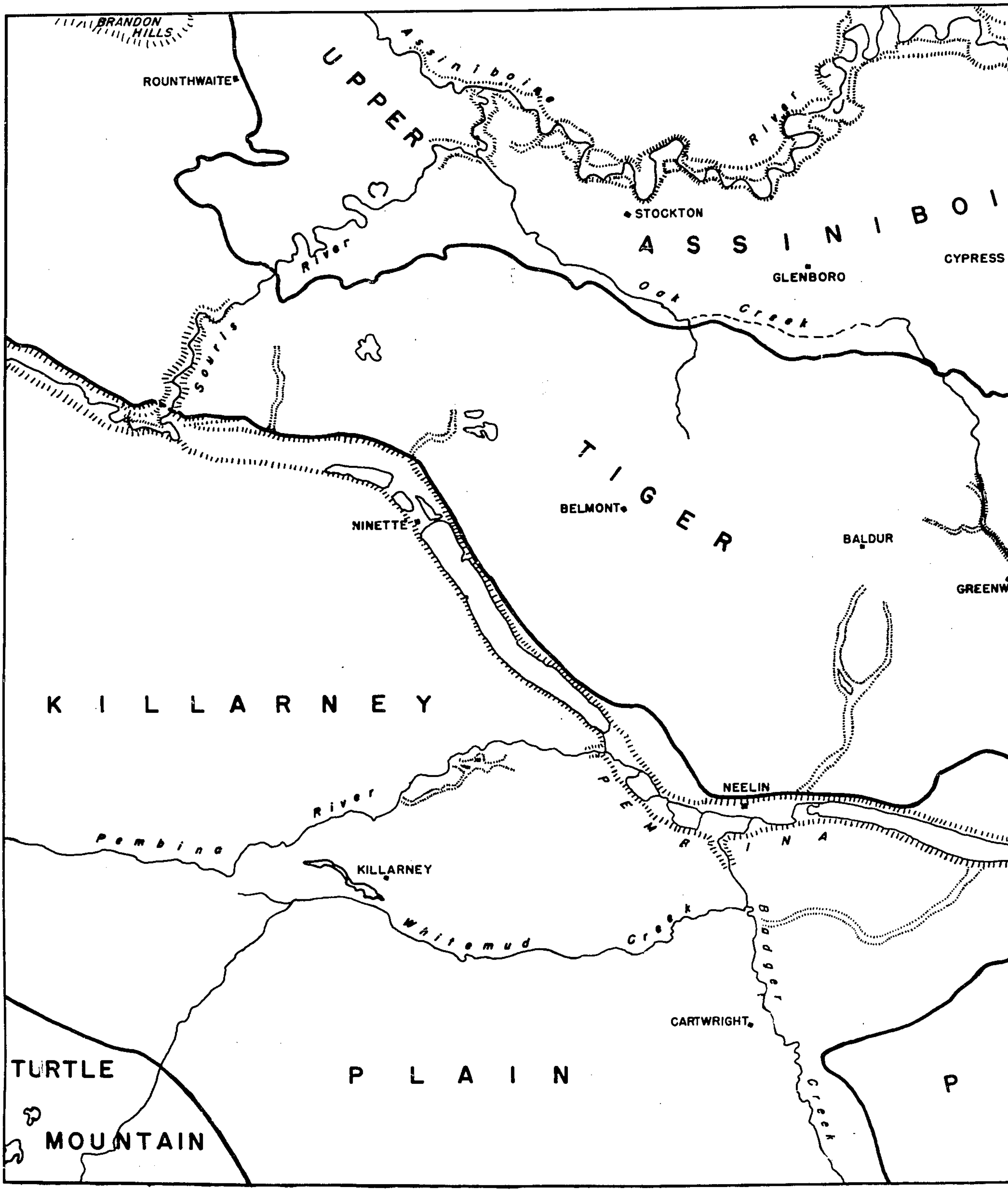
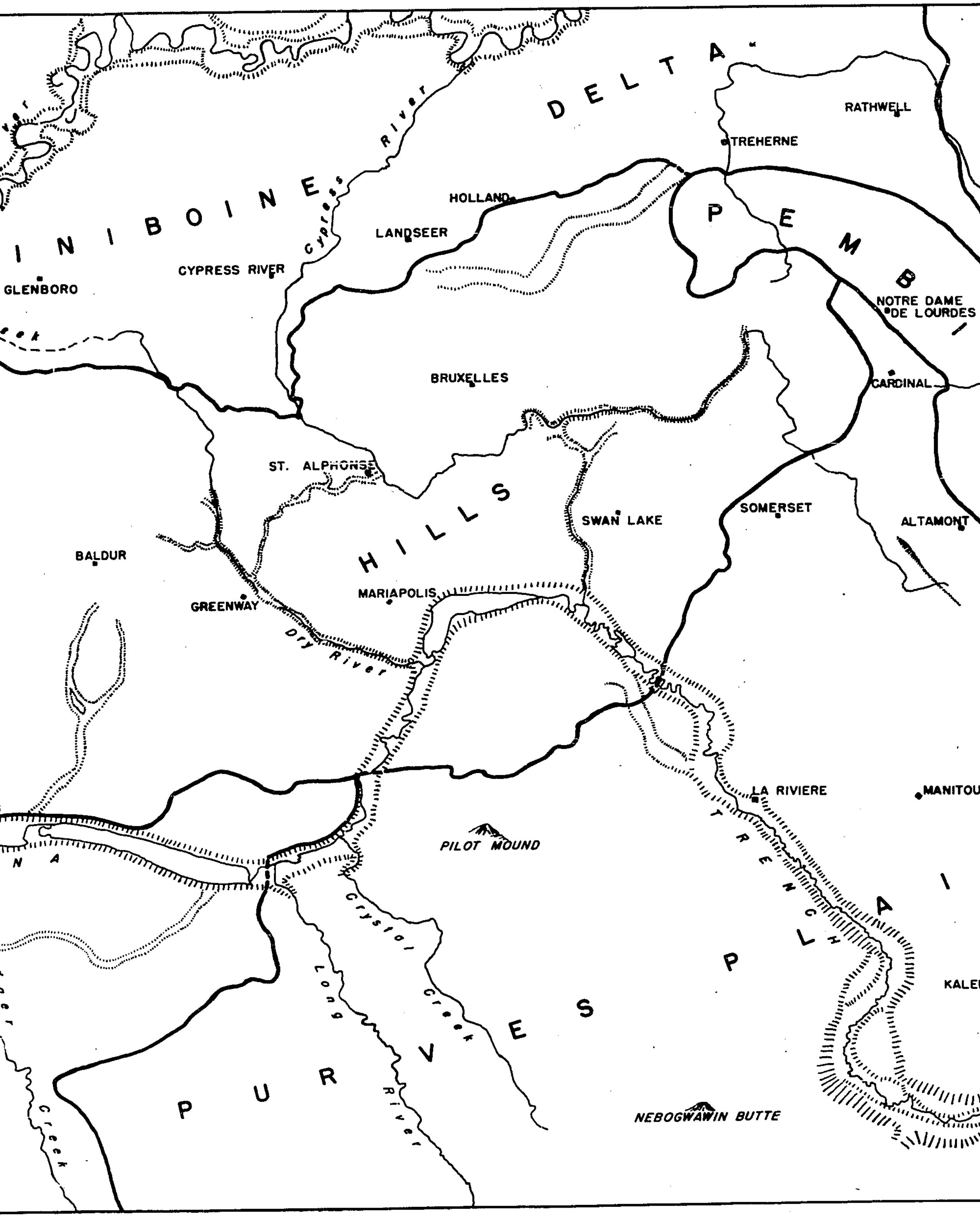


Figure I-I. PHYSIOGRAPHIC DIVISIONS of the TIGER HILLS REGION



HILLS REGION

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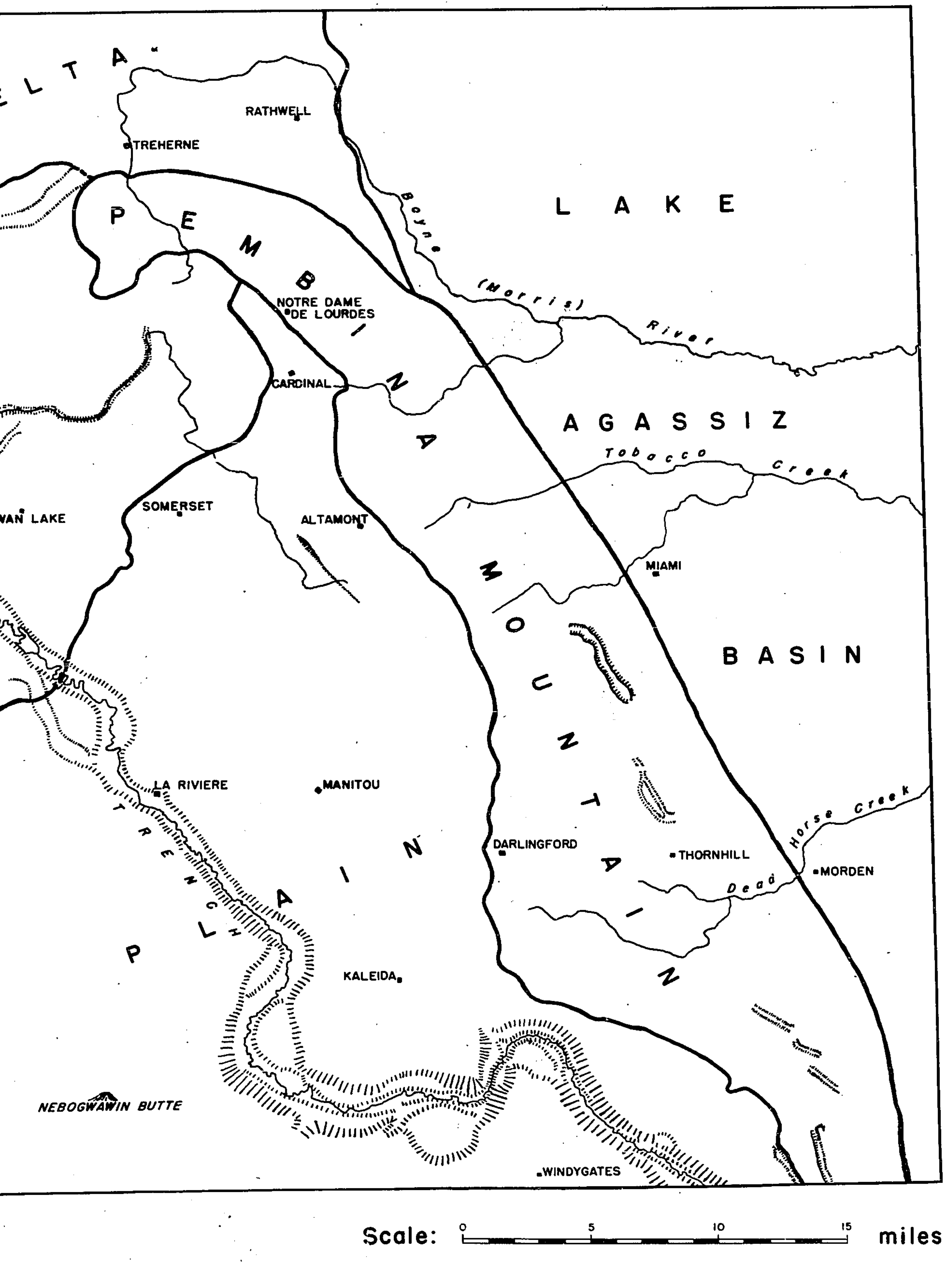
ELTA
RATHWELL
TREHERNE
LAKE
PEMBINA MOUNTAIN
Boyne (Morris) River
NOTRE DAME DE LOURDES
CARDINAL
AGASSIZ
Tobacco Creek
SOMERSET
WAN LAKE
ALTAMONT
MIAMI
BASIN
LA RIVIERE
MANITOU
TRENCH
PLAIN
DARLINGFORD
THORNHILL
Dead Horse Creek
MORDEN
KALEIDA
NEBOGWAWIN BUTTE
WINDYGATES
Scale: 0 5 10 15 miles

Hills subdivision is an east-west belt in the central and western part of the map-area and forms a complex and heterogeneous unit of relatively high relief. Smooth bedrock-cored hills are common and end moraine topography, glacially streamlined features, and small moraine ridges are also present. Pembina Mountain has a knob-and-kettle belt which forms the crest near its west boundary, but most of it is either gently undulating drift plain or glacially streamlined bedrock-cored hills. It slopes steeply to the east and north to form the Manitoba Escarpment; the lower slopes have strandline features.

All the above units are part of the Second prairie steppe. The upper Assiniboine delta is intermediate between the First and Second prairie steppes both in altitude and location. It is a generally uniform plain with extensive sand dunes in the north part of the Tiger Hills region. The Lake Agassiz basin is a level plain in the east part of the Tiger Hills map-area, locally marked by strandline scarps and beach ridges. It forms part of the First prairie steppe.

The highest altitudes in the Tiger Hills region are on Turtle Mountain, where maximum altitudes of 2,300 feet are known. Turtle Mountain slopes gently to an altitude of about 1,900 feet at its base. The Killarney and Purves Plains together with the Tiger Hills and Pembina Mountain landscape areas form one plain with a general altitude of about 1,550 feet. This plain extends to the edge of the Second prairie steppe in the east and to the upper Assiniboine delta in the north. It is rimmed by a belt of relatively high relief, the Tiger Hills and Pembina Mountain, but the hills do not rise very much above 1,550 feet. In the north, the Tiger Hills slope gently down to the upper Assiniboine delta, at about 1,250 feet. East of the upper Assiniboine delta and east of Pembina Mountain is another descent, which at Pembina Mountain amounts to a maximum of 700 feet, into the basin of Lake Agassiz. The lake basin stands between about 850 and 1,000 feet above sea level.

The Tiger Hills region can be visualized as four separate levels: Turtle Mountain in the south-west at about 2,200 feet; the Killarney and Purves Plains, Tiger Hills and Pembina Mountain collectively forming a plain at 1,500 to 1,600 feet; the upper Assiniboine delta at 1,200 to 1,250 feet; and the Lake Agassiz Basin with a mean altitude of about 950 feet.

Drainage of the Tiger Hills region flows through three main systems: the north and northwest parts of the area are drained by Assiniboine River and its tributaries, the largest of which is the Souris River, a cross-axial stream that transects the west end of the Tiger Hills. The south-central and southwest parts of the area are drained by Pembina River which flows off the southeast part of the map-area and ultimately joins Red River. The east and north-east parts of the area are drained by a series of small east-flowing streams, tributary to Red River. The Pembina valley and Assiniboine valley are the major drainage lines of the region and are discussed in detail in Chapter 5. The land-scape areas are described below. The reader is referred to Plates 1 and 3 for places not named on the small-scale diagrams.

FIRST PRAIRIE STEPPE (MANITOBA LOWLAND)

Lake Agassiz Basin

Part of the basin of glacial Lake Agassiz forms the east side of the Tiger Hills region and is a triangle of about 700 square miles with its apex at the southeast corner of the map-area and its base along the north side. The maximum relief is about 200 feet and the local relief about 3 feet. There is a gentle eastward slope of from 8 to 9 feet per mile except near the Manitoba Escarpment (Pembina Mountain) where the slope is about 50 feet per mile. Sand dunes on the Assiniboine delta in the north are as high as 30 feet. Strandline scarps and beach ridges along the Manitoba Escarpment are as high as 20 feet. The mean altitude of the landscape area is about 950 feet above sea-level, and its west boundary is set arbitrarily at 1,050 feet, the base of the Campbell scarp (Fig. 1-2).

Few data are available on the thickness of drift. On the western slope, where wave-cut terraces expose considerable areas of bedrock, the drift is locally absent and thin where present. The thickness increases eastward and widely separated borings suggest that there may be 350 feet of glacial and deltaic sediments in the northeast corner of the map-area.

Alluvial fans form gently sloping plains along several small east-flowing streams. Much of the basin has undergone little, if any, erosion. Beach ridges (bars) from 2 to 10 feet high, 100 to 300 feet wide, and several miles in length are common along the Manitoba Escarpment. Areas of sand dunes are in the north.

Wave-cut scarps are as high as 30 feet, and wave-cut terraces are as wide as 1 mile northwest of Morden. Undoubtedly some of these are lithologically controlled, in part (Chapter 2). Small, shallow valleys trend east. Except where slopes are steep near the Manitoba Escarpment, streams with channels 10 feet wide and 6 feet deep meander on recent alluvial fans. In the sand dunes in the north, a few shallow depressions, generally smaller than 0.25 square mile, are products of wind erosion.

The drainage of the Lake Agassiz Basin flows eastward to Red River. In the north much drainage is internal because precipitation soaks into the sands of the Assiniboine delta. South of the main sand area, the Boyne (Morris) River is the largest east-flowing stream. Still farther south, smaller streams such as Tobacco Creek and Dead Horse Creek drain the lower slopes of Pembina Mountain.

SECOND PRAIRIE STEPPE (MANITOBA UPLAND)

Turtle Mountain

Turtle Mountain, the smallest landscape subdivision, constitutes 46 square miles in the extreme southwest corner of the Tiger Hills region. The altitude ranges from 1,900 to 2,300 feet, giving a maximum relief of 400 feet. Local relief is about 50 feet and varies greatly. Little is known about the thickness of drift on this part of Turtle Mountain; near Mountainside, 13 miles west of longitude 100°, a well penetrated 240 feet of drift. Farther south and only 4 or 5 miles west of longitude 100° another hole penetrated 350 feet of drift.

The landforms, constructional in character, are mainly end moraine with abundant kettles. Streams with relatively steep gradients flow down the east and north slopes of Turtle Mountain and several have cut straths as wide as 100 to 300 feet. On top of Turtle Mountain drainage is unintegrated and lakes smaller than 0.75 square mile are common. Most of these lakes are above 2,000 feet in altitude. The terrain below 2,000 feet slopes northeast at 50 to 100 feet per mile and has comparatively well-integrated drainage. All the streams flow into Pembina River.

Killarney Plain

This physiographic subdivision constitutes most of the southwest quarter of the Tiger Hills region and is approximately 1,135 square miles in area. The maximum relief, from the bottom of the Pembina Trench to the lower slope of Turtle Mountain, is about 600 feet, but local relief is generally 20 feet. The general altitude is 1,525 to 1,600 feet above sea-level. Near Turtle Mountain the Killarney plain slopes northeast at about 25 feet per mile; the remainder slopes toward the Pembina trench at less than

10 or 12 feet per mile.

Wells in township 1, range 15, penetrate 350 feet of drift in a preglacial valley. However, the average drift thickness except for the southeast part of the Killarney Plain, is from 75 to 100 feet. In the southeast the drift thins to 25 or 50 feet near the Purves Plain. The drift is mainly till.

The topography varies from nearly flat and very gently undulating to rolling. The southern and eastern parts are smoothest and are ground moraine and outwash with a few low eskers. The greater part of the plain, in the west and north, is washboard moraine with relief of from 10 to 30 feet (Fig. 1-3). The moraine ridges form a lobate pattern which is convex south in the south and convex southeast in the west. The ridges die out from 3 to 6 miles from Pembina trench, except in the south where they are truncated by it. The area near the trench, on both sides, is relatively flat ground moraine and outwash plain. Small eskers a mile or two long and as high as 30 feet, but generally much lower, are scattered throughout the area of washboard moraine (Chapter 3) and are generally transverse to the moraine ridges. Some eskers change their trend at each washboard moraine. In several places the moraine ridges swing "up-stream", glacially speaking, adjacent to the largest eskers. Knobs of till and ice-contact stratified drift as high as 80 feet are scattered over the Killarney Plain. Undrained depressions are especially abundant in the area of washboard moraines.

Figure 1-2. View of 1050-foot strandline in NW 26-5-7 W. Prin., 5 miles northwest of Miami. The car is on a broad beach bar. This is the Campbell strandline, used by the writer to separate the First and Second Prairie Steppes.

Figure 1-3. View west-southwest from a hill in SW, 15-2 -14 W. Prin., across washboard moraines. The grain elevators in the distance are at Cartwright.

Pembina trench is a flat-bottomed valley about a mile wide and about 135 feet deep beginning at longitude 100° and terminating at Pembina Mountain. In the Killarney Plain it is joined by many V-shaped gullies and by two flat-bottomed valleys, Badger Creek and the upper part of Pembina River. The west end of Pembina trench is in the Souris-Assiniboine watershed. Above the elbow where Souris River turns north across the Tiger Hills toward the Assiniboine River, the valley bottom is incised to about 80 feet. The flat bottomed Pembina trench is dammed in several places by the alluvial fans of its tributaries resulting in several small lakes, chief of which are Pelican Lake and Pembina Lake. Steep-walled ravines furrow the lower slopes of Turtle Mountain, and several streams have cut flat-bottomed valleys there. There are several glacial spillways in the south part of the plain, along the Pembina River and Whitemud Creek. The most striking spillway is a continuation of the valley of Whitemud Creek across Badger Creek along a course following the lobations of washboard moraines (Fig. 3-6). It terminates near the east end of Rock Lake. There are several examples of stream capture in the southwest part of the plain.

Although most of the drainage is through Pembina River, a small part in the northwest enters the Souris-Assiniboine system. The lower parts of the valleys of upper Pembina River, Badger Creek, Long River and Crystal Creek have flood plains graded to Pembina trench. Throughout most of the Killarney plain, drainage is poorly integrated.

Various stages of drainage evolution, by one undrained depression spilling over into another during wet seasons, are present. Shallow undrained depressions number in the hundreds (Pl. 4). Small bodies of outwash gravel and sand have internal drainage.

Purves Plain

The south and east-central parts of the Tiger Hills region form an undulating prairie, designated as the Purves Plain. Its area is approximately 1,035 square miles. The maximum relief, from the lowest point in Pembina trench to the top of a hill in the north, is about 700 feet. Most of the plain is gently undulating with local relief of 5 to 20 feet (Fig. 1-4). In general the plain slopes northwest at 15 to 20 feet per mile; locally, the slope is toward the Pembina trench. The mean altitude of the plain is about 1550 feet. It rises eastward, where its boundary with the Pembina Mountain landscape area reaches about 1,600 feet.

The drift on the Purves plain, in contrast to the other physiographic subdivisions, ranges from 1 or 2 feet to about 40 feet thick, and averages about 8 feet. No buried valleys are known.

Most of the Purves plain is a smooth, gently-undulating till plain that follows the contour of the bedrock surface. The outwash plains in the west of the subdivision are nearly level. North and east of Windygates, is an area of washboard moraines which trend south-southwest. These moraine ridges are 5 to 15 feet high. Several isolated rock knobs

Figure 1-4. View northwest from NW 25-1-12 W. Prin., showing a low esker 5 miles south of Crystal City crossing a silt plain.

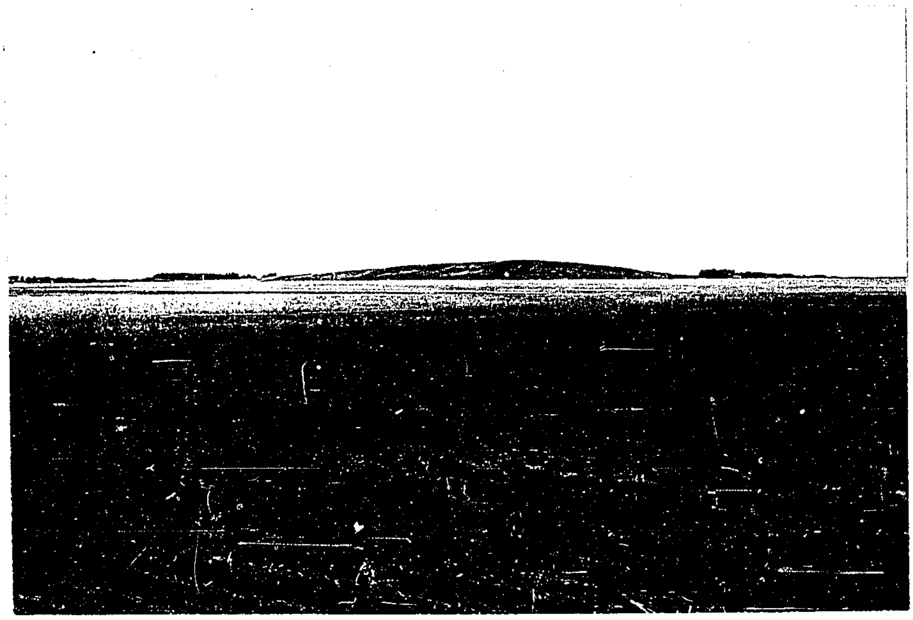

Figure 1-5. View northeast from NW 17-3-11 W. Prin., showing Pilot Mound, a drumlinized bedrock knob. Stoss is to left, lee to right. A very long, low "tail" to the right is not visible.

including Nebogwawin Butte, Pilot Mound, and a ridge 3 miles southwest of Altamont, are as high as 125 feet. Most isolated bedrock hills, except for Nebogwawin Butte, have a drumlin form. The glacially streamlined features grouped around Pilot Mound (Fig. 1-5) trend southeast and are 8 miles long. The ridge southwest of Altamont is a drumlin three miles long trending southeast. A number of short glacially streamlined ridges occur near Manitou. Esker ridges from 0.5 to 3.0 miles long are scattered over the plain; most are short segments of larger features. They are 10 to 25 feet high and 100 to 200 feet wide. Shallow lakes without outlets and as large as 0.5 square mile are scattered through the central and east part of the landscape area.

Pembina Trench forms six miles of the boundary of the Purves Plain in the northwest. It enters the plain northwest of La Riviere and trends southeast and east, bisecting it. The western segment of the trench has the same flat-bottomed character that it has through the Killarney Plain. Long River and Crystal Creek deposited alluvial fans in the trench. The lower reaches of their valleys are also flat-bottomed (flood plains). In the upstream part of the eastern segment of the trench, Pembina River winds through a flat-bottomed valley 150 feet deep. At La Riviere the trench becomes slightly V-shaped due to the numerous alluvial and colluvial fans that form its walls. Terraces occurr south of La Riviere but are difficult to distinguish from the alluvial fans of tributaries. Near Kaleida, the valley is about 3 miles wide from rim to rim, and is about 250 feet deep. Here both cut and valley-fill terraces can be distinguished. The trench has a broad, terraced, V-shaped form for about 19 miles downstream from Kaleida. At the lower end of this segment it is 300 feet deep. For the remaining 7 or 8 miles of its course above the International Boundary the valley is narrower, 1.5 to 2.0 miles from rim to rim and about 450 feet deep. The terraces are much narrower than they are farther upstream. They are mainly valley-fill terraces and slope towards the axis of the trench partly due to differential compaction.

A shallow, flat-bottomed spillway west of Pembina trench northwest of La Riviere is about 0.5 mile wide and represents an early phase in the evolution of Pembina trench. Numerous short, deep ravines are tributary to Pembina trench. Some of these tributaries have terraces corresponding to terraces in the main valley.

Except for a few minor streams in the north and east which flow eastward across Pembina Mountain, all drainage from the Purves Plain flows through Pembina River. In much of the plain drainage is unintegrated.

Tiger Hills[1]

The Tiger Hills subdivision (Fig. 1-6) forms the central part of the Tiger Hills region. It is a rolling area

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1. The reader may wonder how the name of the map-area originated. The "Tigers" that inhabit these hills are known botanically as Lilium philadelphicum, var. andinum (Nutt.) Kerr; the common name Tiger Lily is applied incorrectly; this flower is known generally as the Wood Lily and is not the domestic Tiger Lily.

that trends east-west and has an arm extending into the northwest corner of the map area. A range of morainic hills forms the south boundary and the north boundary is characterized by narrow northward sloping plains north of a belt of hills. Relief is variable and is as great as 200 feet.

The area of this subdivision is about 1,050 square miles. The maximum relief is about 500 feet. The lowest point is along the north boundary (1,250 feet) and the highest on a hill east of Bruxelles (1,750 feet). Over the area as a whole, relief varies greatly because of numerous isolated knobs of ice-contact stratified drift and bedrock.

A plain with average relief of about 15 feet, and containing isolated hills, forms the central part of the Tiger Hills. In the southern belt of hills (end moraine) the relief is about 50 feet, and in the northern belt of bedrock-cored hills and end moraine the relief averages about 100 feet and locally is 200 feet. The regional slope, obscured by the local relief is northward at about 25 feet per mile.

Over the whole subdivision the drift averages about 20 feet thick but it varies from a few inches on some of the bedrock knobs to 100 feet or more in the southern belt of end moraine. Near the present course of the Souris valley through the Tiger Hills is a north-trending buried valley where the drift is at least 150 feet thick.

The complex character of the Tiger Hills subdivision is shown in Fig. 1-6. The range of hills that forms the southern boundary coalesces with the northern belt of hills in the western third of the subdivision to form one

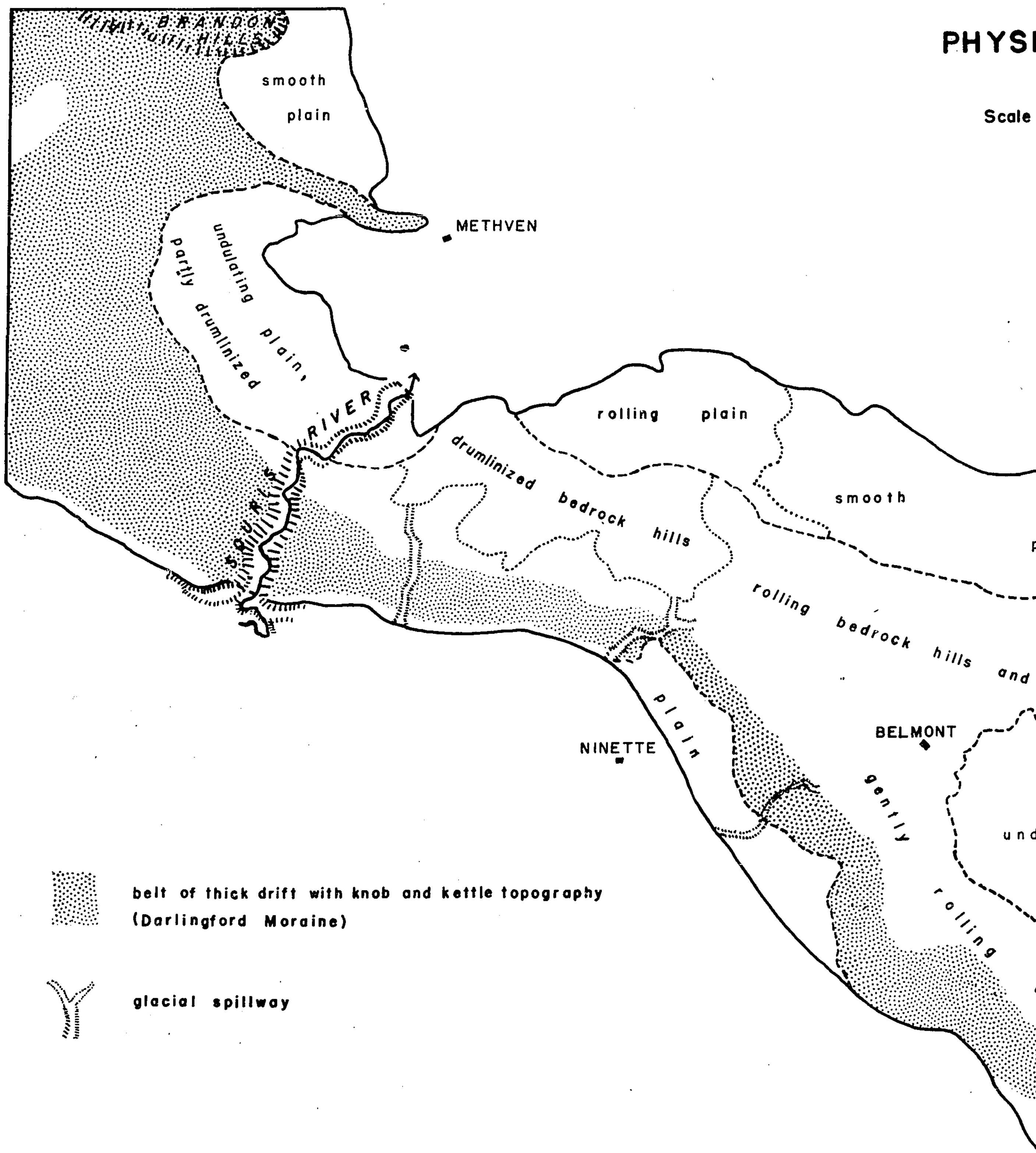
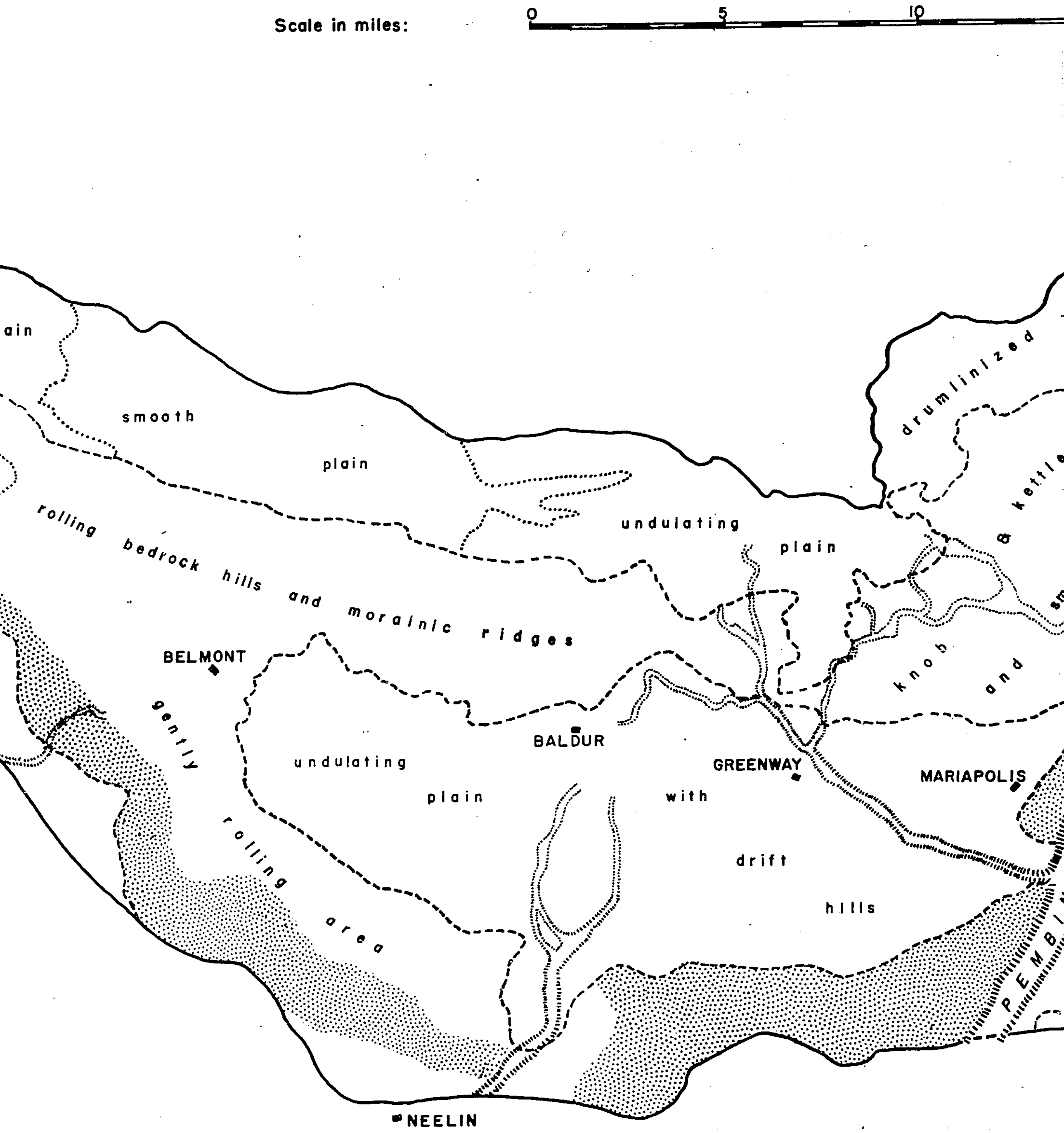
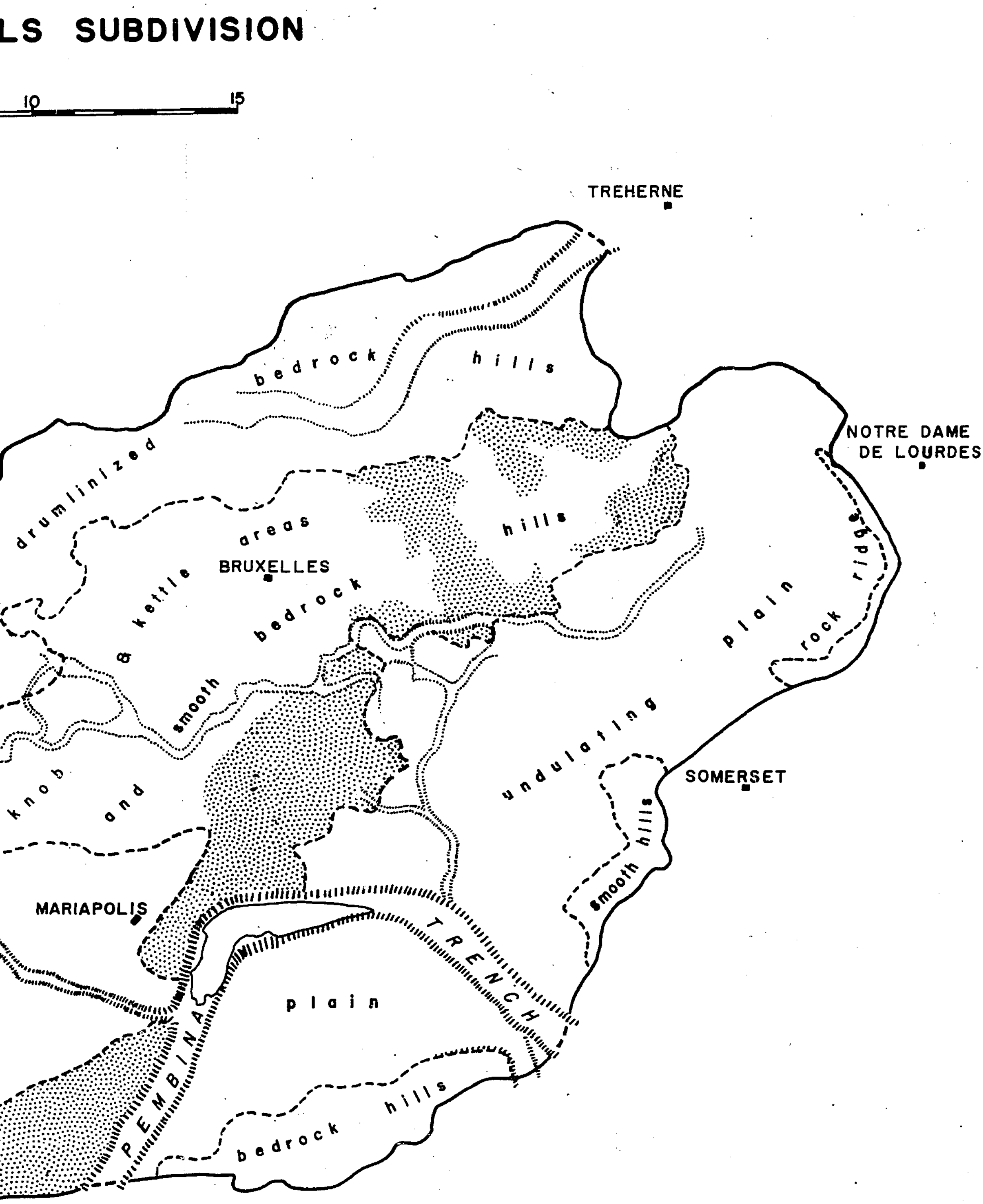

BRANDON HILLS
smooth plain
METHVEN
undulating partly drumlinized plain,
SOURIS RIVER
rolling plain
drumlinized bedrock hills
smooth
rolling bedrock hills and
plain
NINETTE
BELMONT
gently
rolling
PHYS
Scale
belt of thick drift with knob and kettle topography (Darlingford Moraine)
glacial spillway

FIGURE 1-6.

PHYSIOGRAPHY OF THE TIGER HILLS SUBDI




LS SUBDIVISION
10
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TREHERNE
bedrock
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ridge
rock
plain
undulating
smooth
knob
and
SOMERSET
hills
smooth
MARIAPOLIS
TRENCH
plain
PEMBINA
hills
bedrock

broad morainic ridge that swings north at the west side of the Tiger Hills region and extends a little beyond the map-area to the west and north. In the east the two belts of hills are connected by an area of hills about three miles north of Mariapolis. These hills separate the plain between the two ranges into east and west sections. The western section is mainly outwash and ground moraine with a few small washboard moraines. Except for several isolated hills as high as 100 feet, such as the one just south of Baldur, the relief is about 10 to 15 feet. The slope is northward at about 10 feet per mile. The eastern plain is more undulating than the central one and consists of thin drift (ground moraine) on low bedrock hills, and minor outwash plains along the northwest side. The general altitude is about 1,500 feet. The plain slopes gently northwest.

An elongate, east-west trending plain lies just north of the point of junction of the two ranges of hills in the west. East of this the fringe north of the northern range is a rolling area of subdued bedrock hills, modified into drumlin forms (Fig. 1-10) with a thin covering of drift. The western part of the northern fringe is subdued end moraine, ground moraine, and areas consisting of a lag concentrate of cobbles and boulders on a smooth bedrock surface. This plain slopes northward at about 40 feet per mile. Maximum local relief is about 25 feet, but the average local relief is much less.

East of Souris River, the north range of hills and

Figure 1-7. View southeast from hill in SW 12-6-16 W. Prin. showing morainic terrain 3 miles northwest of Belmont. The trees are clustered around small ponds. The scene is typical of ground moraine and low-relief end moraine.

Figure 1-8. View east from S/2 6-6-12 W. Prin. showing bedrock-cored hills and a lake in the Tiger Hills.

its southward extension near Mariapolis are "homogeneous in their heterogeneity". Most of the relief is due to smooth bedrock-cored hills. Along the north side of the belt, many of these are drumlinized. Locally the hills form "islands" of smooth topography in the rougher end moraine. Undrained depressions are common. The end moraine is mainly ice-contact stratified drift and very loose till with knob-and-kettle and pitted topography. Local relief varies from 20 to 200 feet. Many small hills as high as 40 feet either have bedrock cores or are wholly bedrock and have a depression on the side that was in the lee of glacier movement. The depression may be an area of non-deposition (Fig. 1-9). The north range of hills is from 2 to 4 miles wide. The southern extension between the two plains is a little wider.

West of Souris River the drift in the Tiger Hills is thick and bedrock has no influence on the landscape. End moraine is the dominant form and kettles are common. In the extreme northwest the Brandon Hills rise a little above 1,550 feet and are flanked by sharp-crested ridges similar to lateral moraines in the Rocky Mountains (Fig. 1-11). Washboard moraines are scattered through the north half of the hills west of Souris River. The entire north range from Ninette to Baldur is covered with washboard moraines which indicate a former east-west ice margin.

In an embayment facing east in the north-trending part of the Tiger Hills moraine at the west side of the map-area, ground moraine forms a plain that slopes northeast and

Figure 1-9. View from the south of a knob in SE 8-5-12 W. Prin., Note the depression in the lee of the hill.

Figure 1-10. View northeast from SE 29-6-12 W. Prin., showing rock-cored drumlinoid 4 miles southeast of the town of Cypress River. This is typical of the streamlined ridges at the east end of the Tiger Hills and the north end of Pembina Mountain.

east to the Assiniboine Delta. Local relief is about 20 feet or less and there are a few washboard moraines near the Tiger Hills moraine. North and east of the washboard moraines, southwest-trending glacial grooves control the drainage pattern, even though buried by lacustrine silt. A narrow end moraine extends northwest from Methven.

The southern range of hills is composed of end moraine as far east as Pembina trench northwest of Pilot Mound. Knob and kettle topography is characteristic, and kettles are abundant. Local relief is from 20 to 40 feet. On the north side of the range of hills west of Pembina trench are a few washboard moraines. Northeast of Greenway, knobs and ridges (eskers) of ice-contact stratified drift are common. East of the longitude of Pilot Mound the southern range of hills is broken into three segments which are narrower towards the northeast. All have bedrock cores. The gaps between the segments include one about 3 miles wide across Pembina trench, and a 4 mile gap near Somerset. The belt narrows from 2 miles wide north of Pilot Mound to less than 0.25 mile wide near Notre Dame de Lourdes. Here the ridge stands 40 feet above the surrounding plain.

There are at least five steep-sided, flat-bottomed glacial spillways in the Tiger Hills landscape area. The largest is about a mile wide and 50 to 100 feet deep, and trends southwest and west from Treherne to a point south of Landseer (Fig. 1-12). This spillway has a bedrock sill at the west end, and drumlin forms on its sides prove the

Figure 1-11. View north from SE 31-8-18 W. Prin., showing one of the steep-sided morainic ridges on the south side of the Brandon Hills.

Figure 1-12. View southwest from SE 30-7-10 W. Prin., showing the glacial spillway near Treherne. The hills have bedrock cores.

presence of a valley before the last glaciation. This spillway drained the final phase of the Brandon glacial lake (Chapter 5). A smaller spillway about 200 yards wide that trends west-southwest along the south side of the northern range of hills drained an area of outwash west of Notre Dame de Lourdes. This spillway first flowed southwest past Swan Lake to Pembina trench, but later abandoned that route and flowed southwest to St. Alphonse (Pl. 1). It is now occupied by Cypress River. The Dry River spillway extends southeast from Greenway to Pembina trench, and north from Greenway to the headwaters of Oak Creek, which flows into the Assiniboine system. This spillway is graded to Pembina trench at the south end, and has terraces that correspond to terraces in the trench. The Dry River spillway becomes narrower and shallower northward. Its gradient slopes north from Greenway. Dry River conducted meltwater southward from an ice margin and later from a small glacial lake, southeast of Greenway. Still later, it was the outlet of the Brandon lake (Chapter 5).

Another channel drained the outwash plain south of Baldur southward into Pembina trench east of Neelin. At least three minor spillways cross the southern range of hills between Neelin and Souris River gorge. All are cross-axial in character and flowed into Pembina trench. The spillway north of Ninette might have developed into the cross-axial channel of the Souris River but for a bedrock sill at its north end. Three miles east of the Souris gorge a small cross-axial channel may have drained a small glacial lake before downcutting was retarded by a bedrock sill. The last and most important cross-axial channel may have originated as a spillway. What is now the Souris gorge through the Tiger Hills was probably a channel that drained a glacial lake south into the Pembina system. Its life may have been short because the ice margin receded so that the Dry River channel and then the Treherne Channel drained this enlarging glacial lake. Diversion of Souris River through the gorge occured when a tributary of the Assiniboine system captured it by eroding headward (southward) through the spillway. On the other hand, the gorge could have resulted from normal erosion by a north-flowing stream without a reversal of gradient (Chapter 5). The Souris gorge is V-shaped and about 250 feet deep in the middle. Paired terraces have not been recognized and other terraces are sparse.

Drainage of the Tiger Hills landscape area is partly north to Assiniboine River through Souris River, Oak Creek and Cypress River. A smaller amount of runoff enters the Pembina system. In general, drainage is poorly integrated. Many small bodies of outwash sand and gravel have internal drainage. Lakes up to 0.75 square mile in area and other depressions without outlets are common.

Pembina Mountain

Pembina Mountain is a strip about 4.5 miles wide that extends north-northwest from the southeast corner of the map-area to within 7 miles of the northern boundary. It constitutes 360 square miles. The boundary with the

Tiger Hills is arbitrary. The eastern boundary, also arbitrary, is at the base of the Campbell scarp (the 1,050-foot contour). Maximum relief is about 350 feet. The average local relief varies from about 10 feet in the south where ground moraine predominates to 80 feet in the north where moraine and drumlinized bedrock hills are the major features. The regional slope is eastward at about 50 feet per mile and increases to 150 feet per mile near the east side. The mean altitude is about 1,500 feet. Slopes are more gentle (30 feet per mile) in the widest (10 miles) portion which is southwest of Thornhill. The crest of the Darlingford moraine, which forms the western boundary of Pembina Mountain has an altitude of about 1,600 feet.

The thickness of drift ranges from nil in certain places along the east slope where bedrock is exposed to as much as 100 feet in the Darlingford moraine east of Cardinal. Over most of the till plain south of Cardinal the till is from 10 to 20 feet thick. North of Notre Dame de Lourdes where the landscape consists of drumlinized bedrock hills covered by thin drift, several tens of feet of glacial deposits may be encountered in the depressions, but the hill-tops are almost bare.

The principal constructional feature is the Darlingford moraine along the west boundary of the area, where it forms the crest of Pembina Mountain. Where crossed by the International Boundary, the moraine is 0.25 mile wide and 20 to 30 feet high. Its width increases northward to a maximum of 4 miles, just east of Cardinal. From there it trends northwest and west, and is 1.5 miles wide at the point south of Treherne where it leaves the physiographic subdivision. The roughness of the topography varies with the width of the moraine. In the south the depressions are about 10 feet deep whereas near Cardinal a few are 80 feet deep. Other constructional features are beach ridges (bars) like those described in the discussion of the Lake Agassiz basin. Bars are especially well-developed between Thornhill and Morden where there are at least eight bars over 4 feet high and 100 yards wide in an east-west distance of 2.5 miles. They form an area about 9 miles long on the east side of Pembina Mountain. The slope here is eastward at about 75 feet per mile; where the slope is steeper groups of beach bars are generally not found, although single bars may be present.

Erosional landforms are represented by drumlinized bedrock hills in the north (glacial erosion), by several deep flat-bottomed gulleys flowing eastward, and by wave-cut terraces and scarps. Some of the wave-cut scarps are as high as 80 feet. These features have been discussed in the section on the Lake Agassiz basin (p. 13).

Glacial spillways are represented by features variously termed in-and-out channels by Kendall (1902, p. 483), marginal channels by Rich (1908, p. 528-533), and unilateral channels by Hoppe (1950, p. 59). These are terraces cut in the bedrock of the Manitoba Escarpment by meltwater streams. The base and mountain side of the channel were bedrock and the other side was glacier ice. As the meltwater stream cut deeper, a wall of bedrock developed on the downslope side of the channel in some cases. Only knob-like remnants of the downslope sides of the channels remain (Fig. 1-13). Terraces formed in this manner have a gradient toward the south. Their surface is bedrock strewn with boulders. In most cases the unilateral channels on Pembina Mountain begin at ordinary flat-bottomed spillways. Unilateral channels are to be expected where an ice sheet terminated obliquely against the sloping face of an escarpment. The best example, 4 miles southwest of Miami, is 3 miles long and is a true "in-and-out channel" (Kendall, 1902). Another that fits this category is 2 miles north of Thornhill. There are several other unilateral channels south of Morden and all developed from ordinary spillways higher on Pembina Mountain. On the west side of the Darlingford moraine at the point where it crosses into North Dakota, a spillway marks the position of the ice margin when the Darlingford Moraine was built. The moraine ends a mile south of the International Boundary and the spillway, now represented by paired terraces high on the sides of a deep ravine, extends southeast continuous with the trend of the ice margin that deposited the moraine. The spillway terminates in the Pembina valley 6 miles southeast of the International Boundary.

Drainage is eastward to Red River by a number of small streams, namely, tributaries of the Boyne (Morris) River, Tobacco Creek and Dead Horse Creek.

<u>Upper Assiniboine Delta</u>

This physiographic subdivision comprises 750 square

Figure 1-13. View south from NE 13-4-7 W. Prin., showing part of a unilateral channel on Pembina Mountain southwest of Miami.

Figure 1-14. View northeast from NE 13-8-13 W. Prin., of a typical area of sand dunes on the Upper Assiniboine Delta.

miles in the north-central and northwestern parts of the Tiger Hills region. It is a plain with a mean altitude of about 1,225 feet that slopes northward to the Assiniboine valley at about 8 feet per mile. Local relief ranges from 2 to 10 feet, except in areas of sand dunes where it is as great as 50 feet. The Assiniboine valley has a maximum depth of 250 feet.

The drift cover forms a broad wedge, with its thin side at the southern boundary of the upper Assiniboine delta and its thick side (230 feet) at the north boundary of the map-area. The drift is mainly deltaic sand underlain by till.

The entire plain is a constructional land-form, being the topset beds of a delta. About a third of it has been modified by wind action and some dunes are as high as 70 feet (Fig. 1-14). Most of the dunes are from 10 to 20 feet high. Extensive areas are shallow (less than 10 feet deep) "blow-outs" with intervening ridges that are difficult to classify as dunes (Fig. 1-15). As shown on the geological map, some of the dunes form ridges that trend east-southeast or east, and are as long as 12 miles. These ridges are generally 30 to 50 feet high. Except for small active areas, including a few square miles north of the Assiniboine River, 7 miles north of Glenboro, most of the dunes are stabilized by vegetation. There are several beach ridges north of Treherne and 4 miles northeast of Roundthwaite.

The chief erosional feature is the Assiniboine valley system. As already mentioned, it is about 250 feet deep north of Holland and contains several sets of paired

Figure 1-15. View northwest from the Fire Tower south of Glenboro, showing an area of blowouts and low dunes.

terraces (Chapter 5). Valley-fill terraces are alluvium deposited in a long "estuary" during the rising phase of Lake Agassiz II. Corresponding bodies of alluvium form paired terraces in the valleys of Oak Creek and Cypress River. Numerous non-paired terraces and slip-off slopes are present in the Assiniboine Valley. The river meanders on a flat valley bottom and several oxbow lakes have formed. The valley proper becomes shallower upstream and is less than 75 feet deep and 0.25 mile wide near the mouth of Souris River. Downstream from township 8, range 14, the valley is about 2 miles wide, from rim to rim. There are several strandline scarps as high as 20 feet north of Treherne; scarps northeast of Roundthwaite are lower. Several scarps and broad shallow depressions near Stockton are parts of former channels of Assiniboine River. Similar channels are 4 to 6 miles north of Glenboro, 8 miles north and 8 miles northeast of Cypress River, and 4 to 5 miles north of Holland. The last can be traced eastward to the edge of the older delta northeast of Rathwell.

Except for the eastern end of the upper Assiniboine delta which is drained by the Boyne (Morris) River into the Red River system, all runoff flows through Assiniboine River. As much as 80 percent of the landscape area is sand so permeable that there is no surface runoff.

Important physiographic features will be discussed in detail at appropriate places in the text.

Chapter 2

BEDROCK GEOLOGY

INTRODUCTION

Comprehensive reports on the bedrock of southwestern Manitoba were published by Kirk (1930) and Wickenden (1945). More recent information from well logs is summarized from time to time by the Mines Branch of the Department of Mines and Natural Resources of the Province of Manitoba (e.g. Kerr, 1949). A detailed study of the Pembina Valley-Deadhorse Creek area (southeast part of the Tiger Hills region) was published by Tovell (1948).

The writer planned to correlate the Riding Mountain formation with the Pierre Shale in North and South Dakota, where zoning based on Foramenifera was begun by W.R. Horney. The writer submitted specimens to K.M. Waage of Yale University, who made preliminary identifications; however, Waage found that Horney's work had not progressed far before his untimely death, and the writer's project was suspended.

Plate 2 was compiled mainly from the work of Wickenden and Tovell. Bedrock surface contours were inferred from well logs, river cuts, and topography. Also, an average dip of 100 feet in 12 miles southwestward was inferred (Tovell, 1948). The formation boundaries were plotted as they would appear on the bedrock surface. Not all the beds are known in the Tiger Hills region, and much data is derived solely from well records.

The information below is mainly from Wickenden (1945) and Tovell (1948). Remarks on the effect of the bedrock on the geomorphology of the area follow descriptions of pertinent formations.

STRATIGRAPHY

GENERAL STATEMENT

The formations that would form the Tiger Hills region if all overburden were removed range from Jurassic to Paleocene in age. Present exposures are poor and the lower formations (below Favel) in the area are known only from well logs. Many outcrops are on the sides of Pembina trench, where slumping is prevalent. Exposures of contacts between formations are rare. In general the sediments are mainly soft shales with more competent siliceous shales, massive calcareous shale, and siltstones with minor amounts of sand and sandstone. Table 2-1 lists the formations with thicknesses and correlatives in northern United States.

Wickenden lists a probable erosional unconformity in the Jurassic and another erosional unconformity at the base of the Jurassic beds. Below the Jurassic beds, Devonian Silurian and Ordovician beds lie unconformably on Precambrian igneous and metamorphic rock at an altitude of approximately 1,352 feet below sea level, as shown by Commonwealth Manitou well No. 2 (Section 26-2-9 W. Prin.). Thus, roughly 3,500 feet of younger sediments rest on the Precambrian rocks.

Table 2-1 BEDROCK FORMATIONS

Era	Period or Epoch	Formation and thickness	Litholog
Cenozoic	Paleocene	Turtle Mountain 300	Sand and soft shale beds
Mesozoic & Cenozoic	Paleocene ? & Cretaceous	Boissevain sandstone 100	Sand and sandstone
		unconformity ?	
Mesozoic	Upper Cretaceous	Riding Mountain shale	
		Odanah phase 610	Hard siliceous grey shale breaking fis concretions
		Millwood phase 65	Soft waxy greenish- variable thickness
		Vermillion River	
		Pembina member 80	Soft black shale wit bentonite near bas
		Boyne member 150	Buff-weathering, c silty, white-speck shale with iron, i bentonite beds
		Morden member 180	Dark grey soft shal septarian concret
		Favel 170	Grey shale and soft weathering limest
	Upper & Lower Cretaceous	Ashville 40	Dark grey shale, m sand, limestone a
	Lower Cretaceous	Swan River 50	Sand, sandstone, s
	Jurassic	Jurassic 380	Grey shale, calcar variegated shale
		unconformity ?	

Note: The use of Upper and Lower Cretaceous as time terms conforms wit
Survey of Canada

BEDROCK FORMATIONS

Formation and thickness	Lithology	Northern U.S.A. correlative
ırtle Mountain 300	Sand and soft shale with lignite beds	Fort Union ?
oissevain sandstone 100	Sand and sandstone, non-marine	Lance ? Cannonball marine ?
unconformity ?		
ding Mountain shale		Pierre shale
Odanah phase 610	Hard siliceous grey massive shale breaking fissile; ironstone concretions	
Millwood phase 65	Soft waxy greenish-grey shale of variable thickness	
ermillion River		
Pembina member 80	Soft black shale with much bentonite near base	Pierre shale
Boyne member 150	Buff-weathering, calcareous, silty, white-speckled, grey shale with iron, iron-stained bentonite beds	Niobrara
Morden member 180	Dark grey soft shale with septarian concretions	Benton
ıvel 170	Grey shale and soft grey buff-weathering limestone	Benton
shville 40	Dark grey shale, minor silt, sand, limestone and bentonite	Benton
van River 50	Sand, sandstone, shale	Dakota ?
ırassic 380	Grey shale, calcareous shale, variegated shale	Morrison
unconformity ?		

Cretaceous as time terms conforms with the useage of the Geological

JURASSIC

All knowledge of Jurassic beds is from well samples. Sandy, fossil-free limestones, thought to have originated by erosion of Paleozoic rocks, form the base of the Mesozoic section and grade upward into calcareous shales of known Jurassic age. These in turn grade upward into non-calcareous reddish-brown marine shale. Above the marine shale is a series of variegated shales of non-marine origin, containing fauna and flora similar to those of the Morrison formation. The non-marine beds are overlain by 70 feet of gray marine shale. In all the Jurassic rocks are about 380 feet thick.

CRETACEOUS

Swan River group

Rocks of the Swan River group are known from well samples in the Tiger Hills region and from exposures northwest of the area. This Lower Cretaceous group is sometimes erroneously correlated with the Dakota sandstone (the basal member of the Upper Cretaceous). The Dakota sandstone is of non-marine origin, whereas the Swan River group is of marine origin in the Tiger Hills region and assumes a non-marine character farther northwest. In Commonwealth Manitou well No. 2 west of Kaleida, the group is about 50 feet thick. The upper two-thirds are fairly pure quartz sand, and the lower third is medium to dark grey shale.

Ashville formation

The Ashville formation, about 40 feet thick, comprises an upper layer of greasy black shale that is brown where weathered and breaks into flakes or flat chips, and a lower dark grey clayey shale. North of the Tiger Hills region the two phases are separated by a silt or sand layer. The shale is marine but the lack of diagnostic fossils makes its age uncertain; it contains beds of both Upper and Lower Cretaceous age. Thin sand beds and several thin bentonite beds are present.

Favel formation

The Favel formation is about 170 feet thick in the Tiger Hills region. In the only known exposures (NE 11-4-6 W. Prin.) two or three feet of fossiliferous limestone overlie a brown (weathered) clay. Wickenden's description of the formation is based on well logs and exposures outside of the Tiger Hills region. Kirk divided the formation into two parts, the uppermost Assiniboine member and the lower Keld member. Both members consist of "grey shale speckled with white calcareous material". Wickenden implies doubt of the need for subdivision.

The outcrop illustrated in Figure 2-1 is part of the Assiniboine member, which contains several beds of very fossiliferous limestone up to four feet thick interlated with, and overlying, grey speckled shale. The Keld member contains limestone beds a few inches thick, grey calcareous speckled shale, and some beds of bentonitic clay that is white when weathered.

Vermillion River formation

The three members of the Vermillion River formation

Figure 2-1. Road-ditch exposure of the Assiniboine member of the Favel formation, located at NE 11-4-6 W. Prin.

are exposed along the Manitoba escarpment and in the lower part of Pembina trench. These marine beds thicken southwestward and are about 400 feet thick in the Tiger Hills region.

Morden member

Locally, the upper few feet of the Morden member are speckled calcareous shale, but most of the member is "fairly soft, somewhat fissile, dark grey non-calcareous shale that contains large ellipsoidal septarian concretions" (Wickenden, 1945, p. 34). Crystals of selenite are common. The concretions, as large as eight or ten feet in diameter, are concentrated in zones (Fig. 2-2) and are sufficiently numerous to form lithologic terraces along the Manitoba Escarpment. Fragments of concretions occurr in the drift. The Morden member may be as thick as 200 feet in the Tiger Hills region.

Boyne member

The Boyne member is about 150 feet of grey calcareous shale with bentonite beds and some dark grey non-calcareous shale in the lower part. The upper beds contain numerous thin bentonite layers that are commonly iron-stained where weathered; thin bentonite layers occurr throughout the member. Some of the calcareous shale is massive and forms terraces in Pembina trench. The lower part of the member is non-calcareous, and weathers in thin laminae (paper shale). Some pebbles of calcareous shale that occurr in the till of the Tiger Hills region are derived from the Boyne

Member. Probably this member is equivalent to the Niobrara beds in central United States.

Pembina member

The Pembina member forms the upper part of the Vermillion River formation, and is dark grey to black non-calcareous soft shale with numerous bentonite beds near the base. According to Tovell, the black shales grade upward into the Millwood phase of the Riding Mountain formation. North of Mowbray the Pembina member is about 80 feet thick. The lower 15 feet is about half bentonite of economic importance. Ideal locations for strip-mining operations are provided by some of the in-and-out channels along the Manitoba escarpment. Several species of mosasaur, a turtle, fish, and other vertebrates have been found there. The beds slump readily and probably play an important role in mass-wasting along Pembina trench.

Riding Mountain formation

Greenish-grey clay beds and siliceous shale of the marine Riding Mountain formation form the uppermost Cretaceous rocks in the Tiger Hills region. They correlate with the Pierre shale in North Dakota. The upper contact is not exposed, nor is well information available; but the formation may be as thick as 675 feet. Wickenden divides it into two phases, which were recognized much earlier by Tyrrell and MacLean (See Kirk, 1930, p. 124B to 128B). The hard siliceous upper phase was termed the Odanah phase by Wickenden, who accepted Tyrrell's designation. Wickenden gave no name to the lower soft clay

Figure 2-2. Morden member of the Vermillion River formation exposed at Lake Minnewashta southeast of Morden. This part of the member is a dark grey clay. A zone of septarian concretions forms the top of the slope.

Figure 2-3. Exposure of Odanah phase of Riding Mountain formation at SW 10-5-16 W. Prin. A 4-inch bed of bentonite is in massive, siliceous grey shale.

phase, which MacLean had previously called Millwood (using a lithologic correlation with beds farther north so designated by Tyrrell). Tovell (1948) accepted MacLean's usage, which is retained by the writer because the base of the Odanah beds is a lithologic rather than a stratigraphic horizon. The units are termed "phases" in preference to "members".

<u>Millwood phase</u>

Millwood beds occurr in Souris River cuts southwest of Wawanesa, but rapid slumping destroys the exposures. On Pembina Mountain the beds form mud-cracked slopes nearly barren of vegetation. The Millwood phase, about 65 feet thick, is a waxy greenish-grey clayey shale, with a few thin bentonite beds. South of Wawanesa, ironstone concretions as much as 1.5 feet in diameter are concentrated in several horizons. Tovell (1948, p. 5) suggested that the Millwood phase may be more closely related to the Pembina member of the Vermillion River formation, than to the Odanah phase of the Riding Mountain formation.

<u>Odanah phase</u>

The top of the Odanah phase has been eroded away throughout the region. In the southwest corner the contact with the overlying Boissevain sandstone is obscured by drift. The maximum thickness in the Tiger Hills region is estimated by the writer as about 610 feet. The hard greenish-grey siliceous shale that forms the Odanah phase is the most competent rock in the area and forms a very large portion of the glacial drift, both as pebbles and as comminuted material.

Most of the beds are massive and break into fissile fragments when weathered. A few bentonite layers are present (Fig. 2-3). Purple-stained concretions are distributed irregularly through the shale and purple staining of the rock itself is common. The writer submitted a concretion to Messrs. C. Smith and B. Griffin who identified it as mainly limonite and found no manganese. Some joints in the Odanah shale show iron oxide staining, while others are filled with selenite crystals. The rock forms cliffs and is the core of numerous drumlinoids and other ridges. It also forms lithologic terraces. Odanah shale is the principal component of most esker and alluvial gravels in the area.

PALEOCENE

Boissevain sandstone

Outcrops of the Boissevain sandstone are unknown in the Tiger Hills region but the formation is encountered in wells. It occurrs only in the southwestern corner at the region on Turtle Mountain where the drift cover locally confines artesian water in it. The Boissevain formation is a greenish grey medium grained sandstone that weathers to a rusty yellow. Locally, lenses are cemented to form a hard rock suitable for building stone. Fossils are rare but the non-marine character of the beds has been established. The formation is thought to be about 100 feet thick, but no wells have penetrated either the upper or lower contacts. The rock is resistant enough to form a lithologic terrace around the north and west end of Turtle Mountain. Apparently, the

Boissevain sandstone lies unconformably on the Riding Mountain formation. Because of its non-marine origin and the unconformity beneath it, it is tentatively correlated with the lithologically similar Frenchman formation farther west, and may be either late Upper Cretaceous and/or early Paleocene in age (Hume, 1947, p. 196). Mr. Saul Aronow (oral communication) stated that none of these beds have been observed at the east end of Turtle Mountain south of the International Boundary; the contacts shown on Plate 2 are hypothetical and were drawn on the assumption that the beds are extensive and nearly flat-lying.

Turtle Mountain formation

The Turtle Mountain formation consists of shale and sandstone with some lignite. The top of the formation was removed by erosion. Some massive greyish-brown clays at an altitude of 2,250 feet near the International Boundary south of Boissevain may be part of the formation that was disturbed by glaciation. Assuming bedrock is within 50 feet of the surface, and that the beds are horizontal, they may be more than 400 feet thick. Exposures at the west end of Turtle Mountain are mostly of fine white or yellowish sand and sandstone overlain by brownish-grey shales. Most of the lignite beds are too thin to be of economic value, but one pair with a total thickness of five feet has been mined. The formation is not exposed in the Tiger Hills region and may not be present. It is correlated with the upper part of the Ravenscrag formation (Fort Union ? in the United States).

R. W. Lemke (oral communication) suggested that the lower part of the Turtle Mountain formation resembles the marine Cannon Ball formation.

STRUCTURE

DIASTROPHIC STRUCTURES

The bedrock structures observed in the Tiger Hills region are gentle swells with dips measured in feet per mile. Only one fault was observed, near Wawanesa, but others must exist.

Roseisle Swell

Wickenden (1945, p. 54) described a gentle elevation of the top of the Boyne beds from the International Boundary to St. Lupicin to Treherne. This gentle swell corresponds to a vertical distortion of Lake Agassiz strandlines where their slope decreases, northward from Roseisle, and may represent post-glacial crustal movement (Chapter 5).

Darlingford Anticline

Wickenden (1945) noted a small bedrock high in the Pembina Valley south of Manitou. The writer correlated this with a local high indicated by an outcrop of upper Favel beds about seven miles north of Morden (NE 11-4-6 W. Prin.), although the highs may represent separate structures. The amplitude of the anticline is roughly from 30 to 50 feet.

Wawanesa Fault

A small fault that dips southeast and has an undetermined strike is exposed in a cut in Section 15-17-17, W. Prin. The southeast beds dropped 10 or 15 feet. At first this was thought to be a slumped block or an ice-thrust feature, but closer examination proved a small normal fault. Overlying drift is undisturbed. No doubt, similar faults exist but are not exposed.

ICE-THRUST STRUCTURES

Numerous small folds and faults observed in the Odanah shale were caused by glacier thrust. These are particularly common on the south side of Pembina Trench, where a scarp must have been an obstacle to the advancing ice. A minor fold west of Pilot Mound (NW 15-3-12, W. Prin.) is shown in Figure 2-4. Foreign boulders and gravel have been introduced into the broken beds of many of these folds. These ice shove structures are common on the south sides of isolated knobs in the Tiger Hills; the north sides of the knobs are glacial drift. Pilot Mound has a core of disturbed shale with a dome-like thrust structure that inspired the drilling of an oil well. No doubt most drumlinoids have cores of disturbed Odanah shale.

TOPOGRAPHY OF THE BEDROCK SURFACE

Contours of the bedrock surface with an interval of 100 feet appear on Plate 2. The data on which these are based were derived from oral statements by well-owners, and from information from electro-logging and seismic operations kindly made available by the California Standard Oil Company.

In general, the bedrock topography resembles the present topography. The highest area, probably about 1,900 feet is Turtle Mountain in the southwest corner of the Tiger Hills region. East of this, including half the map-area, is

Figure 2-4. Road cut at NW 15-3-12 W. Prin., showing Odanah shale distorted by ice thrust at the south rim of Pembina trench. The trench is to the left, and the thrust came from this direction.

a plain with an altitude of from 1,400 to 1,500 feet. A local high in the northwest corner is at about 1,400 feet. Across the Tiger Hills, between the elbow of Souris River and St. Lupicin, are several bedrock knobs from 0.5 to 2 miles across with a relief of 50 to 150 feet (too small to be shown on pl. 2). On the east side of the area, the bedrock surface of the Manitoba Escarpment slopes steeply from about 1,500 feet to 600 feet, or lower, in 15 miles. Across the north side of the Tiger Hills region the altitude of the bedrock surface varies from less than 600 (?) feet in the east to about 1,000 feet in the middle and increases to 1,400 feet in the northwest corner. This re-entrant in the Manitoba escarpment was made by a large preglacial river, possibly the ancestral Missouri (Todd, 1923), and/or a river which flowed across the plains in the general course of the present Qu'Appelle-lower Assiniboine system (Pl. 6A). Evidence for this other than the present configuration of the system is scant. J.C. Sproule stated (oral communication) that the drift in one place a few miles north of Regina is 700 feet thick; a large preglacial valley must be buried under the drift in this area, and the Assiniboine re-entrant is a logical place for the valley to have crossed the Manitoba Escarpment. A tributary of this ancestral Assiniboine River crossed the International Boundary west of the present Souris River and flowed north through the middle of the basin of glacial Lake Souris (Pl. 6A). A series of bore holes spaced at 1,800 feet revealed youthful valleys as much as 1 mile and 250 feet deep tributary to the larger valley. The bedrock surface slopes gently westward to an altitude of about 1,300 feet at the Saskatchewan boundary. This valley was probably the downstream portion of the former Knife River in North Dakota.

In the Tiger Hills region, the details of preglacial drainage differ from those of the present poorly integrated system. One preglacial stream left the map-area south of the town of Cartwright and drained townships 1 to 3, ranges 15 and 16, and part of Turtle Mountain. A preglacial stream flowed north, winding back and forth across the boundary of ranges 17 and 18, into township 8, range 17 and joined the ancestral Assiniboine River. A shallow buried valley extends north from Rock Lake several miles west of Cypress River town. Several tributaries joined this valley from the southeast. The Pembina valley below La Riviere antedated the last glaciation of the area. North of Windygates, Pembina trench has a bedrock floor at 1,095 feet, or lower, 55 feet below the present valley bottom. Mr. Donald Youngman (oral communication) reported glacial till on the valley floor here in borings made in connection with a damsite. Evidence is scant but at the present time there is no indication that a preglacial valley extended west beyond range 10 or north beyond township 3 or 4. The valley was cut into the steep face of the Manitoba Escarpment and was gully-like in character. The problem of its origin is considered in Chapter 5.

The Pembina trench above La Riviere anomalously crosses two buried valleys, one in township 3, ranges 13 and 14, and one in township 6, ranges 17 and 18. It crosses a col in township 3, range 14, and another in township 4, range 16. Elsewhere (township 6, range 19, townships 3 and 4, range 12) the trench is parallel to the regional bedrock slope. Clearly, most of the trench post-dates the bedrock topography.

Chapter 3

SURFICIAL GEOLOGY

INTRODUCTION

GENERAL REMARKS

Mapping glacial geology requires a compromise between lithologic units and genetic units, and the academic approach emphasises the latter. A text must also be a compromise between description of such forms as end moraine and outwash bodies, and lithologic units like till and lake sand. In this chapter the emphasis is on genetic units, and lithologic descriptions are inserted where they are pertinent. Thus, a discussion of till precedes sections on end moraine and ground moraine, both predominantly till.

MAPPING PROCEDURE

The quality of mapping in the Tiger Hills region varied as the writer learned the techniques best adapted to the problem.

During the field seasons of 1947 and 1948, mapping was secondary to collecting ground-water data. Townships 1 to 6, ranges 18 and 19, were summarily studied in 1947 by driving over the road network and noting topographic differences. Road cuts were examined but no holes were dug. The resulting map was a modification of soils maps by Ellis and Shafer (1940, 1943). When vertical air photographs became available this map was revised and the pattern of washboard moraines added. In 1951 the north part of this area was rechecked by more refined mapping procedure.

In the summer of 1948 a technique similar to that of 1947 was used to map townships 1 to 10, ranges 14 to 17, except that more attention was paid to road cuts.

In 1949 air photographs of the region became available. Collection of ground-water data ceased to be part of the program and all attention was devoted to geological mapping. Townships 1 to 8, ranges 10 to 17 were studied in 1949 and 1950. This work was on a sampling basis; road cuts were studied and auger or spade holes reaching into the C horizon of the soil were put down at every crossroads (1 mile intervals) or more frequently. The data were recorded on the back of air photographs pin-pricked at the location, and contacts were sketched on the photograph itself. The area mapped in 1949 and 1950 was to have been the basis of this dissertation, but the lack of a large-scale base map and the general lack of detail resulting from a technique suited to reconnaisance mapping made expansion of the area to its present size (Pl. 3) necessary.

Late in 1950 a change in mapping technique was made; instead of sampling on a grid basis, a few long traverses were made to establish contacts, and then the intervening areas mapped by following the contacts between the traverses. Extensive areas of ground moraine and sand dunes were mapped by photo-interpretation. Townships 1 to 8, ranges 5 to 9, and townships 7 and 8, ranges 18 and 19 were mapped in this manner. Some contacts in areas previously mapped by the grid sampling method were checked. In general, contacts are readily determined from air photographs, and the earlier work was easily made suitable for a map on the scale of 1 inch to 3 miles.

References will be made to mapping done from 1952 to 1954 north and west of the Tiger Hills region (index on Pl. 6). This work is of the same quality as the later mapping in the Tiger Hills region but is presented in preliminary form.

GENERAL DESCRIPTION OF THE MAP

About one third of the Tiger Hills region was covered by glacial lakes. The resulting lake and delta deposits are in the north and east parts of the area (Pl. 3). The upper Assiniboine delta, in the north, is mainly sand, about half of which has been redeposited by wind action. In the northeast of the map-area, sand deposits of the younger Assiniboine delta in Lake Agassiz have also been modified by wind. The sands of the older and younger deltas are separated by an area of clay north of Rathwell. This clay probably represents the bottomset beds of the upper delta. In the east and southeast the lake deposits are dominantly silt, and are covered by thin bodies of clayey alluvium along the present streams. Beach ridges of Lake Agassiz are common along the Manitoba Escarpment and extend a short distance beyond it northwest from Treherne where they fade out on the upper Assiniboine delta.

The remaining two-thirds of the Tiger Hills region (the Second Prairie Steppe) are covered by glacial deposits. In the southwest of the map-area is a large tract of end moraine, comprising a rough area on Turtle Mountain and a large belt of washboard moraine in the Killarney plain. The washboard moraines form a lobate pattern as of an ice tongue retreating northwestward. The Darlingford moraine is one of the most conspicuous end moraine deposits and forms the crest of Pembina Mountain. From Notre Dame de Lourdes it trends slightly northwest then southwest to meet Pembina trench north of Pembina Lake (Fig. 1-6). From Pembina Lake west it is parallel to Pembina trench as far as the west boundary of the map-area. At the west boundary it turns north to Brandon Hills. The Darlingford moraine varies in width from about 0.25 mile in the east to 4.0 miles in the west. It is composed of sandy till except north of Pembina Lake where it is mainly ice-contact stratified drift. Ground moraine, characterized by numerous drumlinoids between Learys and Baldur and between Hilton and Methven, and areas of subdued end moraine elsewhere, borders the Darlingford moraine on the north side. In the Baldur-Hilton area, washboard moraines form lobate patterns between bedrock-cored hills. A branch of the Darlingford moraine extends east to Methven from south of the Brandon Hills. A similar extension trends west towards Souris (Pl. 6). The Darlingford moraine truncates older washboard moraines near Windygates, thus forming a topographic discontinuity.

Numerous areas of outwash gravel and sand in the south central part of the Tiger Hills region are associated with a clayey, gritty silt that may be partly eolian in origin. These deposits are 2 to 10 feet thick and overlie till. The till forms ground moraine from 5 to 20 feet thick on a smoothly undulating bedrock surface.

Most of the ice-contact stratified drift deposits north of the Darlingford moraine are kame moraines and transverse eskers; a few small eskers are parallel to the direction of ice movement. South of the Darlingford moraine, ice-contact stratified drift forms ridges from 0.5 to 1.0 mile long that are parallel to the direction of ice movement (southeast) indicated by drumlinoids, striated boulder pavements, till-fabric analyses, and the pattern of washboard moraines. Some of these ridges are interpreted as interrupted eskers as long as 11 miles, e.g. the one passing through Crystal City (Fig. 3-12).

Waterworked drift is a lag concentrate of boulders, gravel, and sand that forms the surface of wave-cut terraces along the Manitoba Escarpment and much of the narrow plain between the Tiger Hills and the Assiniboine delta.

The chief bodies of alluvium are the Cypress River alluvial fan, alluvial fans along the base of the Manitoba Escarpment, and terraces and flood plains in the Assiniboine and Pembina valleys. Valley-fill terraces in the Assiniboine valley consist of lake and fluvial sand, silt, and clay and contain mollusk shells. Valley-fill terraces in Pembina trench are poorly sorted shale gravel and sand and contain almost no organic matter. From the base levels and organic content of these alluvial fills it is clear that the one in Pembina trench is associated with an early phase of Lake

Agassiz and the one in the Assiniboine valley with a much later phase. Terraces higher than the alluvial fill in Pembina trench are covered with outwash gravel.

SURFICIAL DEPOSITS

GENERAL

Introduction

The surficial deposits of the Tiger Hills region are of two types: (1) those deposited from glacier ice directly, or by meltwater, and (2) those deposited by non-glacial streams or in lakes. Although the lake deposits were laid down in glacial lakes, they originated not from the ice front but from non-glacial streams entering the lakes on the opposite side, and are not different from any other lake deposits.

The large size of the area and the reconnaisance nature of the survey restricted the studies of sediments mainly to general description. No characteristic such as lithology or weathering by which drift of one age could be distinguished from older or younger deposits was discovered. Sedimentation studies dealing with till fabric, roundness of pebbles, and provenance are discussed at the end of this chapter. Except for the till fabric analyses, results were negative.

The following discussion of the constitution of glacial deposits forms a preface to later descriptions of specific deposits.

Materials (Mechanical aspect)

Types of till

Most of the deposits are adequately described under their own headings, but the term "till" does not appear as a map unit even though most ground moraine, washboard moraine and end moraine is predominantly till. Hence, a detailed consideration of till is presented before the discussions of moraine forms.

Till is defined by Flint (1947, p. 102-114) and Pettijohn (1948, p. 212-223) as a direct glacial deposit in which water activity plays a minimum role. Tills vary from place to place depending on source materials, and there is a gradational sequence from till to stratified drift. These factors combine to produce a number of "facies" that complicate correlations within a region.

From his observations of existing glaciers in the Rocky Mountains of Alberta, the writer concluded that there are four principal phases in this gradational sequence: (1) lodgement till, plastered on to the subglacial floor under great pressure, (2) till formed under subaerial conditions by melting out of englacial debris at the sole of the glacier, (3) superglacial till (ablation moraine) lowered from the surface of the glacier by melting, and (4) glaciofluvial deposits.

Lodgment till is apparently deposited from basal ice by very slow melting (pressure melting) which frees the debris trapped in the sole of the glacier and allows it to be plastered on to the subglacial floor. No sorting whatever takes place. The resulting deposit is a very compact mixture of clay, sand, silt, pebbles, and cobbles (Sample 51-66, Fig. 3-1a) that generally has a crude fissility and a statistically preferred orientation of pebbles parallel to the direction of ice movement. Pebbles and cobbles are faceted and striated and their corners are subrounded by intense abrasion.

The second phase generally rests on lodgment till and is commonly separated from it by a well-defined plane, but the contact may be gradational. It contains the same type of subglacial debris as does lodgment till and may have a similar grain-size distribution. The chief difference is that this material is not compact. The interstitial ice in the subglacial debris melts from the top as well as from the bottom so that there is no load on the material as it emerges from the glacier. Elongate boulders and cobbles are oriented parallel to the direction of ice movement, but the englacial orientation of pebbles and smaller particles is destroyed by collapse when the supporting ice matrix melts. When saturated with water this till is semi-fluid and displays thixotropic properties. When dry, the deposit is uncompact and lacks well-defined pebble fabric and fissility. It is produced from the thin edge of the glacier margin during retreat. Small amounts of the clay and silt fractions may be removed by water and wind, although where observed by the writer, most of the meltwater apparently evaporated or seeped

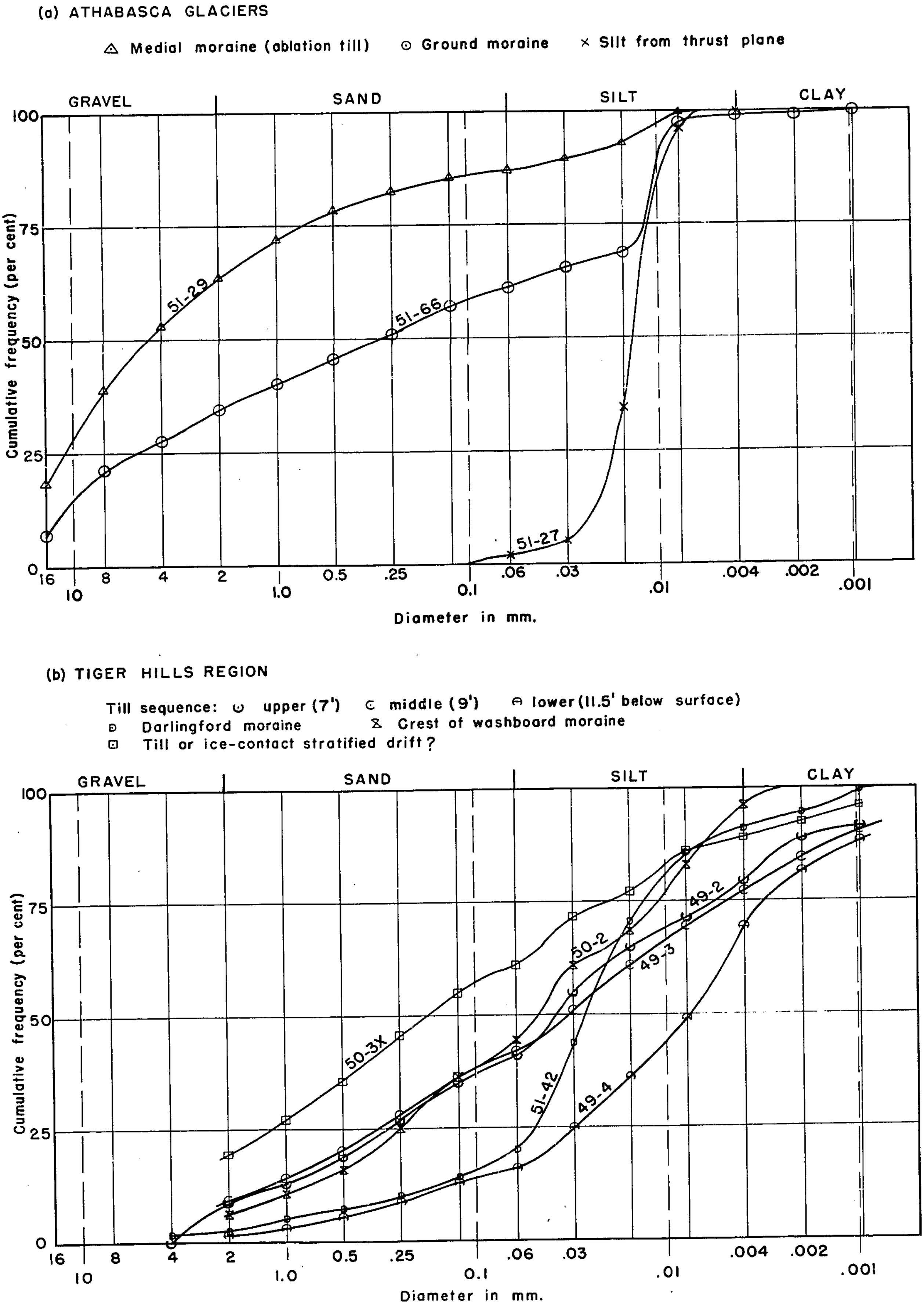


Figure 3-1. Grain-size distribution of glacial sediments. Sample numbers are text references.

away. This type of till forms thin sheets whose thickness is governed by the amount of debris in the sole of the glacier, generally 6 or 8 inches. The thickness might be greater under other conditions of climate, subglacial floor, type of debris in the ice, etc. Some deposits mapped as superglacial till (ablation moraine) may have formed in this manner.

Superglacial till also termed ablation moraine (Flint, 1947, p. 111-114), forms the third phase. Material thrust up into the ice above irregularities in the subglacial floor and in the thrust zone near the margin (Salisbury, 1902) emerges on the surface as the glacier melts. The debris is generally in a crushed condition and the fragments are angular. The average grain size is relatively coarse as there is a much smaller proportion of silt and clay than in the first two phases. Ablation moraine becomes thicker as the ice melts beneath it and frees more debris. When more than 2 inches thick it insulates the ice and retards melting; it rarely becomes thicker than 3 or 4 feet. Like the second phase, ablation moraine is not compact. The chief differences from the other phases are the angularity of the fragments and the larger average grain size. If underlying till, in place of bedrock, is carried up in the glacier thrust planes, the resulting ablation moraine may be indistinguishable from the second phase.

Glaciofluvial deposits, including ice-contact stratified drift and outwash, form the fourth depositional phase. Meltwater streams in and on the ice collect glacial debris and redeposit it in crevasses, depressions in the ice, and beyond the margin of the glacier. These streams generally have steep gradients and can transport small boulders. Gravel and sand are deposited in and near the ice while sand, silt, and clay, are deposited considerable distances beyond the margin. The sand grains are generally angular to sub-angular. Pebbles, cobbles and boulders are sub-round to well rounded, and glacial facets and striae are mostly destroyed by abrasion.

Whether the second and third phases can be recognized in southwestern Manitoba is doubtful because the constituents were derived from pre-existing glacial sediments, and their diagnostic characteristics of particle shape, rounding, grain size, etc., were established previously before redeposition. The second phase may be indistinguishable from lodgment till modified by severe frost action of the present winter climate.

Tills of the Tiger Hills region

Mechanical analyses of several tills of the Tiger Hills region are shown graphically in Figures 3-1(b) and 3-2. Sandy till (specimens 49-2, 49-3, and 50-2) is most abundant and generally comprises about 10 to 20 percent clay, 30 to 40 percent silt, and about 40 percent sand and coarser particles. It is generally compact and has a crude fissility (Fig. 3-3) which is commonly horizontal but may stand at angles as high as 60°. Oxidation of the till is slightly more advanced along the planes of fissility. Preferred orient-

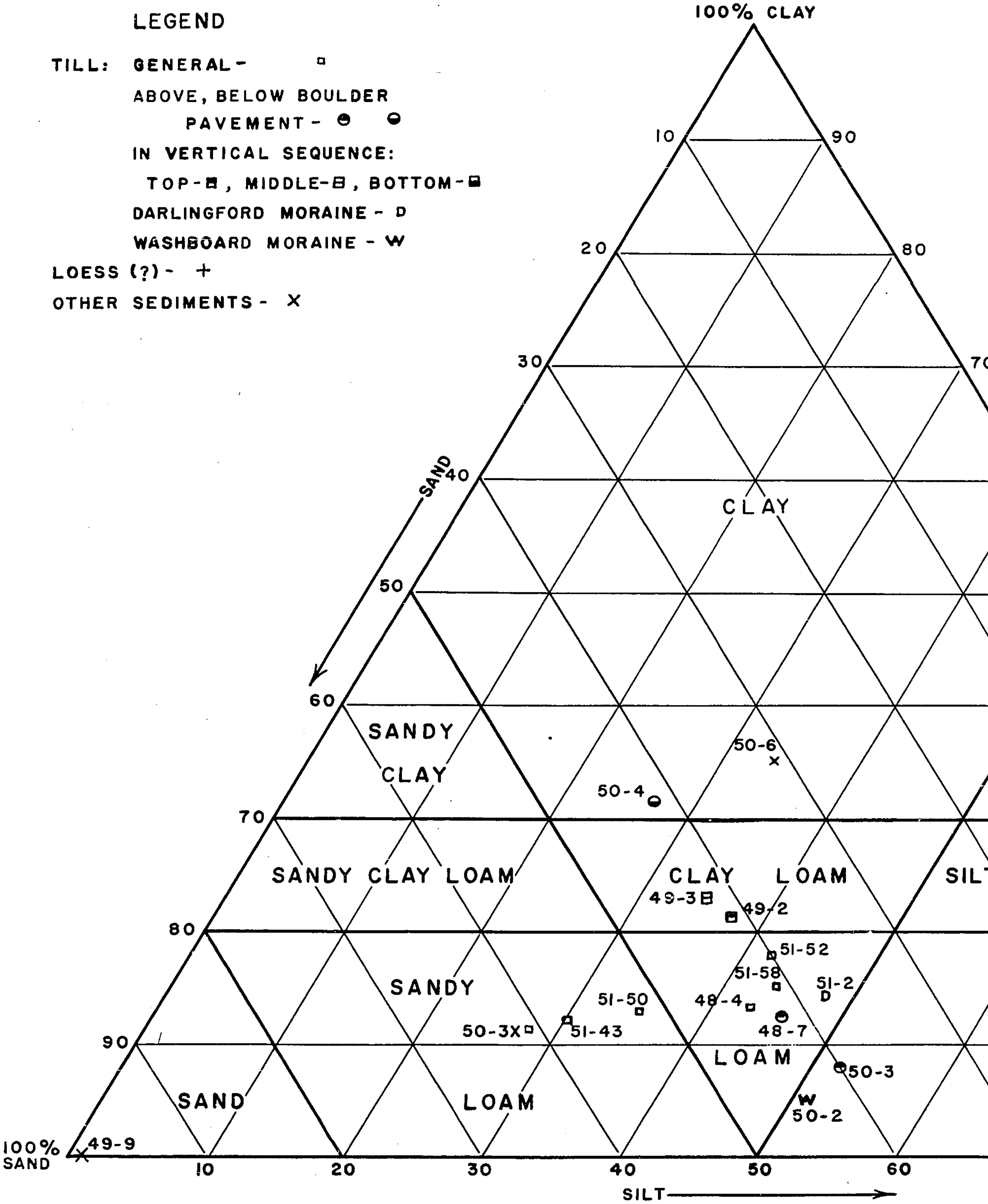
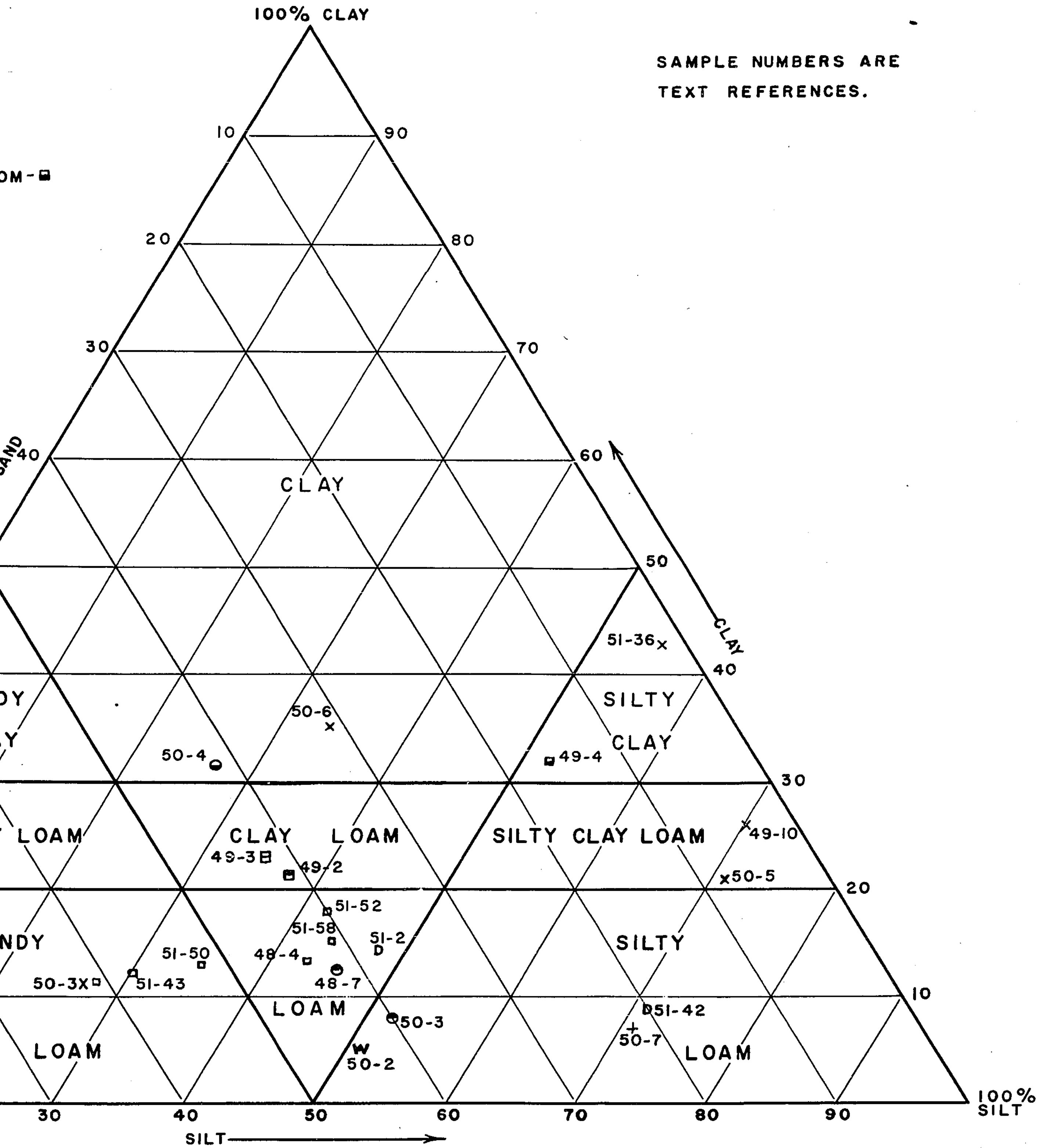


Figure 3-2. Mechanical analyses of soil samples



l analyses of soil samples

Figure 3-3. Specimen of sandy till, slightly disturbed during removal, showing well developed fissility. The shovel blade on which the specimen rests is 9 inches wide. Fissility is not apparent when the till is saturated with water.

ations of pebbles parallel to the direction of ice movement are well developed in this type of till. Boulders and pockets of compact silt and sand are common. In general, the tills of the Tiger Hills region are not stony compared to tills of the northeastern United States. This is probably because (1) the constituents may have been handled several times during the Wisconsin age by glaciers, rivers, and lakes which isolated the coarser particles or reduced their size before they were incorporated into the present glacial deposits, (2) the till is derived mainly from local bedrock: relatively soft shales, sandstones and siltstones which do not survive long as boulders or cobbles in the glacial "mill", (3) such source areas of harder stones as the belt of Paleozoic rocks bordering the Precambrian shield and the Precambrian shield itself are so remote from the Tiger Hills region that stones from them were thoroughly dispersed and reduced to small sizes by the time they arrived. The most abundant pebbles are dolomites (dolostones) and limestones.

The various undulations (corresponding to modes in a histogram) on the cumulative grain-size distribution curves (Fig. 3-1) may result from the comminution of rocks of different lithology, e.g. limestone, shale, and granite. In a ball mill supplied with an excess of coarse material, comminution progresses by crushing until a certain critical grain size predominates over all others. The abrasion becomes the dominant process and, as comminution continues, the product of abrasion which is finer than the product of crushing forms the preponderant grain size. 1/ Thus, in grain-size distribution curves of glacial deposits, especially, there may be modal classes for preponderant grain sizes of both crushing and abrading processes for each kind of rock present. In samples 51-66 and 51-27 (Fig. 3-1(a)) the preponderant size is the silt fraction. The modes in samples 49-2 and 50-2 (Fig. 3-1(a)) may be the combined effects of preponderant grain sizes from crushing and abrading of different rocks including shale, dolomite and granite.

Clay tills contain 20 percent or more of clay (Sample 49-4, Fig. 3-1(b)). They generally comprise a high percentage of Odanah shale and commonly underlie 10 to 20 feet of sandy till. Samples 49-2, 49-3 and 49-4 were taken from 7 feet, 9 feet and 11.5 feet, respectively, below the surface in a new excavation in NE 13-1-17 W. Prin. The two upper samples are sandy till and the lower one is clay till. The uppermost specimen is oxidized to a moderate dark yellowish-brown color. Fractures in the middle specimen are brown but the bulk of the specimen is dark grey when moist. The lowest specimen of till is olive-grey when moist and is the "blue clay" referred to by the inhabitants of the area. There is generally no distinct break between the sandy and clayey till. Locally, a striated boulder pavement separates

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1. H.A. Lee, unpublished oral communication; Mr. Lee was working on his Ph. D. dissertation for the University of Chicago, and kindly volunteered a limited discussion of previous engineering experiments on crushing that might be applicable to glacial deposits.

a lower clayey till from an upper sandy till, but there is no leaching or oxidation to suggest an interval of subaerial exposure. Clay tills are uncommon in the Tiger Hills region and are known mainly from well records and observations in places where shale bedrock is near the surface.

A third type of till, silty till (Sample 51-42, Fig. 3-1(b)) forms much of the eastern part of the Darlingford moraine. As much as 70 percent of the aggregate is silt and pockets of sand are common. The silty character may be due to redeposition of silty sediment which was either (1) in an earlier lake deposit in the Lake Agassiz basin or (2) outwash deposited by the glacier that retreated northwest. Some very silty till forms washboard moraines east of Killarney; it may represent glacial reworking of outwash or a lake deposit.

A gravelly deposit on the north side of the Darlingford moraine is transitional between till and outwash, and (Sample 56-3X, Fig. 3-1(b)) may be compared to ablation till (Sample 51-29, Fig. 3-1(a)). The deposit may be older outwash or alluvium reworked by ice. The problem of distinguishing till from ice-contact stratified drift in the area between Notre Dame de Lourdes and Greenway is difficult. In one attempt, roundness was measured by visual comparison of each pebble with a chart prepared by Krumbein (1941, facing p. 68). In this system a sphere has a roundness of 1.0 and a very angular pebble has a roundness of 0.1. In the two samples studied, the roundness of pebbles in the different size grades (less than 16 mm., 16 to 24 mm., 24 to 32 mm., and greater than 32 mm.) showed little variation, and for statistical purposes they were all grouped together. A sample of ice-contact stratified drift from a pit in NW 32-6-10 W. Prin. consisting of 104 pebbles showed a mean roundness of 0.35 with a standard deviation of ±0.12. An analysis of 127 pebbles from sandy lodgment till in SE 3-7-11 W. Prin. gave a mean roundness of 0.44 with a standard deviation of ±0.12. When shale stones were excluded from the analysis of till pebbles in order to give a lithology more comparable with that of the problematical deposit, the mean roundness was 0.49 and the standard deviation ±0.08. Clearly, the till pebbles are the roundest. This probably is due to intense abrasion of till particles, whereas ice-contact stratified drift and ablation drift particles are first crushed and then elevated to an englacial position where they undergo no abrasion. The material in SE 3-7-11 W. Prin. is certainly sorted but resembles ablation moraine more than outwash or other stream-transported material. At the outset of this study it was thought that stratified drift particles would be rounder than lodgment till particles which would in turn be rounder than ablation till. The situation is evidently more complex, so the method was dropped. 1/

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1. Studies of roundness in the Tiger Hills region lead to no significant conclusions but the following generalizations are of interest: (1) Pebbles subjected to crushing and little water action, as in ablation moraine and in some ice-contact

Figure 3-2 is a ternary diagram showing mechanical composition of several soil samples. Discussions of these materials appear in appropriate places later in the chapter.

Lithologic Composition

Thousands of pebbles were studied in a fruitless effort to obtain evidence for the direction of ice movement in the Tiger Hills region (see p. 141 to 152). The lithologic composition of the pebble fraction of the drift tabulated below is based on 10 samples totalling 2,414 pebbles from the southwest part of the map-area. The pebbles were from 1.0 to 10 cm. long.

Lithology	Percentage
Quartzite and chert	2.1
Odanah Shale	17.3
Limestone	16.7
Dolomite	39.0
Granitoid rocks	14.3
Mafic aphanites	7.4
All others (Sandstones, schists, etc.)	3.4

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stratified drift, have a roundness of 0.35 or less. (2) Pebbles subjected to glacial abrasion as in lodgment till have roundnesses ranging from about 0.35 to 0.50, commonly about 0.45, (3). Pebbles subjected to considerable stream action have roundness ranging from 0.5 to 0.7.

Roundness studies are mainly of descriptive value and can be used to distinguish ablation drift from other types of drift, and as evidence to the type of material overrun by a glacier and incorporated into later deposits.

Odanah shale may form as much as 90 percent of the drift where it is thin and especially on or near bedrock hills. In a given till sample, the number of Odanah shale fragments is inversely proportional to the grain size. The alluvial fill in Pembina trench is predominantly Odanah shale pebbles and sand. In the Assiniboine delta, dolomite pebbles are the most abundant stones and granitoids are next in abundance, whereas Odanah shale pebbles are sparse. The dolomites and granitoids may have originated anywhere from east to north-northwest of the Tiger Hills region.

The coarse and very coarse sand fractions of the till comprise 60 to 80 percent rock fragments with quartz grains with a small proportion of feldspar. The medium to very fine sand fractions are 50 to 70 percent quartz, 10 to 40 percent rock fragments, about 10 percent feldspar, and contain small quantities of pyroxene and/or amphibole, limonite, and biotite. Sponge spicules and Foraminifera from the Cretaceous rocks are common. Detailed mineralogic studies of the sand sizes were not made, and the fractions finer than sand were not examined.

Thickness

The general thickness of drift in the Tiger Hills region can be determined by comparing the topographic contours (Pl. 1) with the bedrock surface contours (Pl. 2), and was discussed by physiographic subdivisions in Chapter 1.

The thickness of drift varies from nil on certain terraces and glacial spillway floors to more than 400 feet in a buried preglacial valley south of Cartwright. The drift of the upper Assiniboine delta may be as thick as 300 feet north of Glenboro. The drift cover on most of the bedrock hills in the east half of the map-area is from 3 to 15 feet thick. The Brandon Hills and Turtle Mountain have 150 to 300 feet of drift in places, but reliable data are scant. In the Lake Agassiz basin the sediments may be as thick as 200 feet along the east side of the map-area, and wedge out to nil at places along the base of Pembina Mountain. There are at least two lithologically different till sheets separated by a boulder pavement in the south-west part of the area. The till above the boulder pavement ranges from 8 to 40 feet thick, and averages about 20 feet. Near Pelican Lake, till in the Darlingford moraine may be more than 100 feet thick, and it may be still thicker in the Brandon hills.

In the buried valley south-west of Cartwright, sand and gravel beds comprise more than 15 percent of the surficial deposits and seem to separate two till sheets; available well logs are too vague to warrant any conclusions. Ice-contact stratified drift is generally more than 20 feet thick and forms much of the Darlingford moraine north of Pembina Lake. Ice-contact stratified drift near Babcocks may be as thick as 150 feet. Stratified drift from 25 to 100 feet thick occurs in the Tiger Hills between Glenora and Holland.

Probably the most massive single drift deposit is the upper Assiniboine delta, locally comprising as much as 255 feet of deltaic sediments. A test hole drilled by the California Standard Company was logged as follows:1/

Location: SE 20-9-14 W. Prin. (south of Carberry)
Altitude of ground: 1,199 feet.

Depth in feet	Lithology
0-85	Medium grained sand, 90 percent clear rounded to sub-angular quartz grains; some yellowish to orange grains; dark minerals 5 percent.
85-255	Light to dark grey silty clay with numerous included sand fragments as above.
255-325	Gravel interbedded with dark grey silty clay as above. Pebbles angular to subangular, calcareous, buff to light brown in color.
325	Bedrock (shale).

The gravel and clay between 255 and 325 feet may be partly till, and was omitted from the thickness of deltaic sediment mentioned above.

Thick clay in the Lake Agassiz basin is underlain by till. Unfortunately, available well logs are difficult to interpret because locally bedrock (e.g. the Morden member of the Vermillion River formation) is indistinguishable from lake clay, and drillers also apply the term "clay" to till. A representative well log follows, with the writer's interpretations in parentheses:

Location: NE 14-5-6 W. Prin. (near Rosebank)
Altitude of ground: 940 feet.

Depth in feet	Lithology
0-30	yellow clay (oxidized silt and lake clay)
30-133	black clay (lake clays, possibly varved)

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1. The writer is indebted to Dr. J.D. Allan for having the surficial deposits logged.

133-134	coarse sand and gravel (glaciofluvial deposits)
134-137	clay and gravel (till?)
137-159	black clay
159-162	coarse sand
162-192	sand and clay (Ashville formation ?)-bedrock
192-202	fine sand (Swan River formation ?)
202-211	clay (Jurassic rocks ?)

Statements made by several well owners indicate that about 40 to 60 feet of lake clay rest on till which extends down to 120 or 140 feet and overlies sand and gravel deposits, possibly of glacio-fluvial origin. As the sand and gravel deposit forms a good aquifier, most wells penetrate no deeper; hence no single well log shows the whole section. A reasonable estimate of maximum drift thickness is the Lake Agassiz basin, within the Tiger Hills region, is about 200 feet.

Descriptions of Deposits

In the following discussion the surficial deposits are described in stratigraphic sequence as shown by the map legend (Pl. 3). In general, the terminology follows Flint (1947). Symbols and map colors are mentioned for the reader's convenience. The deposits fit into both geomorphic and sedimentary units, in accordance with the requirements of historical interpretation.

BEDROCK SURFACE

Map symbol k; color indigo blue.

Wave action in glacial Lake Agassiz and current action in glacial spillways removed the drift in several small areas in the Tiger Hills region, and left only a few widely scattered boulders (Fig. 1-13). Where the stones are so numerous that they cover the rock surface (e.g. 2 miles northwest of Morden) the area is classified as water-worked drift. Much of the extensive wave-cut bedrock terrace along the Manitoba Escarpment near Morden was locally defended by concretions (Fig. 2-2). The largest area of bare (except for a thin soil profile) bedrock is between Treherne and the town of Cypress River. Here, combined wave and current action removed the glacial deposits except for a few low ridges that may be esker remnants. These ridges consist of as much as 3 feet of sand and gravel covering low "anticlines" of shattered bedrock. The "anticlines" may be the tectonic "beta layers" of eskers described by Madsen (1900, pp. 47-50). Several square miles of bare bedrock form the floor of a spillway 7 miles northwest of La Riviere; minor areas of bedrock occur along Pembina trench near Ninette and in the area of waterworked drift north and east of Hilton.

The exposed bedrock is of late Cretaceous age and includes all the beds from the Morden member of the Vermillion River formation to the Odanah phase of the Riding Mountain formation.

GLACIAL DEPOSITS

Ground Moraine

Map symbol gm; color sienna brown.

Ground moraine is mainly sandy lodgment till with a fissile structure and a fabric in which the preferred orientations of the long axes of pebbles are parallel to the directions of ice movement. Included pockets of waterlaid sand, silt and gravel, either admixed or well-sorted, are commonly distorted by post-depositional ice movements. Ground moraine forms a till sheet from 2 to 20 feet thick east of the longitude of Clearwater and from 20 to 40 feet thick west of Clearwater.

Ground moraine is distinguished from end moraine on the basis of relief, on the assumption that areas of rleatively high relief will align into belts of end moraine as mapping progresses. The line of demarcation, arbitrarily placed in a zone having from 5 to 8 feet of local relief, separates end moraine with its hummocky topography and abundant undrained depressions from undulating to gently rolling ground moraine.

The drainage of the ground moraine is poorly integrated and is the result of one closed depression overflowing into another until a shallow channel forms. In the rolling country in the east half of the Tiger Hills region, the drainage pattern in ground moraine developed from shallow gullies consequent on newly exposed slopes.

A circular ridge was mapped in ground moraine in section 9-4-19 W. Prin. (Pl. 3). Similar circular ridges from 200 to 1,200 feet in diameter and generally less than 7 feet high are abundant farther west. Except for the example cited above, they all are west of longitude 100° and are outside the scope of this dissertation. The writer thinks they are periglacial phenomena.

A few low moraine ridges extend from end moraine into ground moraine north of Ninga. Until the origin of washboard moraines is proved, the writer deems it advisable to map these ridges as ground moraine or end moraine according to their relief.

Drumlins

Drumlins are common features of ground moraine north of the Darlingford moraine between Notre Dame de Lourdes and Greenway, and between Hilton and Souris River. Long, low, streamlined ridges also extend southeast (leeward) from Pilot Mound, and from unnamed hill 2.5 miles southwest of Altamont. The glacially-streamlined features north-west of Souris River near Nesbitt (Pl. 3) are grooves rather than ridges. The grooves are well developed near Wawanesa and effect the direction of drainage even though they are overlain by at least 15 feet of lake silt. The streamlined features south of Lake Killarney also are grooves. In the Purves plain, Tiger Hills, and Pembina Mountain, the drumlinoids have rock cores of Odanah shale and tails of till or crushed shale. The tails of many drumlinoids north of the Darlingford moraine are mainly till. They might strictly be called "crag and tail" features (Salisbury, 1902, pp. 83-84) except that the bedrock is so weak that the boss-like character of the "crag" did not survive glaciation. Each of the drumlinoids at Pilot Mound and near Altamont has a large bedrock knob near the stoss end (Fig. 1-5) and a long, low tail 3 to 5 feet high and 40 to 100 feet wide at its distal end, composed mainly of crushed shale. The system of streamlined ridges at Pilot Mound is 10 miles long including gaps and offset ridges.

Three drumlinoids in SE 3-6-15 W. Prin. (Fig. 3-4, and Pl. 4) have tails of sandy till. At the point in Figure 3-4 where the western drumlinoid crosses the east-west road, a small circle indicates the site of a fabric analysis made in till 2 to 3 feet below the crest of the drumlinoid, which is here 3 to 5 feet high. Analysis of 101 pebbles showed a preferred orientation with bimodal distribution and an arithmetic mean of 142°. The drumlinoid is slightly curved, but its general direction is about 191°. The direction of flow of the ice that deposited the surficial till south of the Darlingford Moraine was about 140°, as is indicated by striated boulder pavements, fabric analyses, and the trends of drumlinoids, eskers and minor moraines. Hence, the till in the tail of the drumlinoids in SE 3-6-15 W. Prin. may have been deposited by the same southeast-flowing ice sheet, whereas the drumlinoid itself was formed by ice flowing at 191°. If so, this drumlinoid is an erosional feature and not a true crag-and-tail in which the rock boss is erosional and the tail is depositional. One fabric analysis is hardly an adequate basis for a general conclusion and the inference of an erosional origin of these drumlinoids is speculative. More analyses would probably support the idea that these drumlinoids were eroded from till deposited by a southeast-moving glacier. 1/

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1. Evidence that older till deposited by southwest moving ice was overriden by southward-moving ice is found in a fabric analysis of ground moraine in NW 16-3-6 W. Prin. 4 to 5 feet

Figure 3-4. Portion of RCAF vertical air photograph showing the area around SE 3-6-15 W. Prin. Three drumlinoids extend from top (north) to bottom near the center. The glacier flowed from north to south. Several washboard moraines are seen near the center, mainly west of but also crossing the drumlinoids. A subordinate esker trends south in the lower left (southwest) corner.

End Moraine

Map symbol em; color terra cotta.

Flint (1947, p. 127) defined an end moraine as "a ridgelike accumulation of drift built chiefly along the terminal margin of a valley glacier or the margin of an ice sheet". By this definition, an end moraine implies only a still-stand or period of relatively slow recession of the margin of a continental glacier; it does not necessarily represent the line of farthest advance except in a valley glacier. It is very difficult to distinguish a pause in retreat from a minor re-advance of an ice-sheet margin.

Areas having a relief greater than 8 feet and containing numerous knolls and undrained depressions are mapped as end moraine. It was expected that small areas of end moraine would integrate into features like the Darlingford moraine (Fig. 1-6, and Pl. 6) as mapping progressed. 1/

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below the surface. The results gave a distribution having an arithmetic mean of 157° and a minor mode at 67°, the whole distribution having a standard deviation of ±47°. This till was deposited by the older southeast-moving ice sheet that deposited the Darlingford moraine. Explanation of this may be that the ice from the northwest travelled over a plain whereas that from the northeast climbed the Manitoba Escarpment before reaching the site of the fabric analysis. The advance up the escarpment was by a series of submarginal englacial thrusts over ice whose flow has been obstructed. Thus, debris was transported in an englacial position to the ice margin (i.e. the Darlingford moraine) and did not form ground moraine.

1. The line separating ground moraine and end moraine is arbitrary and in the southwest corner of the Tiger Hills region the boundaries may not agree with the writer's later concepts. However, revision would not change the historical picture presented in the present work. Ground moraine there may have a maximum of 20 feet of local relief instead of a maximum of 8 feet. Unsatisfactory as the map of this area may be now, it is nevertheless certain that no prominent features comparable to the Darlingford moraine were overlooked.

The material comprising end moraine is commonly sandy till. The Darlingford moraine is dominantly silty till and contains some stratified drift. Bodies of stratified drift are generally more abundant in end moraine than in ground moraine. Stratified drift occurs both as pockets and as irregular masses in the till and as ridges, hummocks, and irregular plains (eskers, kames, and pitted outwash).

Three types of end moraine are grouped into one map unit. The normal "classical" type of end moraine is represented by the Darlingford moraine. Washboard moraine (p. 72) is shown by dotted lines indicating the trends of moraine ridges in Plate 3. All other end moraine areas are incipient end moraine, terrain that is rougher than most ground moraine but that does not form a distinctive ridge or belt.

Normal End Moraine

The Darlingford moraine south of Thornhill (Fig. 3-5) has local releif of 5 to 15 feet; adjacent ground moraine has less than 5 feet relief. Near Notre Dame de Lourdes the relief of the Darlingford moraine ranges from 10 to 40 feet and adjacent ground moraine has 100 feet of relief owing to the configuration of underlying bedrock. Here the end moraine has knob-and-kettle topography and the ground moraine is a smooth veneer of till on drumlinized bedrock hills. These conditions are common in the eastern part of the Tiger Hills.

The till of the Darlingford moraine is silty (Fig. 3-1(b), sample 51-42; Fig. 3-2, samples 51-2 and 51-42). A

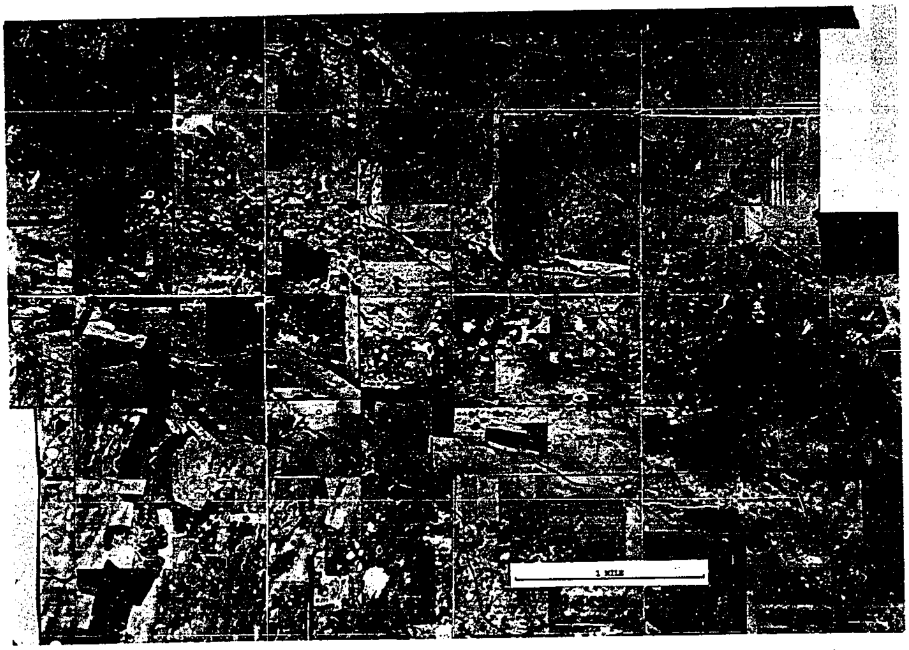

Figure 3-5. Mosaic of RCAF airphotos centered around section 6-2-6 W. Prin. North is at the top of the photograph. The Darlingford moraine crosses it from northwest to southeast. The symbol em refers to end moraine, gm to ground moraine and o to outwash. The boundaries between the deposits are drawn on the photograph. In the southwest, poorly developed washboard moraines trend south-southwest and form a topographic discontinuity (Ruhe, 1952) with the Darlingford moraine.

fabric analysis was made 7 feet below the ground level in a new road cut south of Darlingford (NW 5-3-7 W. Prin.). The till here is sandy and has horizontal fissility (Fig. 3-3). Sand and silt are present as distorted masses. The results of the fabric analysis show a wide distribution of pebble orientations centered around an azimuth of 30° and having with a standard deviation of ±46°. This represents ice flowing from the Lake Agassiz basin and suggests (1) that preferred orientations are not as well developed in end moraine as in ground moraine - an idea that gains further support from the writer's meagre data - on recent moraines in front of Athabasca Glacier - and (2) that this section of the Darlingford moraine is intermediate between an end moraine and a lateral moraine. A lateral moraine is in contact with its glacier for a longer time than the corresponding end moraine, and its deposit may be more massive. South of Darlingford, the end moraine is lower and much less massive than it is to the north; the north part undoubtedly was occupied by the ice margin for a longer time than was the south part.

Locally, hummocky bodies of ice- contact stratified drift in areas of end moraine are large enough to be mapped. Some workers (Deane, 1950, p. 10) would call them "kame moraine". They appear on the map as ice-contact stratified drift with the symbol (em) in parenthesis to indicate that they are part of the Darlingford-Tiger Hills moraine system. Most of these areas are in townships 5 and 6, ranges 11 and 12.

The position of the Darlingford-Tiger Hills moraine system in the Tiger Hills (Pl. 3, Fig. 1-6) is not clear because of the inclusion of incipient end moraine and washboard moraine. 1/ From the southeast corner of the map-area (Section 6-1-5 W. Prin.) it extends north-northwest beyond Notre Dame de Lourdes to section 21-7-9 W. Prin., then curves southwest. For the next 14 miles the moraine is characterized by small areas of ground moraine, outwash, and ice-contact stratified drift ("kame moraine"). The Darlingford moraine forms a west-trending ridge south of Dry River and meets Pembina trench east of Neelin. It extends northwest from Neelin along Pembina trench and is separated from it by outwash plains as wide as 2 miles. In the crook of Souris River elbow the moraine ridge is subdued and a few washboard moraines occur. The ridge form dominates north from section 8-7-19 W. Prin. to the Brandon Hills. A small branch of the moraine extends south-west and then west from section 28-8-19 W. Prin. towards the town of Souris (Pl. 6). A similar branch 6 miles long extends east through Methven. The latter extension points toward the town of Cypress River and represents part of the ice margin of the Brandon lake (Chapter 5). While end moraine was being deposited at Methven, the eastern end of the Brandon lake ice margin shifted north through township 6, range 11, and deposited ice-contact stratified drift.

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1. The eastern part has been previously unnamed. Upham (1896, p. 176-177) referred to the part south of the Brandon Hills as the Itasca moraine and extended it southeast into North Dakota.

Washboard Moraines

Description and distribution:

"Washboard moraine" is a descriptive term coined by Mawdsley (1936) to refer to small, uniformly spaced moraine ridges in parallel arrangement. Less desirable terms often applied are: "annual moraines", a term that implies unproved periodic deposition (Lawrence and Elson, 1953); "minor moraines", a general term that also refers to larger features lacking systematic spacing; and the European term "Randmoranen" which implies origin at the margin of a glacier. These terms have been used loosely and undoubtedly have included several similar features of different origins.

Washboard moraines, where well developed, are ridges 10 to 15 feet high (Fig. 1-3) and from several hundred feet to more than a mile long as in township 2, range 14 (Fig. 3-6). They are spaced at about 300 to 500 feet from crest to crest, or 12 to 15 ridges per mile. Near large eskers the ridges are curved upstream, but they are unaffected by small eskers (Fig. 3-6; Pl. 4). In contrast, small eskers may be offset at the ridges (Fig. 3-13) and rest upon them or cross them through gaps.

The size and pattern of washboard moraines vary in different areas. Near Windygates (township 1, ranges 6 and 7) the ridges are straight, and generally less than 7 feet high. In the Tiger Hills between Neelin and Hilton (Pl. 4), the ridges are scattered in groups, are curved, and are generally no higher than 6 feet; several cross drumlinoids (Fig. 3-4).

North of Holmfield, washboard moraines are expressed not as ridges, but as the areas between series of closed depressions that often contain ponds. The depressions are commonly elongate transverse to the direction of ice movement, and are aligned in series parallel to the direction of ice movement (Pl. 4). The till in this area of "kettle chains" north of Holmfield is predominantly sandy silt, and seems to be less compact than other tills in the Tiger Hills region.

Washboard moraines occur throughout the northern part of the Killarney plain, and are best developed between Holmfield and Clearwater. The pattern and structure of the moraines and their relationship to eskers is displayed best northeast of Cartwright (Fig. 3-6).

In the absence of air photographs showing the trends of the ridges, some of the washboard moraines in the Tiger Hills region would be mapped as end moraine and others ground moraine (cf. Pl. 3 and Johnston, 1934) depending on their relief. For example, the trend of the former ice margin south of Pelican Lake as inferred from end moraine on Johnston's map is transverse to the trend indicated by washboard moraines (Pl. 3) and striated boulder pavements. Although Johnston's moraine represents rougher topography, it does not represent a single position of the ice margin.

Constitution and till fabric:

Washboard moraines are predominantly sandy till (sample 50-2, figs. 3-1(b) and 3-2) and may contain a little more stratified drift, as contorted masses, than does nearby

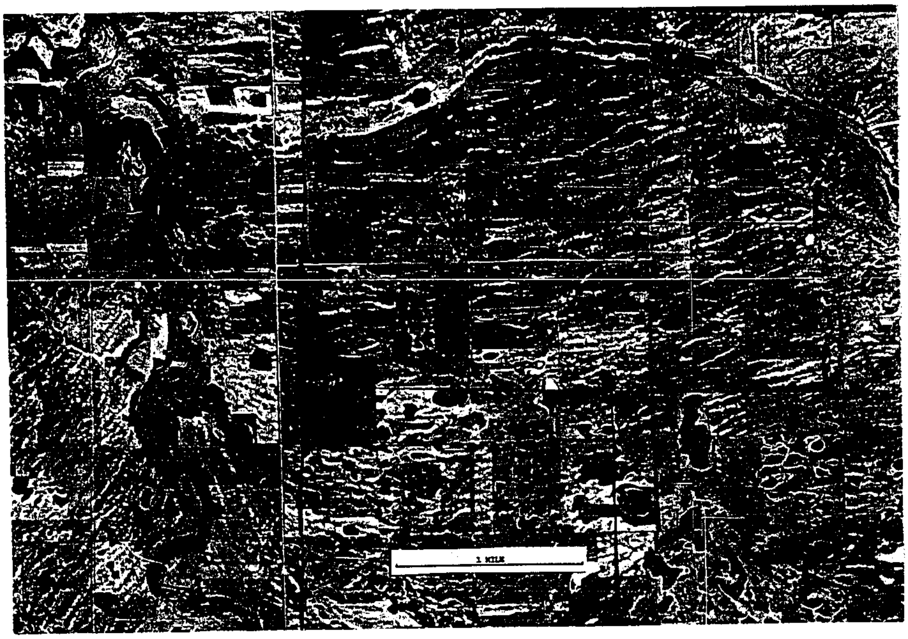

Figure 3-6. Photomosaic compiled from RCAF air photographs taken northeast of Cartwright, showing the central part of township 2, range 14. Badger Creek flows north (from bottom to top) on the west (left) side of the illustration. Washboard moraines form a lobate pattern with reentrants along Badger Creek and an esker which is south of the large ponds (black areas) in the southeast part of the area. An abandoned portion of the Whitemud Creek glacial spillway winds east across the top of the illustration. A small esker, offset between washboard moraines, appears at the center of the west side. Remnants of a large esker, mostly destroyed by Badger Creek, are indistinct.

ground moraine. When freshly exposed, the till has a crude platy or fissile structure (Fig. 3-3) generally ascribed to the lodgment of drift from the base of the moving glacier.

Till-fabric analyses show well-developed preferred orientations of pebbles parallel to the direction of ice movement in the core of the moraine, and random orientations or orientations parallel to the trend of the ridge near the surface. H.G. Ignatius (oral communication) found that pebbles in the till of some washboard moraines in Finland were oriented with long axes in the direction of glacier flow, transverse to the moraines.

With the help of Mr. Ignatius, six till-fabric analyses were made in a moraine northeast of Cartwright (NW 17-2-14 W. Prin.). This moraine trends at 110° and is near remnants of a large esker eroded about 12 feet high and 250 feet long by Badger Creek. A fresh cross section through the moraine exposed sandy till with a fissile structure and small bodies of ice-contact stratified drift near the sides of the ridge. Two fabric analyses in the base of the moraine, one in the center and one at the south side, indicate strong preferred orientations of 160°. Two analyses in the central part of the moraine midway between base and crest show strong preferred orientations of about 180°. An analysis near the crest of the ridge shows a moderately well-developed pebble fabric oriented at about 125°, and another on the north side of the ridge show a nearly random orientation, with a slight preference at about 100°. These analyses indicate that the ridge has a core of lodgment till an an outer layer in which either (1) the original fabric was modified by movement under the influence of gravity; or (2) the material is ablation drift. The results of till-fabric analyses on six other moraines are presented in Table 3-1.

Table 3-1. Results of miscellaneous till-fabric analyses in washboard moraines.

Location (W. Prin.)	Trend of moraine	Depth of analysis	Ma	σ	Type of distribution
NE 19-2-13	75°	3 ft.	93°	±42°	bimodal
NW 29-2-13	75	2	89	45	bimodal, poorly developed
NW 20-2-14	90	4	175	43	monomodal, well developed
SW 9-1-7	30	3	157	42	bimodal
SW 17-1-7	45	5	78	32	very monomodal, well developed
SE 34-2-12	45	5	118	51	trimodal

All these analyses were in the crests of the ridges. For explanation of the statistical terms see p. 161-165. Ma is the preferred orientation of pebbles.

Three of these analyses show pebble orientations roughly parallel to the moraine ridges and three show fabrics parallel to the direction of ice movement.

<u>Previous work</u>:

Space does not permit a comprehensive review of the literature on washboard moraines. They were first recognized by De Geer (1889) who suggested a subaqueous origin; since then, they have been noted by C.J. Anrick, H.M. Bannerman, Gustaf Frodin, A. Gavelin, Karl Gripp, C.S. Gwynne, Herman

Hedstrom, A.G. Hogbom, Gunnar Hoppe, N.G. Horner, Gunnar Lindekrantz, Gosta Lundqvist, Carl Mannerfelt, J.B. Mawdsley, G.W.H. Norman, Matti Sauramo, J.S. Sproule, Victor Tanner, E. Teiling, and W.B. Wright. 1/ The papers before Gwynne (1942, 1951) described washboard moraines in areas that were formerly submerged, either in the sea or in glacial lakes. Hence the early theories of origin require the presence of a body of water. Because of one correlation of moraine ridges with varved clays by De Geer (1940), the early theories also seek to explain cyclical (annual) deposition. Hoppe (1948) showed that the varves and washboard moraines in the Norbotten area of northern Sweden can not be correlated with each other and he doubted that the moraines have any periodic significance. The writer (Lawrence and Elson, 1953, pt. 2) attempted to prove that if the washboard moraines on the Canadian Prairies have a time significance, it must be an annual rather than a longer (e.g. 11-year sunspot cycle) period; however, he inclines to Hoppe's point of view.

Mawdsley (1936) presented a theory typical of the subaqueous group: seasonal melting increased the depth of water in a glacial lake, which caused the periphery of the glacier to float and produced crevasses parallel to the margin. During the high-water season, debris melted out of the ice and fell

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1. The writer is indebted to H.G. Ignatius for assistance in making fabric analyses, and for discussing several Norwegian and Swedish papers that lack English or German summaries. Only the most pertinent references are listed in the bibliography.

into the crevasses, and formed ridges when the supporting ice finally melted.

Gwynne suggested that minor (washboard) moraines form on land near the ice margin in a subglacial position, but he did not explain how.

Origin of Washboard moraines:

The washboard moraines in the Tiger Hills region, and in most other places on the Canadian Prairies, were never submerged in water and a valid theory of origin must not require subaqueous conditions. An acceptable theory must account for the following facts:

1. The cores of the moraines are lodgment till.
2. A layer of till with a random pebble fabric, or with a pebble orientation parallel to the axis of the moraine covers the core.
3. The moraines are locally superimposed on drumlinoids.
4. The moraines are discontinuous and are rarely longer than 1 mile.
5. The crests of the moraines are generally 300 to 500 feet apart.
6. The moraines curve upstream near large eskers but not at small eskers. Small eskers are offset at the moraines and may overlie them.

Washboard moraines would be valuable records of glacier recession if they could be proved annual. The writer's hypothesis permits, but does not prove, annual deposition.

Hypotheses of origin of washboard moraines in the

Tiger Hills region are discussed below. The last (seventh) hypothesis is the writer's theory; it satisfies the conditions listed above.

1. Any hypothesis requiring deposition under subaqueous conditions (e.g. Mawdsley's theory, p. 77) is not applicable.

2. Gripp (1938) observed push moraines (Stauchmoranen) formed of debris shoved into ridges by minor readvances of a retreating ice margin. Push moraines are more closely spaced than most washboard moraines. A preferred orientation of pebbles parallel to the direction of ice movement would not be likely to result from the push process. Eskers could not be deposited on moraines formed in front of (i.e. beyond) the glacier.

3. Moraines commonly form by debris melting out of an ice cliff or steep ice slope and falling or sliding to the ground. A crude pebble fabric parallel to the ice margin might result from this process, but there could be no core of lodgment till. Moraines formed in this way are generally hummocky and irregular and contrast with the relatively uniform ridges of washboard moraines. Small eskers might extend from moraine to moraine, but they would underlie rather than rest on the ridges, and the eskers would not be offset at each ridge.

4. Goldthwait (1951) and Ward (1952) observed moraines forming at the margin of the Barnes Ice Cap, on Baffin Island. On a smaller scale these moraines form a pattern similar to washboard moraines. They form when debris, brought to the sur-

face in thrust planes, slides down the steeply sloping ice margin and accumulates at the edge forming an insulating layer of drift that retards melting. A trough forms by more rapid melting of the clean ice behind the drift and isolates it from the glacier as an ice-cored moraine. Meanwhile more debris collects on the glacier side of the trough, and the cycle is repeated there. The ice cores melt slowly and lower the moraines to the ground as a series of low ridges parallel to the ice margin. The length and size of these ridges depend on the concentration of debris in the thrust planes. Goldthwait (1951, fig. 2) shows the moraines as about 50 feet wide and about 100 feet from crest to crest. Assuming they form on a larger scale under suitable conditions, these moraines may be represented on the Canadian Prairies. If the ice core was rich in debris and melted very slowly, a till fabric (englacial) parallel to the direction of ice movement might exist inside the moraine. Small eskers can not be formed on these moraines. The spacing of the moraines depends primarily on the concentration of debris in the ice rather than on any cyclical climatic phenomenon.

5. The writer observed transverse till ridges emerging from Saskatchewan Glacier where debris compressed in thrust planes had been elevated into nearly vertical "dikes" of till as thick as 6 inches and several feet in height. When supporting ice melted the "dikes" slumped into ridges 1 to 2 feet high and 4 to 6 feet wide. If this happened on a larger scale, ridges resembling washboard moraines could result. However, it is doubtful that the till fabric survives the slumping process,

and that a single thrust plane would provide enough debris for a washboard moraine. The spacing of these ridges in front of Saskatchewan Glacier is erratic, and the crests are not as regular as washboard moraines. Small eskers could form in the ice, and might have the same relationships to the ridges as in the case of washboard moraines.

6. Till ridges parallel to an ice margin could be formed from ground moraine by closely-spaced meltwater channels along a retreating ice margin. The ridge between two channels would have a core of lodgment till and an outer layer in which the lodgment fabric might be destroyed by mass-wasting. However, eskers could not be superimposed on such ridges, and the inter-ridge areas would have characteristics of outwash channels with specific gradients and alluvial floors.

7. Washboard moraines in the Killarney plain probably originated by subglacial thickening of ground moraine at a zone of thrusting developed where the brittle surface ice of the glacier extended to the subglacial floor and pinched out the plastic ice (Fig. 3-7, also fig. 3-13).

According to several workers (see Flint, 1946, p. 17) an ideal glacier consists of a surface layer of brittle ice from 100 to 250 feet thick that grades into flowing ice made plastic by the load above it. At the margin or terminus, where a glacier is too thin to have a plastic zone, movement may occur along shear planes in the brittle ice. Some brittle ice is continually being thrust forward over stagnant ice near the margin. The thrust zones extend from the subglacial floor to

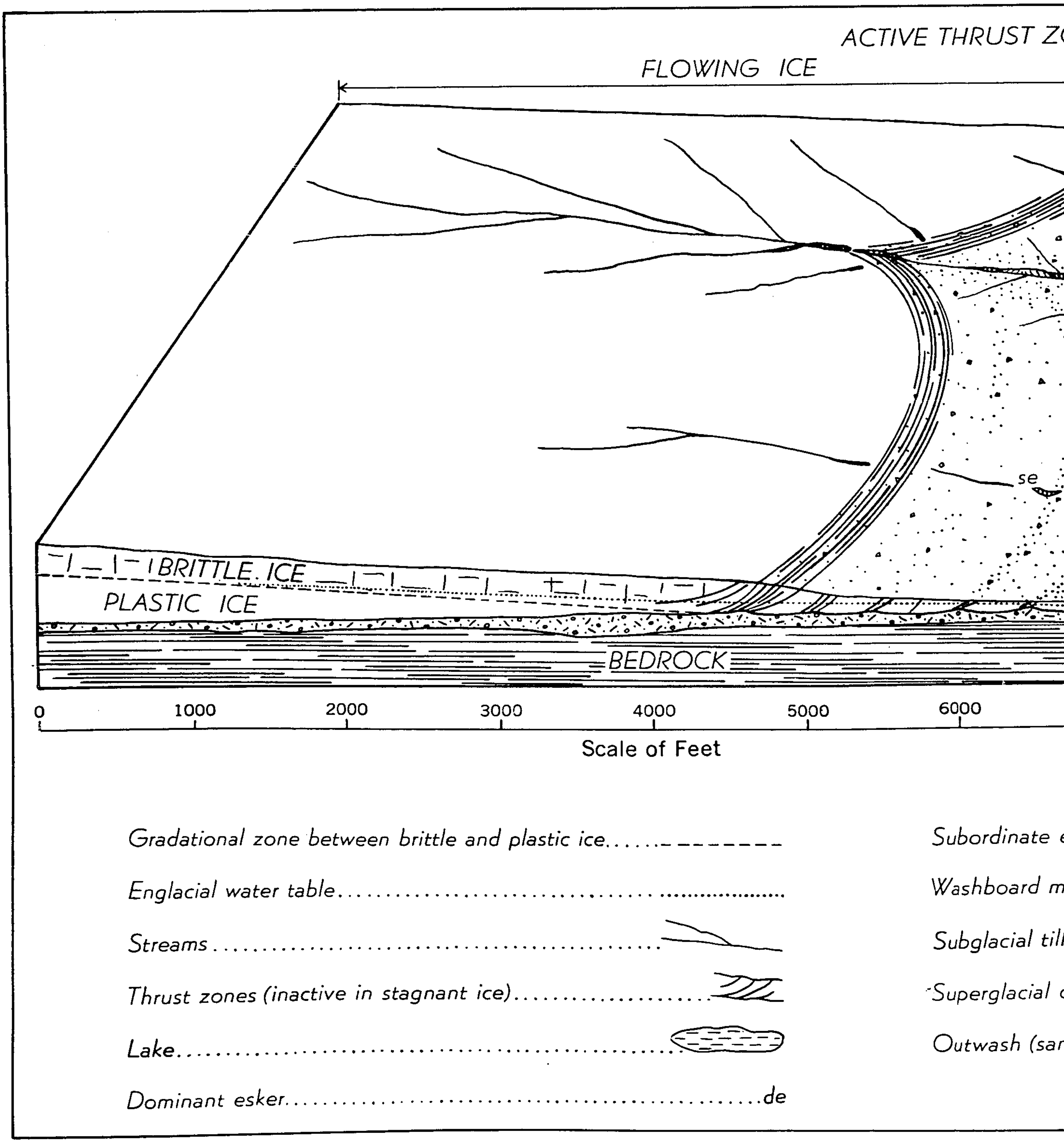


Figure 3-7.
Origin of washboard moraines, showing rel
dominant and subordinate eskers.

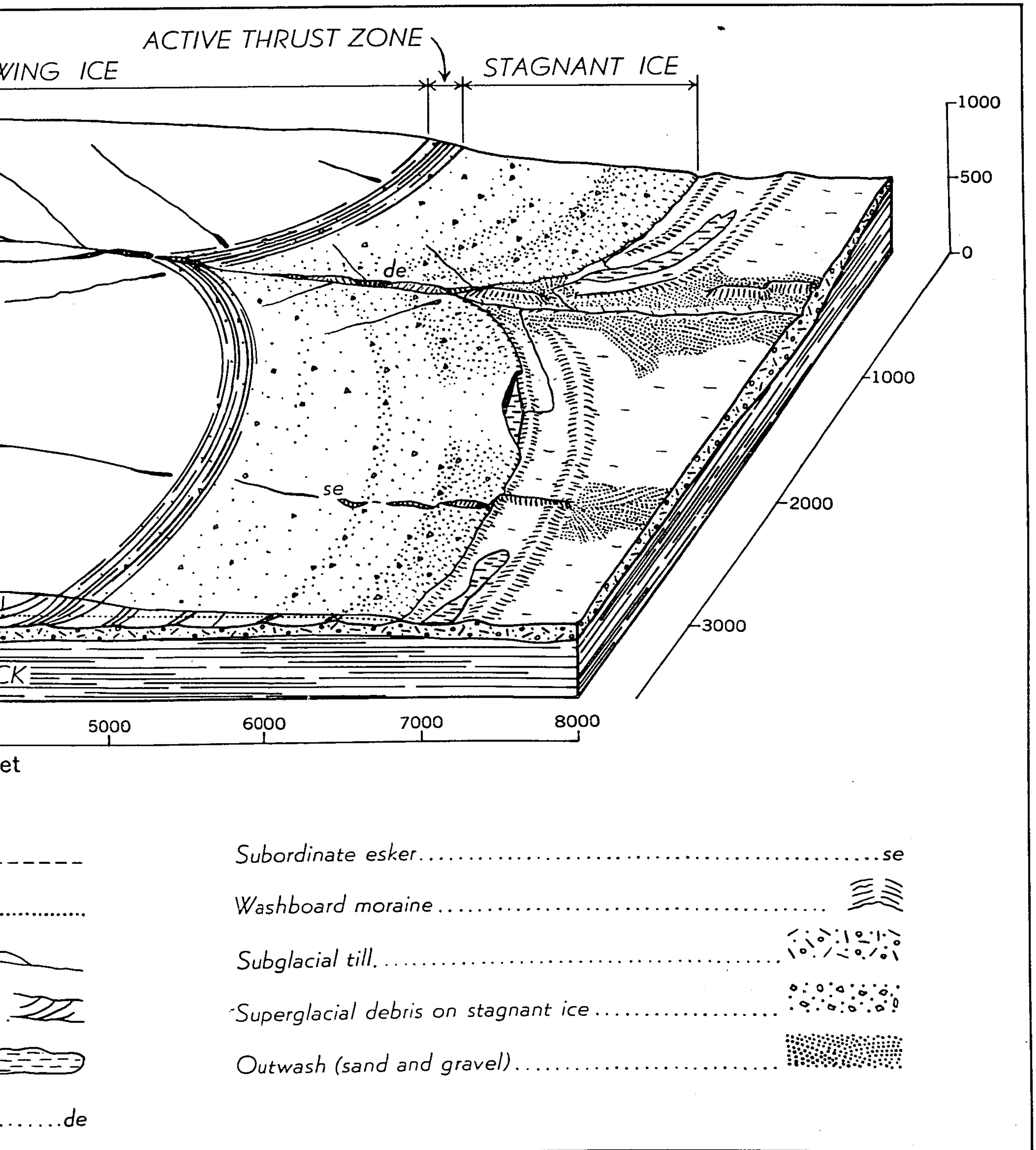


Figure 3-7.
oard moraines, showing relationship of
ubordinate eskers.

the surface, and the thrusts transport basal debris to englacial and super-glacial positions.

In a relatively thin ice sheet of the type that covered southwestern Manitoba, marginal retreat results when ablation exceeds nourishment and causes glacier thinning. The ice surface slopes gently at its periphery (5 to 10 degrees) and the plastic ice pinches out some distance back from the margin so that the brittle layer forms a border or "apron" of dead (stagnant) ice. Where the plastic zone pinches out, brittle ice moves by slipping along shear planes and may deposit lodgment till at the base of the thrust zone as well as transport subglacial and englacial debris to the surface (superglacial debris). Where super-glacial debris is thin it accelerates melting so that the surface may be oversteepened at the thrust zone. However, superglacial drift more than 21 inches thick insulates the ice and retards melting. The thicker the debris, the slower is ablation. The effect of the slower melting under ablation moraine is to make the apron of stagnant ice much wider than might be expected from the simple geometric relationship between the brittle ice layer 200 feet thick and the 5-to-10-degree slope of the surface upstream from the thrust zone. As much as 2 feet of ablation drift may accumulate before the ice is all melted and the stagnant ice may be several thousand feet wide.

Meltwater saturates the lower part of the fractured and crevassed brittle ice layer and the more permeable stagnant ice; the water table so formed has a gradient toward the ice margin. Flow of water at the water table accelerates melting and opens englacial channels in which englacial and some super-glacial debris may collect. As the ice margin retreats the water table at a given point subsides, and the englacial channels are cut down to keep pace with the falling water table and the debris in them eventually is lowered to the subglacial floor. Under the stagnant ice, the subglacial floor is characterized by parallel ridges of lodgment till previously deposited at the base of former zones of active thrusting. The englacial channels (now almost subglacial) shift laterally to accomodate to the lowest points in the ridges that they cross; thus an offset pattern is produced in the eskers that represent the former channels when the ice finally melts.

During the summer season of glacier thinning, 35 to 50 feet of drift-free ice may melt (Lawrence and Elson, 1953, p. 100-101). The thrust zone retreats as the brittle layer pinches out the plastic ice and the apron of stagnant ice becomes wider. During the winter season of little or no melting, the thrust zone stops retreating, is stationary, and deposits a subglacial ridge of lodgment till. Once ice becomes stagnant it can be reactivated only by increase in thickness. The thickening caused by thrusting of active ice over the stagnant ice in one season is insufficient to cause any appreciable advance of the basal part of the thrust zone. Whether or not a ridge of lodgment till (washboard moraine) forms at the base of the thrust zone depends on the condition of the subglacial floor behind it; ridges may be discontinuous because conditions are not everywhere favourable for the ice to pick up subglacial debris. The ablation moraine is lowered by melting until it rests on the former subglacial surface and forms a mantle over the washboard moraines.

A lobate pattern of washboard moraines adjacent to large eskers results when the englacial water table conforms to a depression in the subglacial floor. The water table gradients cause meltwater to concentrate in the depression and a valley caused by accelerated melting due to increased water circulation, forms in the surface of the glacier. A large englacial or subglacial meltwater channel may develop in the axis of the valley, and the debris that collects in it later forms an esker. The rapid thinning near the channel produces a reentrant in the ice margin. Because the zone of thrusting is parallel to the ice margin, moraines deposited at the base of the thrust zone have a lobate pattern.

This hypothesis accounts for all the characteristics of washboard moraines in the Tiger Hills region, and admits the possibility of cyclical deposition without requiring it. The availability of subglacial debris to the thrust planes may be a more important control than cyclical climatic phenomena (Goldthwait, 1951). The amount of ablation moraine derived from thrust planes has a profound effect on the rate of thinning near the glacier margin, and hence, on the recession of the ridge-depositing thrust zone.

Significance of End Moraine

The Darlingford moraine and its associated deposits illustrate several aspects of the significance of end moraine. The part of the moraine between Treherne and Notre Dame de

Lourdes is on a bedrock headland that split the relatively small Assiniboine valley ice lobe from the main ice sheet flowing south up the Red River valley. This segment of the moraine is in township 7, ranges 8, 9, and 10. It is a well developed till ridge 1.5 miles wide and 9 miles long, situated between outwash plains in the south and drumlinized ground moraine in the north. The part of the ice margin that deposited this moraine was stationary while the margin to the east and west retreated as much as 15 miles.

R.F. Flint (1947, p. 129) noted that

".......slowly flowing but rapidly melting ice produces much stratified drift whereas rapidly flowing but slowly melting ice produces much till."

The Darlingford moraine 9 miles west from Notre Dame de Lourdes is predominantly till. In a belt 22 miles long between section 36-6-10 W. Prin. and Greenway, the moraine is a complicated plexus, nearly 8 miles wide, of ice-contact stratified drift and ground moraine. It is inferred that the flow of ice in this belt was slow compared with flow near Notre Dame de Lourdes. The retarded flow may have been due to (a) greater distance from the main axis of flow, and (b) the impeding of flow by local bedrock knobs. Whereas the high, steep escarpment of Pembina Mountain was an obstacle which the ice overrode 3 to 4 miles, the slightly lower, gently sloping upland area north of Mariapolis was overriden 10 to 12 miles. Hence, the till ridge about 1.5 mile wide near Notre Dame de Lourdes is equivalent to a belt of ice-contact stratified drift about 8 miles wide north of Mariapolis.

While the normal end moraine near Notre Dame de

Lourdes and the ice-contact stratified drift north of Mariapolis were deposited, a segment of normal end moraine formed northwest from Neelin; the ice margin also withdrew as much as 10 miles to the bedrock-cored Tiger Hills north of Baldur, depositing at least 60 washboard moraines. At the same time, near Souris River elbow, normal end moraine and several washboard moraines were deposited, the ice margin withdrew from 6 to 10 miles north to Methven forming the margin of a glacial lake as it retreated, and then deposited a second normal end moraine at Methven.

The Darlingford moraine is progressively smaller in cross-section south from Notre Dame de Lourdes, which suggests that the ice margin withdrew from the southern part first. South of the International Boundary the former ice border is marked by a meltwater channel contiguous with the moraine.

To summarize, the following contemporaneous deposits may be used to interpret the various conditions during the retreat of different parts of the same ice margin; the distances given are measures of margin retreat:

1. Two normal end moraines separated by several washboard moraines and 6 miles of glacial lake.

2. A normal end moraine and more than 60 washboard moraines.

3. Minor ground moraine and 8 miles of ice-contact.

The climatic conditions that controlled the position of the ice margin were uniform throughout the Tiger Hills region. Nothing specific is known about rates of flow, rates of flow, rates of melting, supply of debris, or the effect of topography over which the ice flowed; but it is inferred that flow was retarded by (a) bedrock-cored hills and (b) increasing distances from the axis of the ice lobe. Where the ice flowed vigorously up the Manitoba Escarpment south of Treherne, as is indicated by drumlinized bedrock hills, it deposited a normal end moraine of till. Where ice flow was retarded by the bedrock-cored Tiger Hills and an opposing slope of 25 feet per mile, it deposited ice-contact stratified drift. On the gentle slopes (horizontal to 10 feet per mile) where ice flow was slightly retarded by bedrock hills but not by an opposing slope, washboard moraines were formed. Thus, the Tiger Hills region provides support for Flint's generalization and suggests further relationships between glacier metabolism and glacial deposits.

By means of dendrochronology, D.B. Lawrence (Lawrence and Elson, 1953) found that, when the general rate of recession was suitable, Herbert Glacier, in Alaska, deposited moraines during the minima of the 11-year sunspot cycles. The time interval between moraine ridge deposition decreased and the sizes of the ridges decreased as the rate of recession increased, until only unpatterned ground moraine was deposited, as at present. Some of the small moraines are annual deposits. Thus, there is a relationship between the rates of nourishment and recession of a glacier (its <u>metabolic rate</u>) and its sedimentary record. Moraines decrease in size as the general rate of recession increases. The sensistivity

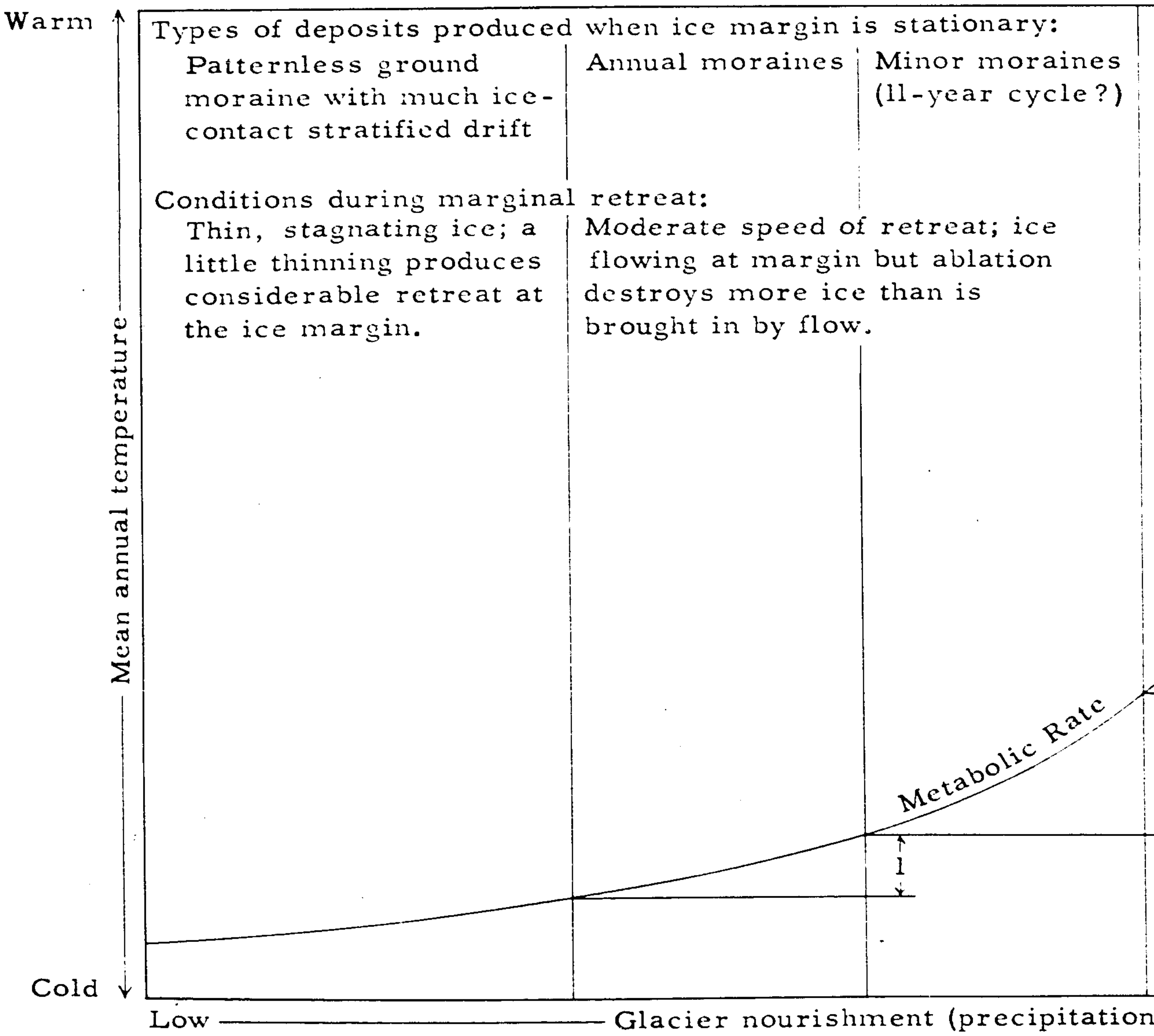


Figure 3-8.

Metabolic rate of glaciers and types of deposits forn
1, 2, 3 represent minimum climatic fluctuations req
cyclical feature such as an end moraine.

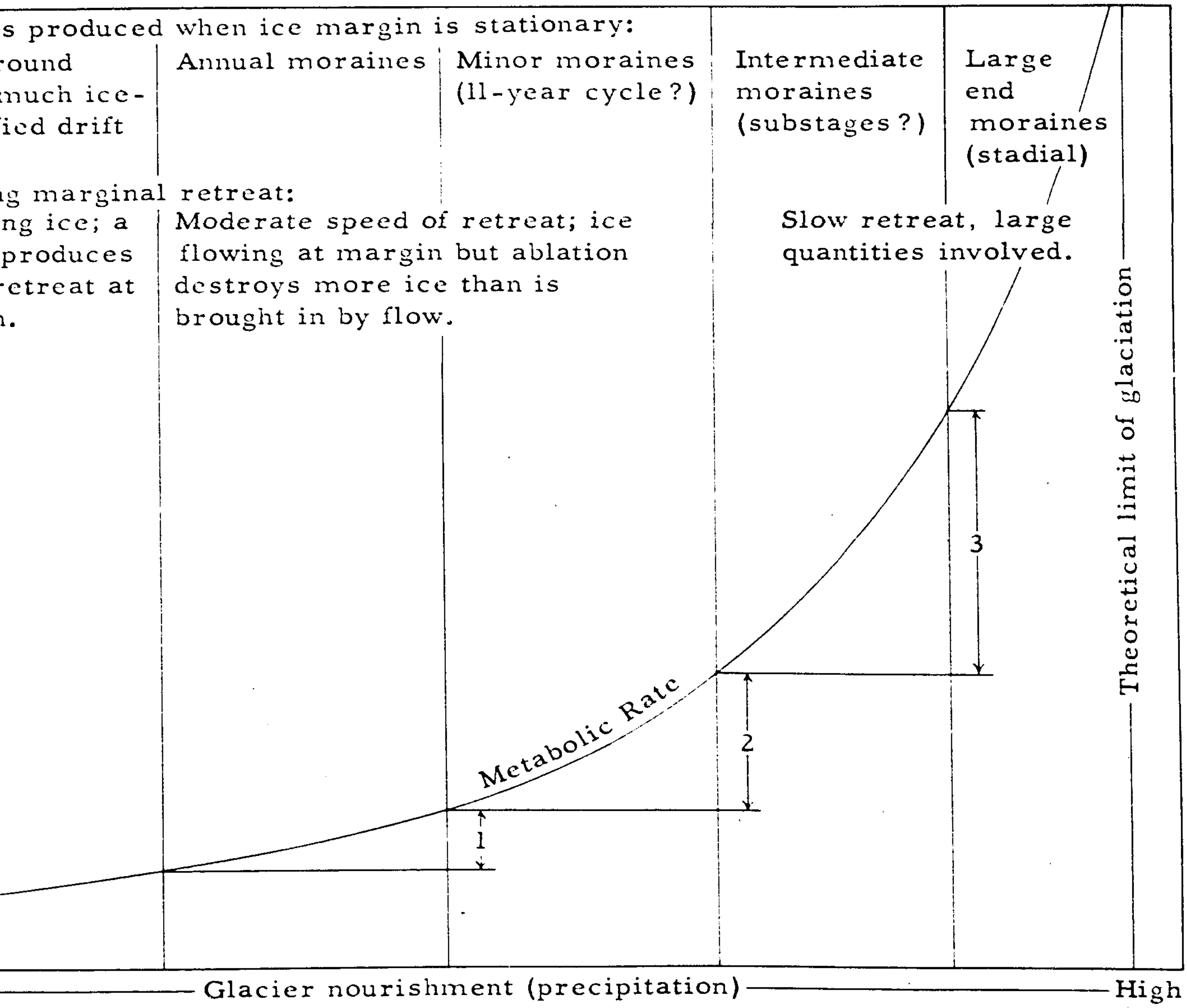


Figure 3-8.
bolic rate of glaciers and types of deposits formed during retreat.
3 represent minimum climatic fluctuations required to produce a
cal feature such as an end moraine.

of an ice sheet to climatic fluctuations, as indicated by its deposits, becomes greater as the metabolic rate becomes lower. When flow and ablation both are greatly reduced, the ice sheet is nearly stagnant and recession results in deposition of patternless ground moraine and ice-contact stratified drift (Fig. 3-8). A slightly higher metabolic rate results in deposition of such minor moraine ridges as washboard moraines. If nourishment and melting are both vigorous, large end moraines of stage and substage value, like those in the Great Lakes region, are formed, and the small climatic fluctuations that produce washboard moraines in cold, dry climates do not influence the deposits.

A low metabolic rate may have been responsible for the abundance of washboard moraines, the remarkable development of eskers, and the scarcity of large end moraines in central and north-central Canada. The metabolic rate of glaciers in this region should be very low because of high latitude and continental climate with low temperatures and precipitation. On the other hand, in the warmer climate of the Great Lakes region where the metabolic rate of glaciers should be high, the expected large end moraines do exist, and features common in areas with low metabolic rates are relatively scarce.

Striated boulder pavements

Definition

The term boulder-pavement was used by Hugh Miller the elder in 1852 (see Miller, 1884, p. 159) to designate a single horizontal layer of boulders embedded in till, with their flat upper surfaces lying in a common plane and bearing striations oriented in the direction of glaciation. According to Hugh Miller the younger (1884, p. 161), Archibald Geikie later applied the term striated pavement to the same phenomenon. However, Geikie's term has been used at times to refer to areas of striated bedrock surface, and the elder Miller's term has been applied to unglaciated concentrations of cobbles and boulders on wave-cut terraces (Spencer, 1895, p. 35-38). Hence, in order to avoid all ambiguity the term striated boulder pavement is employed here in the sense of Miller's boulder-pavement. The individual stones in a striated boulder pavement are pavement stones (or cobbles or boulders).

Previous literature

Striated boulder pavements have received relatively little attention in geological literature. According to Miller (1884) they were first reported by Charles Maclaren in 1828, then by Milne Home in 1838, and again in 1845 and 1848 by Mr. Smith of Jordanhill. In 1852 the elder Hugh Miller lectured on boulder-pavements near Edinburgh. Hind (1859, p. 64) reported "tiers of boulders" in Saskatchewan that were probably striated boulder pavements. All these observations were made before the theory of glaciation was fully accepted, and these men attributed pavements to subaerial or subaqueous erosion, or the action of partly grounded icebergs. Stoddard (1859), Miller the younger (1884), and Gilbert (1898) discussed striated boulder pavements in the light of the theory of glaciation. Gilbert's refinement of Miller's hypothesis is the most acceptable theory of origin, and is discussed below. Spencer (1895) thought that pavement stones collected at the bases of wave-cut scarps, and that wave action removed the fine sediment under them until they were lowered to a level at which the waves were no longer effective (wave base). It is not clear whether he was applying this theory to striated boulder pavements or to belts of boulders that are lag concentrates marking abandoned strandlines. Coleman (1933, p. 29-30 and 1941, p. 68) summarily explained striated boulder pavements as the result of boulders being concentrated on the surface of earlier glacial deposits by subaerial erosion during interglacial intervals, and then being pressed into the substratum during subsequent glaciation. His theory fails to account for the lack of leaching and oxidation of the substratum that should occur during a long interval of subaerial erosion. Holmes (1944) discussed the use of pavement boulders as interglacial evidence.

Distribution of striated boulder pavements

Striated boulder pavements are more common on the Canadian Prairies than previous literature indicates. There seems to have been at least one time interval when conditions over large areas of the plains were favourable for their formation.

More than 30 pavements in the region between Manitou (Pl. 1) and 12 miles west of Virden (Pl. 6) were studied, and at least 10 occurrences in wells and basement excavations were reported to the writer. In the Pelican Lake area (Pl.4) at least 14 pavements, mainly in the south half of the area, were examined. The best exposures are in stream and road cuts in the Killarney plain; two of these, at Ninette and near Lena, are described in detail below. One pavement was observed in a cut on a bedrock-cored hill north of Greenway (Fig. 3-9(a)).

Striated boulder pavements have been observed elsewhere about 15 miles north of Regina, Saskatchewan, and 20 miles west of Medicine Hat, Alberta, by the writer. A.M. Stalker (oral communication) reported several poorly developed pavements in Alberta, between the Porcupine Hills and 30 miles north of Edmonton. A pavement near Minot, North Dakota, was shown to the writer by R.W. Lemke. Hind (1859, p. 64) reported two horizontal tiers of boulders, evidently pavements, separated by 20 feet of drift, along South Saskatchewan River north of the present city of Saskatoon. Tyrrell (1892, p. 139E) reported pavements in Manitoba near Binscarth, 80 miles northwest of Brandon.

<u>Description of striated boulder pavements</u>

In most exposures a single striated boulder pavement separates an upper sandy till, 6 to 25 feet thick, from a lower, clayey till. Less commonly, the substratum is either crushed Odanah shale with a clayey matrix or sand or silt. Two pavements in one cut northeast of Holmfield (SW 34-2-15 W. Prin.) are separated by 6 feet of till; striations on both pavements trend from 135° to 140°. The best examples of pave-

Figure 3-9(a). Striated boulder pavement resting on shaly till and overlain by sandy till, exposed in a road cut near the top of a bedrock-cored hill 6 miles north of Greenway (NE 2-6-13 W. Prin.).

Figure 3-9(b). Exposure showing a striated boulder pavement underlying till and overlying compact silt with a fissile structure 5 miles northeast of Killarney (NE 30-3-16 W. Prin.). See also Fig. 3-28(a).

ments, found at Ninette and near Lena, are described below.

More than 50 pavement boulders are exposed in the bottom of a borrow pit about 1 acre in extent west of Ninette (NE 13-5-17 W. Prin.). The areas of the faceted upper surfaces of individual stones range from 0.25 to 25.0 square feet. The pavement boulders are about 30 feet apart on the average, but many small pavement stones were removed by earth-moving machinery. Pavement stones are generally spaced from 1 to 5 feet apart, but may touch each other or be separated by as much as 100 feet; they tend to occur in clusters. The direction of the striations on the pavement at Ninette varies from 110° to 135°, with a mean of about 122°.

At the highway junction 1 mile north of Lena (NE 34-1-17 W. Prin.), several episodes of road construction exposed 214 pavement stones in a total of 900 feet of road cut. The stones form a horizontal plane in which several gaps as long as 100 feet contain no pavement stones. The areas of facets on individual stones ranged from 0.1 to 3.5 square feet. The directions of the striations varied from about 100° to 160°; the mean of 105 measurements was 138°, with a standard deviation of ±14°. The pavement stones at Lena are generally smaller than those at the Ninette exposure, and the direction of striation is less uniform. Studies at these and at other exposures indicate that a striated facet of 3 square feet or more is a reliable indicator of the direction of ice movement.

Till-fabric analyses were made on vertical faces above and below the pavement at Lena (Fig. 3-36). An analysis of the clayey sandy till below the pavement showed a preferred pebble orientation of 158°, with a standard deviation of ±40°; the preferred orientation judged from a rose diagram was 145°. An analysis of the sandy till above the pavement showed a weaker preferred orientation having three modes and a statistical mean of 129°, with a standard deviation of ±48°; a rose diagram suggested a mean of 140°. The results of the fabric analyses conform to the direction of ice flow indicated by the striations, within the limits of accuracy of the method. It is inferred that there was no significant change in direction of ice flow either during or after the formation of the striated boulder pavement. Distortion of thin, parallel sand layers in the till below the pavement (Fig. 3-36) indicate that the pavement stones were pushed southeastward by glacier movement.

Till underlying striated boulder pavements contains more clay-size particles than overlying till. Mechanical analyses at the Lena exposure gave the following results:

	Clay size	Silt	Sand	Sorting coefficient
Upper till	8 percent	52	40	5.6
Lower till	31	27	42	11.6

Much of the clay in the lower till is derived from Odanah shale, which is more abundant than in the upper till. Pavement stones at Dand (Pl. 6) rest in broken shale with a clay matrix. Poorly-sorted clayey till apparently holds pavement stones better than sandy till during the facet-cutting interval. Stones in a pavement between two sandy tills west of

Virden have no distinct facets on their upper surfaces and no distinct direction of ice movement can be measured. The degree of development of facets seems to depend on the cohesiveness of the till, from which it is inferred that the till may not have been frozen during pavement formation. Presumably, frozen tills of different textures would hold stones equally well.

Direct comparison of the lithology of tills and pavement at Lena is not possible because cobbles and boulders are too sparse in the tills,and the lithologic composition of the pebble fraction may not be comparable with that of the cobble and boulder fraction. However, the results of pebble counts of the tills at Lena, disregarding Odanah shale (a common constituent of till but never found as pavement stones) are presented with the lithology of the pavement:

	Lower till (pebbles)	Pavement (cobbles & boulders)	Upper till (pebbles)
Granitoid rocks	15 percent	77 percent	13 percent
Dolomite and limestone	68	15	75
Other rocks (excluding shale)	17	8	12

Both upper and lower tills are lodgment types, and the differences between the pebble counts are insignificant (Table 3-5, p. 150). As anticipated, pavements are composed mainly of granitoid rocks resistant to crushing and abrasion; probably weaker carbonate and shale were comminuted during pavement formation.

Pavements underlain by silt and sand were observed in cuts in NE 30-3-16 W. Prin. (Fig. 3-9(b)) and NW 2-4-14

W. Prin., and were reported in wells near Holmfield. The pavement stones are embedded in the sand or silt, and have well developed facets lying in the plane of the till contact. The silt and sand are compact and have a fissile structure; crossbedding in the sand (Fig. 3-28(a)) was deformed by glacier movement.

The till below the pavements is not leached, nor is oxidation in the underlying till greater than in the overlying till. Weathering phenomena, therefore, do not indicate a period of subaerial erosion during which pavement stones might have been concentrated.

All the pavements observed were approximately horizontal. The subaerial erosion that generally occurs in an interglacial or interstadial interval increases the percentage of slope in an area (Ruhe, 1950, Fig. 2), but the agency that formed the pavement flattened the slopes. This suggests that pavement-stone concentration was by subglacial erosion, perhaps aided by some as yet unknown englacial process (e.g. changes in competency to transport various sizes of debris, caused by changes in regimen), rather than by subaerial erosion. The levelling effect of glacial erosion is apparent on the top of a bedrock-cored hill north of Greenway where the boulder pavement (Fig. 3-9(a)) is horizontal rather than parallel to the sides of the hill.

Origin and significance of striated boulder pavements

Miller (1884) theorized that striated boulder pavements formed by selective subglacial erosion of till contemporaneous with deposition; he did not suggest an interval in which stones might be concentrated by subaerial erosion of earlier drift. In restating Miller's theory, Gilbert (1898) also emphasized the concentration of pavement stones by selective subglacial erosion of till but admitted the possibility of a subaerial erosional interval. He thought that when the glacier moved over a till sheet stones were dragged along and rotated until they attained stable positions that offered least resistance to glacier flow (e.g. tabular stones assumed horizontal positions - see Gilbert, 1898, Fig. 1), and then were pressed into the underlying till as the smaller sizes were removed by erosion. The upper surfaces of the pavement stones were abraded by the debris-laden ice and a striated facet was formed. Gilbert stated (Idem. p. 774):

"If this explanation is correct, a bowlder-pavement records an epoch of local till erosion by a glacier. The epoch may be a mere episode interrupting a period of till deposition by the same glacier, or it may be part of a stage of advance following a long interglacial interval."

The Miller-Gilbert theory explains the striated facets on the upper surfaces of pavement stones, their uniform position in a horizontal plane, and their concentration in a single layer. If the original till sheet was thin enough and overlay sand or silt, the stones formerly in till would be pressed into the sand or silt when the till was removed by erosion. If pressure and friction caused melting at the sole of the glacier, stones would be held more firmly by adhesive clay till than by sandy till, and facets would be best developed on pavement stones held by clay till. If the subglacial erosion was the result of rejuvenation of an ice sheet that had been shrinking and took place far back from the margin, there would be no leaching or oxidation of the substratum and there might be no marked change in the direction of flow.

Holmes (1944, p. 432), in considering the value of pavement boulders as interglacial evidence, noted:

"Comparison of the relative concentration of boulders in the pavement and in the subjacent till may afford a general index as to the minimum thickness of till removed, which may exceed the average depth of weathering of the supposed earlier till sheet. In that event, however, at least part of the boulders may bear evidence of having been in the weathered zone and may constitute valid evidence of interglacial time."

He continued to describe a stone with a weathering rind and an unweathered facet that must have been cut after a period of interglacial weathering had produced the rind.

According to Holmes' criterion, at least 50 feet of till would have to be removed by erosion to concentrate the pavement stones in southwestern Manitoba, though any such estimate is highly subjective. Several hundred pavement stones were examined by the writer but none was observed to have a facet cutting both a weathering rind and a fresh core as described by Holmes. Several boulders of intrusive rock were weathered throughout so that recent exposure to atmospheric conditions and earth-moving machinery has destroyed the striations on the facet. These boulders generally do not have cores of fresh rock. They may have passed through several glaciations and intervals of interglacial weathering, but they do not constitute evidence that the pavement stones were concentrated from it either by subglacial or subaerial erosion.

An undocumented report of a piece of wood found in till in a well at a level similar to that of pavements in wells several miles away, near Holmfield, is the only evidence for an interglacial interval associated with the pavements in the Tiger Hills region.

Conclusion

Striated boulder pavements are well developed in southwestern Manitoba and may represent a single subglacial erosion surface. The direction of ice flow was essentially the same before, during, and after pavement formation. There is little evidence that the pavement stones were concentrated by subaerial erosion during an interglacial interval. The pavements were probably formed subglacially when rejuvenation of an ice sheet, following a time of shrinking that might have been of substage magnitude, increased its erosion power. Thus, the striated boulder pavements are probably a subglacial expression of one of the Wisconsin substages. R.F. Flint (oral communication in the field) remarked that the pavement facets might have formed following the Tazewell-Cary interval.

Ice-contact Stratified Drift

Map symbol isd; color scarlet red.

General Remarks

Ice-contact stratified drift comprises bodies of generally poorly-sorted sand, gravel, and silt (Fig. 3-10), bounded by ice-contact slopes at which the sediments rest at their angle of repose; it indicates stagnation and fairly

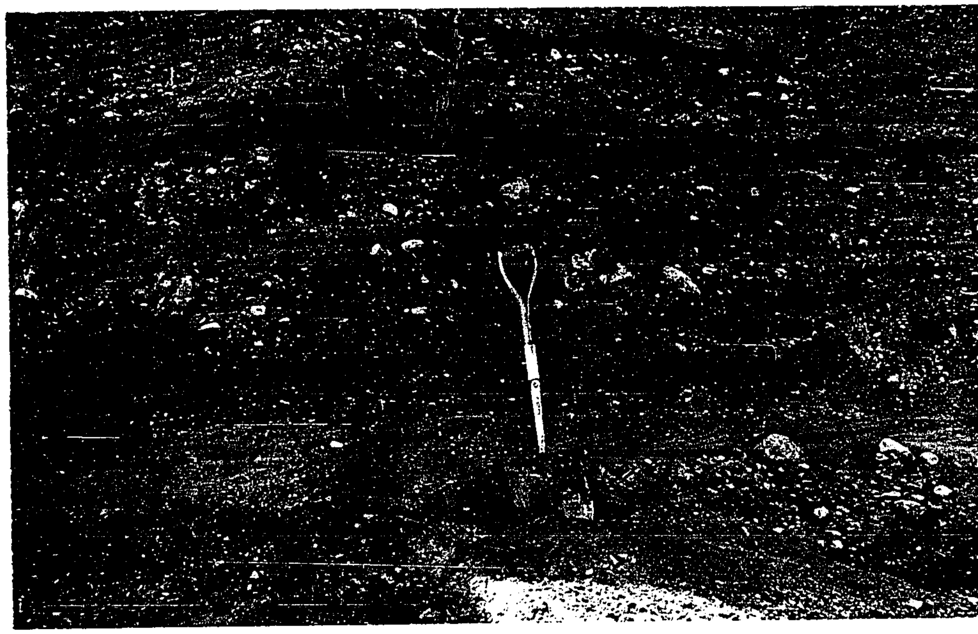


Figure 3-10. Vertical section in a gravel pit 3 miles east of Ninette (NE 28-5-16 W. Prin.), 200 to 300 feet in front of the Darlingford-Tiger Hills moraine. The shovel is about 3 feet long. Note the poor sorting and that grain size ranges from silt to cobbles.

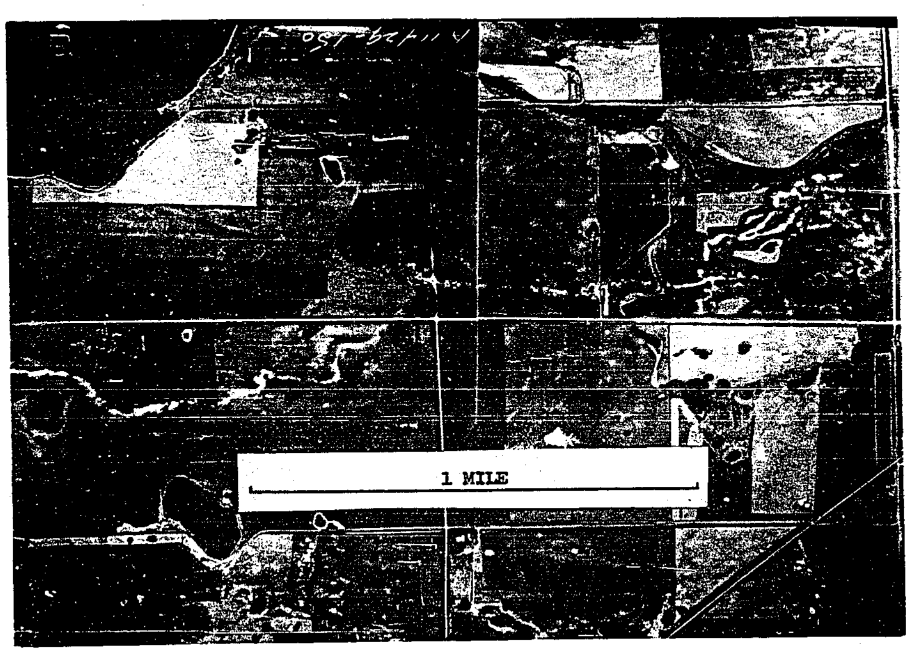


Figure 3-11. Mosaic of RCAF vertical airphotos showing a small esker west of Mariapolis. Erosion of topsoil on the esker gives it a light tone in the photographs. The esker forms a ridge 5 to 15 feet high.

rapid melting of an ice sheet. Ice-contact stratified drift occurs as irregular bodies with from 5 to 100 feet of relief ("kame moraines") in townships 5 and 6, ranges 10 to 12, where it forms much of the Darlingford moraine (Pl. 3); it occurs as pitted outwash grading into an outwash fan north of Ninette; as innumerable small eskers scattered through the Killarney and Purves plains (Fig. 3-12); and as moulin kames in sections 15-2-14 W. Prin., 8-2-12 W. Prin., and 24-4-13 W. Prin. No special symbol is used for eskers on Plate 3 because their color and outline make them obvious.

Ice-contact stratified drift is predominantly medium to coarse sand and pebble gravel (dominantly pebbles of Odanah shale). Glacial striae and facets on the pebbles were destroyed by abrasion during stream transportation. Slump structures, inclusions of till, and cross-bedding are characteristic features. Minor folds and faults resulted from deformation by slumping when supporting ice melted. The sediment shown in Figure 3-10 is typical of ice-contact stratified drift, although it is actually outwash.

Current ripple marks (Shrock, 1948, p. 92-107) in a small body of ice-contact stratified drift in NE 33-2-17 W. Prin. on the south shore of a bay of Lake Killarney, indicate that beds of well-sorted sand that dip 25° northeast were deposited by water flowing southwest. The present attitude of the beds is the result of differential lowering by melting of underlying ice. From the attitude of these beds and the shape of the lake, the following mode of origin of Lake Killarney is suggested: a pre-existing depression, probably part of a former valley, was filled with ice and subsequently was overridden by the ice sheet; the ice in the depression was stagnant. During glacier retreat this lenticular body ice in the Lake Killarney basin remained, and ice-contact stratified drift was deposited on it. The drift near the edges was lowered into its present inclined position when the buried ice melted. The ice in the lake basin may have been of glacial origin or may have been a lake that froze solid under the frigid conditions of glacier advance; a frozen lake would have the lenticular form necessary to produce differential lowering of the sediments on its margins. Glacial grooves on the south side of the lake (Pl. 4) indicate that the depression antedated the last ice advance, and the bays and inlets suggest a former valley system. The lake now has a fairly uniform depth of about 20 feet, and the shores are cliffs from 5 to 20 feet high cut in till.

Eskers

As far as the writer can ascertain, eskers have not been reported previously in this part of Canada. Probably this is a result of their small size, the scarcity of road cuts and gravel pits, and, until recently, the lack of air photographs. Typically, eskers in the Tiger Hills region are inconspicuous at ground level (Fig. 1-4). Vertical air photographs proved invaluable for mapping eskers (Figs. 3-4, 3-6, 3-11, and 3-20).

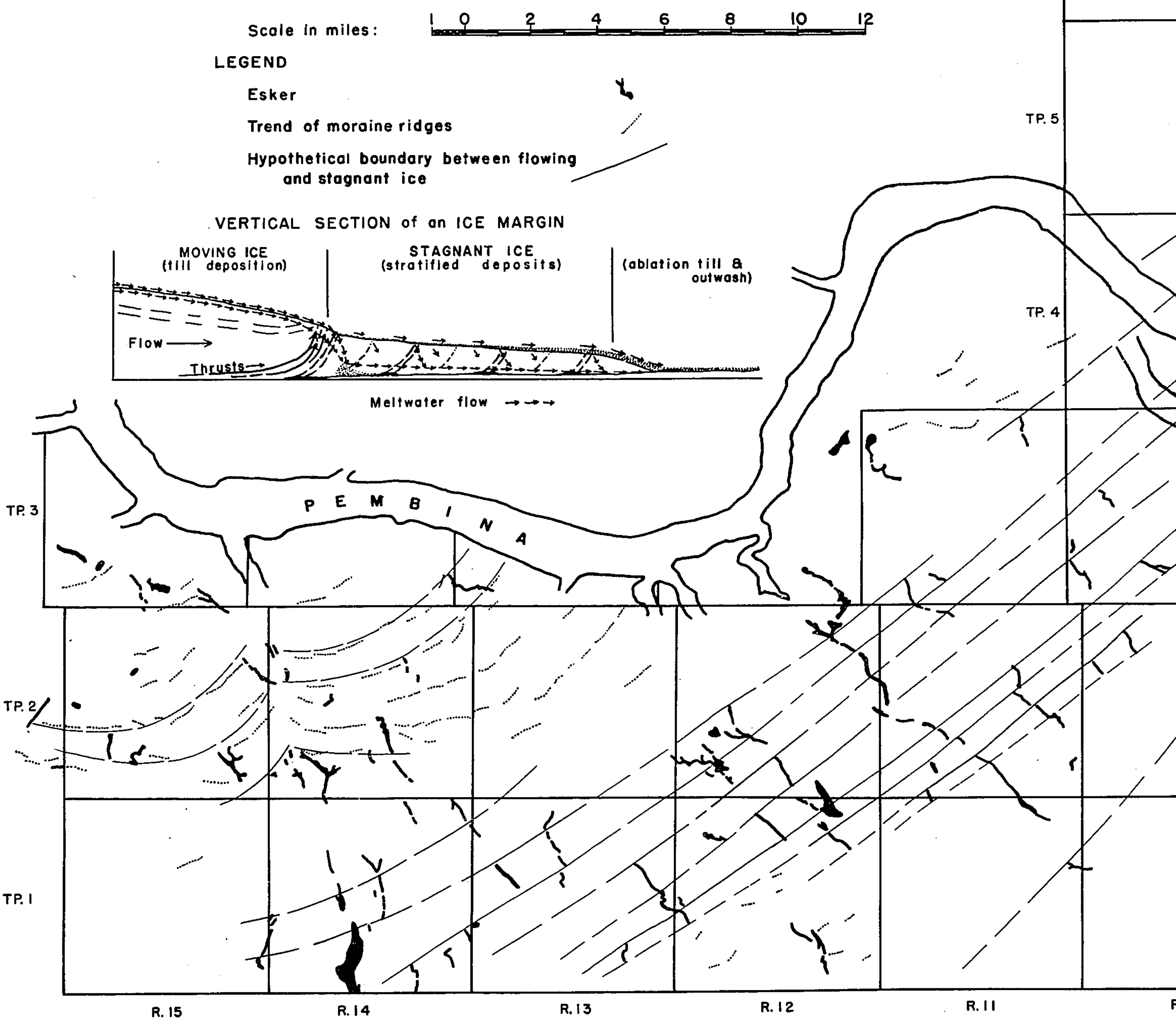
Most of the eskers in the Tiger Hills region comprise one or more collinear ridges from 100 to 500 feet wide, from 5 to 25 feet high, and generally less than 1 mile long. Several of these ridges form longer esker systems near Crystal City, Clearwater, and Cartwright. The system that trends southeast through Crystal City is about 12 miles long, whereas the one near Clearwater is 6 miles long.

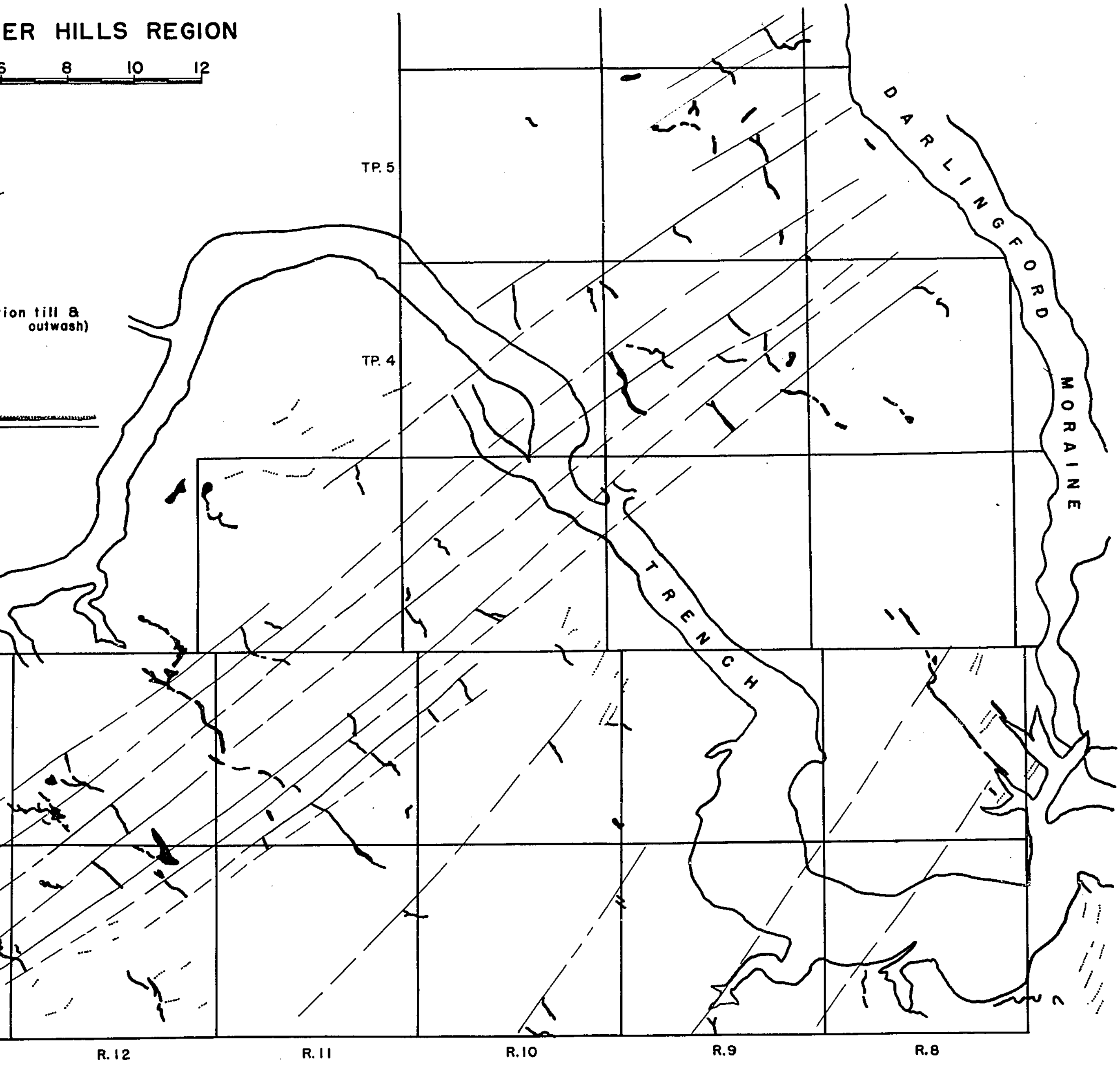
For purposes of discussion, the eskers in the Tiger Hills region are divided into three classes: (1) segmented eskers, represented by the esker systems at Clearwater and Crystal City and several shorter isolated systems on the Purves plain; (2) transverse eskers, parallel to the inferred former ice margin and more or less transverse to the direction of ice flow, which occur in the Tiger Hills between Glenora and Mariapolis; and (3) eskers associated with washboard moraine, some of which apparently modify the pattern of the moraines whereas others are modified by the moraines.

Segmented Eskers

Most of the segmented eskers are southeast-trending series of collinear ridges 5 to 15 feet high (Fig. 3-12). An esker segment is defined as a ridge of ice-contact stratified drift separated from other collinear ridges by gaps, abrupt changes in direction, or changes in the character of the ridge (e.g. individual esker segments may be narrow ridges, broad ridges, sinuous ridges, or massive bodies of ice-contact stratified drift). The mean length of esker segments on the Purves plain, disregarding several very short segments, is from 0.7 to 0.8 mile. Segments range from a few hundred

FIGURE 3-12. SEGMENTED ESKERS IN THE TIGER HILLS REGION

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feet to 3 miles in length. Interpolation between collinear segments is justified by the work of S. Aronow (oral communication) who found by drilling between collinear segments in North Dakota that gravel deposits without topographic expression occupy the gaps. This gravel was apparently deposited in a subglacial meltwater channel incised into underlying ground moraine and forms part of the esker.

The eskers are composed of gravel (dominantly shale pebbles), sand and silt in various proportions (sample "Esker", Fig. 3-16). Exposures are too few to indicate the direction of flow of streams that deposited the eskers from crossbedding and median grain size; however, it is assumed that the streams flowed southeast. It is not possible at present to show that a segment comprises gravel at the upstream end and sand or silt at the downstream end, and hence, is a single depositional unit.

The breaks between esker segments show parallelism in position and type (e.g. simple gaps, offsets, or changes in character of the esker). These breaks may record former ice margins: roughly parallel lines can be drawn through the breaks to suggest successive ice-margins (Fig. 3-12). The esker segments between any two of these lines have similar characteristics, which suggests that there was a common depositional environment.

Segmented eskers may have formed as shown in the inset "vertical section of an ice margin" (Fig. 3-12). In this diagram thick active ice flows from the left against thin stagnant ice on the right. Where the active ice is obstructed by stagnant ice, thrusting occurs and debris is carried upward from the sole to the surface of the glacier. There may be a zone of deposition by lodgment at the base of this thrust zone (shown by a short heavy line in Fig. 3-12), where washboard moraines form (p. 80-84; Fig. 3-7). The debris carried to the surface of the ice by upthrusting speeds melting by absorbing radiation where it is thin, near the active thrust zone, and retards melting by acting as an insulating layer where it is thick, near the ice margin. Much of the surficial drift is transported by meltwater, enters the ice through moulins and crevasses, and is deposited as ice-contact stratified drift in eskers and kames. Eskers and kames would be destroyed by ice movement if they were deposited in flowing ice; hence, they must form in the stagnant-ice distal to the thrust zone. Melting of the stagnant-ice is governed by (1)climate, which would be uniform within the Tiger Hills region in any given season, and (2) distribution of superglacial drift, which may produce local variations in melting and, hence, in ice-contact stratified drift deposits. During retreat, melting exceeded glacial flow in summer, the stagnant ice apron expanded inward toward the glacier, and eskers lengthened headward. When melting stopped, in winter, the zone of thrusting stopped retreating; glacial or subglacial channels that may have extended back beyond the thrusting zone during the summer were closed. This hypothesis is a modification of the "winter lines" theory established by S.A. Andersen (1931) by joining the kinks and gaps in adjacent eskers in Denmark. In southern Manitoba the spacing of washboard moraines (5 to 10 per mile) and the mean length of the esker segments (0.7 to 0.8 mile) are not compatible with both "annual moraines" and "winter lines". The"winter lines" may represent periods comparable to the 11-year sunspot cycle, if the washboard moraines are truly "annual moraines". As already noted, the timing of washboard ("annual") moraines is still unproved.

Transverse Eskers

In townships 4, ranges 12 and 13, between Glenora and Dry River, and 0.5 to 2 miles west of Mariapolis (Fig . 3-11) are several esker-like ridges that lie parallel to nearby end moraines and minor moraines, and are more or less transverse to the presumed direction of ice flow. One of these ridges south of Dry River is nearly 6 miles long, and, like adjacent ridges, has straight portions that suggest a fracture pattern (Flint, 1947, p. 148). The ridges are mainly sand with minor gravel, and are from 15 to 30 feet high and as wide as 500 feet. In the north half of section 13-4-13 W. Prin., two parallel ridges have a combined width of 0.25 mile. This particular mass of stratified drift is connected to a large mound (probably a "moulin kame" 1/) in section 23-4-13 W. Prin. by a small esker. These ridges lie in a shallow basin north of the Tiger Hills - Darlingford moraine

1. Debris deposited by a glacial stream plunging down a moulin (F.T. Thaites, 1946, p. 42, fig. 53).

that was undoubtedly occupied by stagnant ice. These transverse eskers may have been partly deposited in crevasses open to the sky.

Eskers associated with washboard moraines

Examples of eskers designated as (1)subordinate and (2) dominant, with respect to washboard moraines, occur in townships 2, ranges 14 and 15, (Plates 3 and 4, Fig. 3-6). A typical subordinate esker trends southeast through NE 24-2-15 W. Prin. (Figs. 3-6 and 3-13). Dominant eskers are best represented by a number of remnants, some too small to map, along Badger Creek, which form the axis of a reentrant pointing north into the generally convex-southward, lobate pattern of washboard moraines (Fig. 3-6; Pl. 4).

Subordinate Eskers

The subordinate esker mentioned above is shown in figure 3-13, in which washboard moraines appear as northeast-trending ridges crossed by the southeast-trending esker (stippled). The washboard moraines do not change direction where the esker crosses them; on the other hand, the esker changes direction where it crosses the moraines. The esker forms a ridge slightly higher than the moraines and is superposed upon them. Several moraine ridges are slightly flattened close to the esker, but this modification is uncommon. The washboard moraines must have been covered by glacier ice in which the esker formed. Other examples of subordinate eskers are in sections 6-3-13, 31-4-17, 29 and 30-4-17, 21-4-17 and 15-5-18 W. Prin. (Pl. 4). Many eskers in wash-

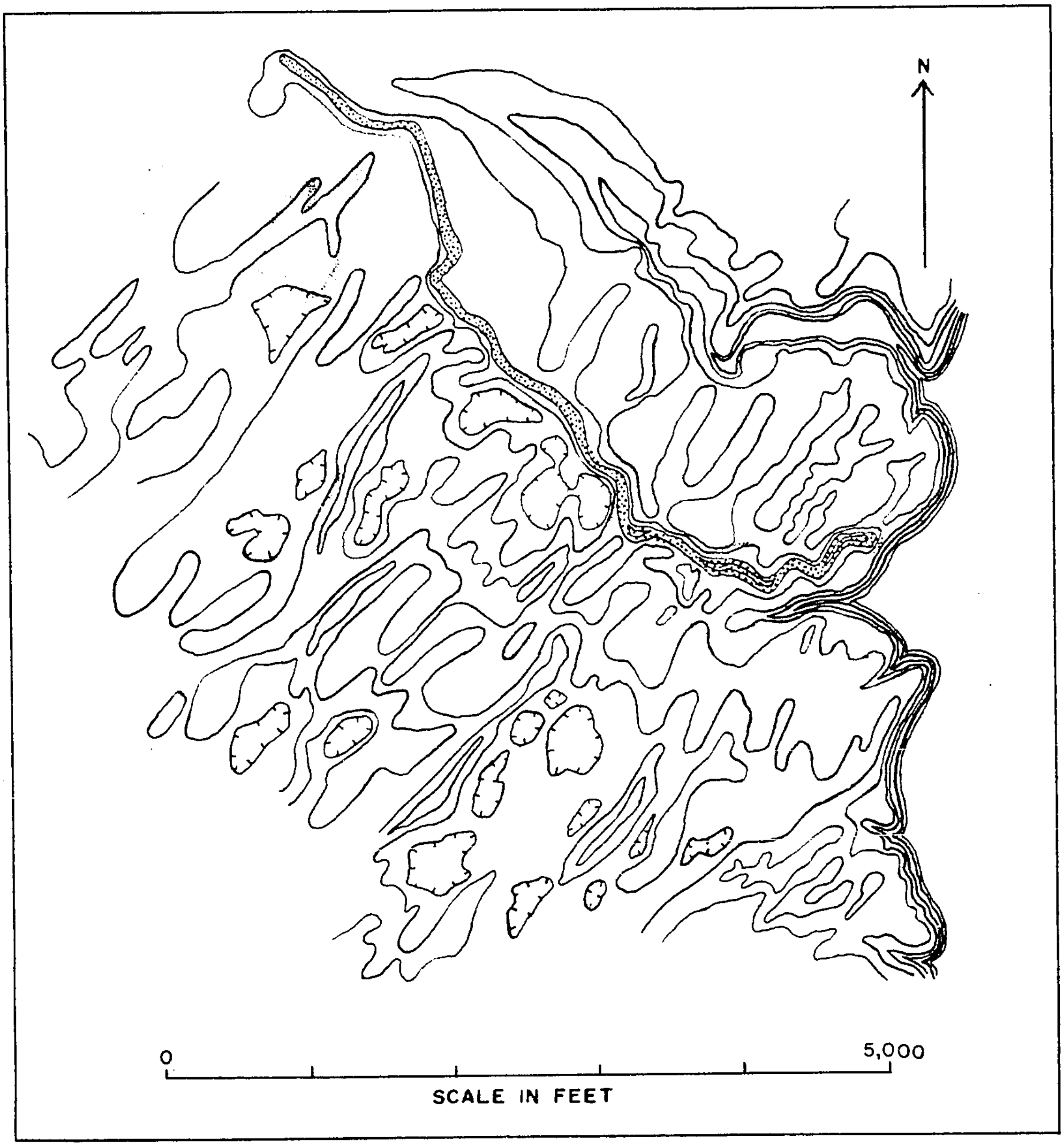


FIGURE 3-13. FORM-LINE MAP OF SUBORDINATE ESKER

Esker stippled; remainder of area is till. Form-line interval approximately 3 to 7 feet. Located 3 miles north of Cartwright, Manitoba.

board moraine are not associated with any change in direction of the moraine ridges, but cross them at right angles and may or may not have minor offsets at moraine ridges. Some moraines are subdued near the esker, which suggests that part of the debris that might have formed moraines was carried away by englacial and subglacial meltwater.

Dominant Eskers

Two dominant eskers occur near Cartwright (Pl. 4); one trends north through Cartwright and is represented by remnants of a gravel ridge along Badger Creek. The second trends south-southeast through sections 15, 10 and 3, Township 2, range 14. It is shorter and is 4 miles east of Cartwright. Dominant eskers occupy an "interlobate" position with respect to the pattern of washboard moraines. Thwaites (1946, p. 42, fig. 53) apparently considered ice-contact stratified drift in this situation to be interlobate moraine; however, the dominant eskers near Cartwright were deposited in minor reentrants in a single ice margin rather than between two distinct glacier lobes.

Dominant eskers are much larger than the subordinate type; remnants of the Cartwright esker, in sections 6, 7 and 19-2-14 W. Prin., are 20 to 50 feet high and 300 to 500 feet wide; most of it has been eroded by Badger Creek. If the extent of reentrant angle in the pattern of washboard moraines is a valid criterion, the esker originally may have extended north as far as Pembina trench, a distance of about 7 miles. Near Cartwright, it is flanked by outwash.

The esker formed in the center of a superglacial valley. This valley collected meltwater, and thus, maintained a greater rate of glacier thinning than prevailed in adjacent areas; it perpetuated itself by increasing its glacial watershed as the glacier retreated, until a change in the glacier regimen or in the glacial drainage system ended the process. Inception of drainage eastward through the Whitemud Creek spillway, or recession of the glacier to higher ground may have ended the self-perpetuating reentrants near Cartwright.

The lobate pattern of moraines adjacent to the dominant esker 4 miles east of Cartwright (Sections 15-, 10-, and 3-2-14 W. Prin.), is not as well developed as the pattern adjacent to the Cartwright esker. Like the one at Cartwright, this esker is flanked by sandy outwash. The esker begins as a knob about 50 or 60 feet high in section 15,and tapers down to a ridge 10 to 20 feet high farther south. The reentrant in the washboard moraines is only about 0.9 mile deep; in other respects the relationships are similar to those of the Cartwright esker.

It is evident from the large cross section of both these dominant eskers and associated bodies of outwash that a well-developed glacier drainage system that caused ablation in excess of the supply of ice by flow, maintained a zone of thin ice that extended back into the glacier and produced a lobate pattern in marginal and submarginal deposits (see p. 84).

Internal structure of eskers

Gravel pits in eskers show cut-and-fill bedding generally found in sand and gravel deposited by rapidly flowing streams. On the sides of eskers, beds dip outward at the angle of repose of sand and gravel and indicate that slumping occurred when the ice walls that supported the esker melted away; they also may represent postglacial mass-wasting. Some low eskers show little slumping and probably were deposited in low subglacial tunnels like those seen now at the termini of Victoria and Saskatchewan Glaciers. The bulk of this type of esker may occupy a channel cut into ground moraine. Sediments deposited in such subglacial channels would not accumulate to a height that necessitated support from the ice.

Masses of till found in some eskers vary in dimensions from 1 or 2 feet to two-thirds of the cross section of the esker; however, these masses constitute only a very small portion of the sediment in the esker. Locally, some eskers are covered with till from 2 to 6 feet thick: several ridges south of Cartwright (e.g. sections 2- and 12-1-15 W. Prin., sections 2-11-14, and 23-1-14 W. Prin.) have been mapped as moraines because auger holes 3 to 4 feet deep showed only till; stratified drift may form the cores of the ridges.

Linear bodies of stratified drift in the central part of the east half of township 7, range 12, near Landseer, rest on bedrock (Pl. 3). These ridges, from 2 to 5 feet high and as wide as 100 feet, are formed of silt, sand, or fine to medium gravel. Road cuts across several of these ridges show a low anticlinal structure in bedrock underlying the stratified drift; the best example is on the south side of SE 11-7-12 W. Prin. The bedrock in this area is an incompetent bentonite-bearing shale that may be highly plastic when water-saturated and subjected to the pressure of an ice sheet.

Madsen (1900, pp. 103-108) described eskers in Denmark that have what he termed alpha and beta layers. The alpha layer consists of ordinary sand and gravel with cut and fill bedding and forms the bulk of the esker. The beta layer is in the bottom of the esker and comprises beds of sand and fissile till compressed laterally so that near the center of the esker the fissility and bedding stand on edge. Near the sides of the esker, fissility and bedding dip outward. Madsen suggested that the beta layer is older than the alpha layer, and represents an earlier esker which was compressed by ice movement and later eroded by meltwater to form the younger alpha beds.

Nearly all the drift near Landseer, has been removed by (1) current action at the upstream end of the glacial spillway southwest of Treherne and (2) by wave action during the highest phases of Lake Agassiz, and only the beta layers remain of the eskers. The writer's conception of the mode of formation of these features differs from Madsen's eskers as indicated follows:

The pattern of ridges suggests a set of crevasses rather than eskers, which are generally more sinuous. In either tunnels or crevasses the pressure on the subglacial floor would be only the weight of the glacial water table plus the accumulated sediment. On both sides of the tunnels or crevasses, the floor bears the full load of the glacier, and a local pressure differential exists. Thus, minor flow of bedrock (a plastic shale) towards the zone of least pressure occurs and causes gentle doming of bedrock in the crevasses or tunnel and drift contemporaneously with drift deposition. Low anticlinal ridges of this type occur on the soft Queenston shale of the Lake Iroquois plain between Hamilton and Toronto, Ontario.

PROGLACIAL SEDIMENTS

General

Proglacial sediments are formed of glacial debris transported from the glacier by streams with the result that ice-contact slopes play no part in their morphology. Pitted outwash constitutes the transitional zone between glacial and proglacial deposits. Beyond it lies outwash without ice-contact slopes. Proglacial sediments are mainly deposits of aggrading streams; some eolian sediments, derived from outwash and deposited under peroglacial conditions, are also included.

Outwash

Map symbol O; color violet.

Outwash fans

Extensive areas of silt, sand, and gravel deposited by meltwater streams in a belt between Clearwater and Swan

Lake, and smaller outwash fans are scattered throughout the Tiger Hills region, mainly south of the Darlingford-Tiger Hills moraine system. The largest of these are: along Pembina trench west of Neelin; south from Baldur to Neelin; and southeast from Killarney to the International Boundary with an eastward extension to Cartwright; west of Notre Dame de Lourdes; and east of Cardinal. These outwash fans are mainly medium to fine pebble gravel. Sand is second in abundance. The outwash in the Crystal City-Clearwater district is mainly silt. This silt is undoubtedly outwash near Clearwater, but it grades into a clayey silt of enigmatic origin a few miles to the southeast (see below). Rarely, outwash contains minor amounts of poorly-sorted clay, commonly as a layer 1 or 2 feet thick overlying sand and gravel.

Outwash deposited only a few score feet from the ice margin shows great variation in degree of sorting (Fig. 3-10). As distance from the ice margin increases, sorting increases, the mean grain size decreases, and pebbles are more rounded. Adjacent to a former ice margin (e.g. in section 28-5-16 W. Prin.) the outwash may be more than 16 feet thick, but in most of the Tiger Hills region it is from 2 to 8 feet thick and has a mean thickness of about 3 feet. Characteristically, outwash has a dentritic pattern; coarse sand and fine gravel is localized in channels that generally have a dark tone on the air photographs (Fig. 3-14, 3-15) but are imperceptible to the observer on the ground; the depth of these channels is generally less than 1 foot. The

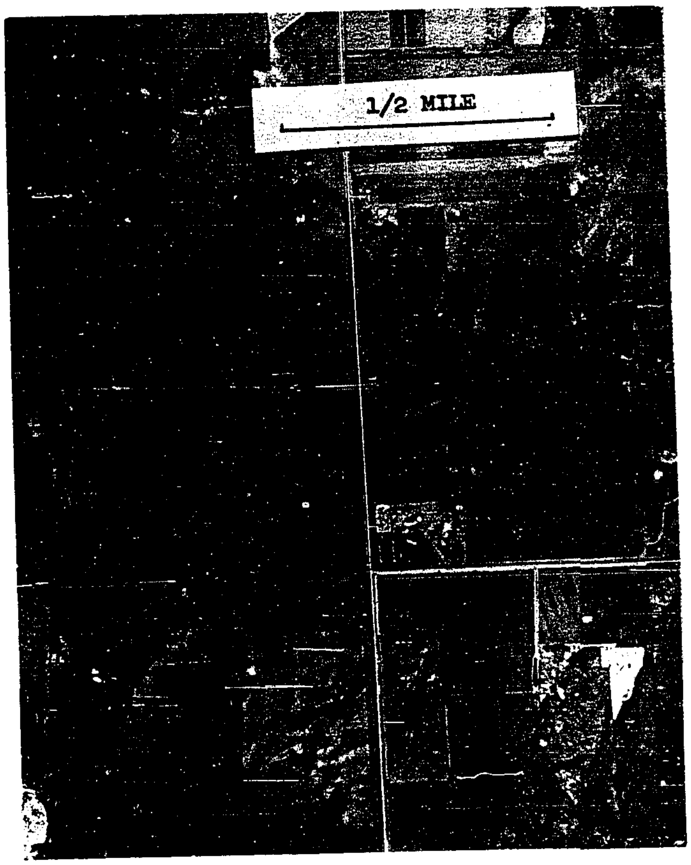


Figure 3-14. Portion of RCAF vertical airphoto showing a pattern typical of outwash. Differences in tone are caused by differences in the sizes of the sediments (sand and fine gravel). Local relief amounts to 1 or 2 feet. The crossroad is NE 31-4-13 W. Prin., 2.5 miles southeast of Baldur.

dendritic pattern of the outwash contrasts with the pattern of ground moraine and washboard moraine (Fig. 3-15). In section 28-5-16 W. Prin. the surface of an outwash fan slopes away from the position of the former ice margin in a profile that is concave upwards, similar to the gradient of a stream. Most outwash fans appear as flat areas, though careful surveying would show slopes similar to stream gradients.

The lithologic composition of outwash gravel is essentially the same as the pebble fraction of adjacent till, except that where there is no local source of bedrock (Odanah shale) there is less bedrock in the outwash than in nearby till, and the outwash contains more dolomite, granitoid, and "other" pebbles than does the till.

Valley Trains

Flint (1947, p. 135) defined a valley train as "a long narrow body of outwash confined within a valley." The Pembina trench downstream from section 23-2-9 W. Prin. contains three sets of terraces that represent valley trains.

Pembina trench downstream from La Riviere was at least partly excavated before the last glaciation. When the last ice margin withdrew northwestward up the valley, coarse outwash gravel composed mainly of large shale pebbles and a few cobbles was deposited on a broad valley floor, remnants of which form terraces in the wide parts of the valley near sections 33-1-7 W. Prin., 14-1-8 W. Prin., and 23-2-9 W. Prin. This gravel contains less than 5 percent limestone, dolomite

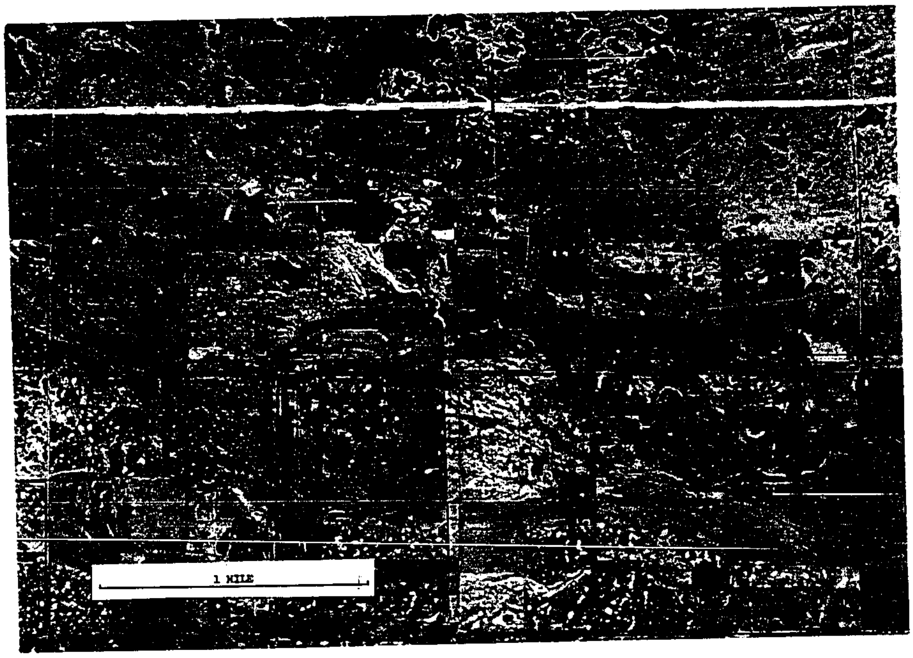


Figure 3-15. Mosaic of RCAF vertical airphotos 3 miles west of Cartwright, showing the northern part of township 1, range 15, W. Prin. North is at the top of the illustration. Outwash with a dendritic pattern extends from northwest to southeast; it is bordered on the south by ground moraine and on the north by a belt of end moraine about 0.3 mile wide. Washboard moraines appear in the upper right-hand corner.

and Precambrian pebbles, all of which are well-rounded. Three sets of terraces represent a succession of three valley trains, each with its own gradient beginning at an ice margin position and ending at Pembina Mountain (Pl. 5(b)). The base levels of these valley trains (Fig. 5-6, gradients 1, 2, and 3; Pl. 3, older alluvium) were formed by two meltwater channels along the Manitoba Escarpment (p. 27-28) and by the apex of the Pembina "delta" (Chapter 5, p. 220-222).

Problematical Silt

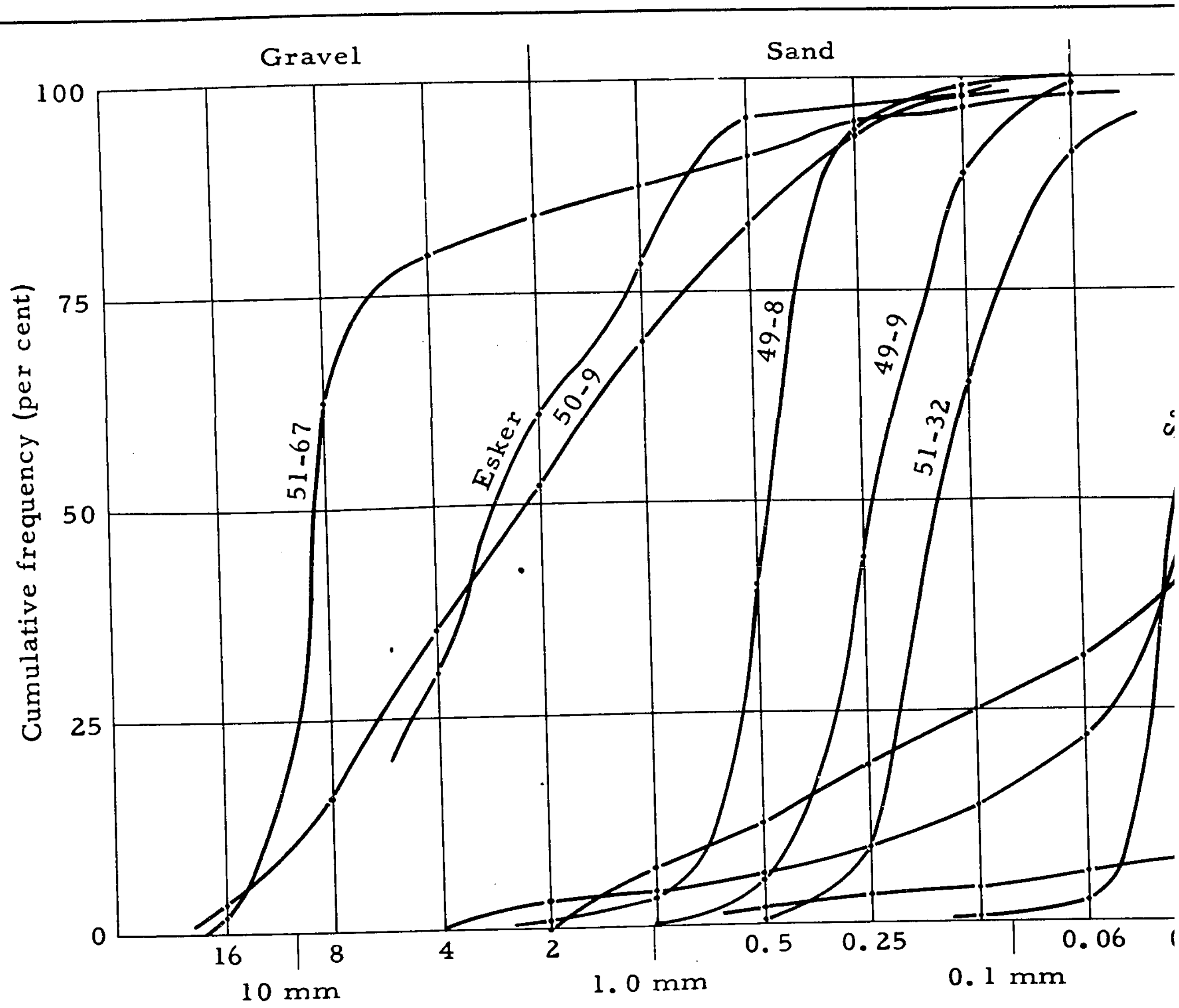
Map symbol si; color rose.

Extensive areas in the central part of the Purves plain (townships 1 to 3, ranges 9 to 11, township 4, ranges 9 and 10, and township 5 range 10) are covered with as much as 6 feet of silt. This silt (sample 50-7, Fig. 3-16) is more sorted than outwash (sample 50-6), but less sorted than loess (S & F no. 4, Fig. 3-16). The data in Table 3-2 illustrate the problem of determining whether the deposit is of glaciofluvial, lake, or eolian origin.

Table 3-2. Characteristics of silt-sized sediments

	Specimen	Median diameter	Sorting coefficient
1.	50-7 Problematical silt	.028 mm	2.47
2.	50-6 Outwash	.017	8.33
3.	49-10 Lake silt	.009	2.02
4.	51-27 Glacial silt	.013	1.21
5.	Loess, Krumbein & Pettijohn	.014	1.49
6.	Loess, Krumbein & Sloss	.0066	1.58
7.	Dust, Swineford & Frye	.032	1.43
8.	Loess #1, do	.035	1.23
9.	do #4 do	.032	1.45
10.	do #10 do	.027	1.64

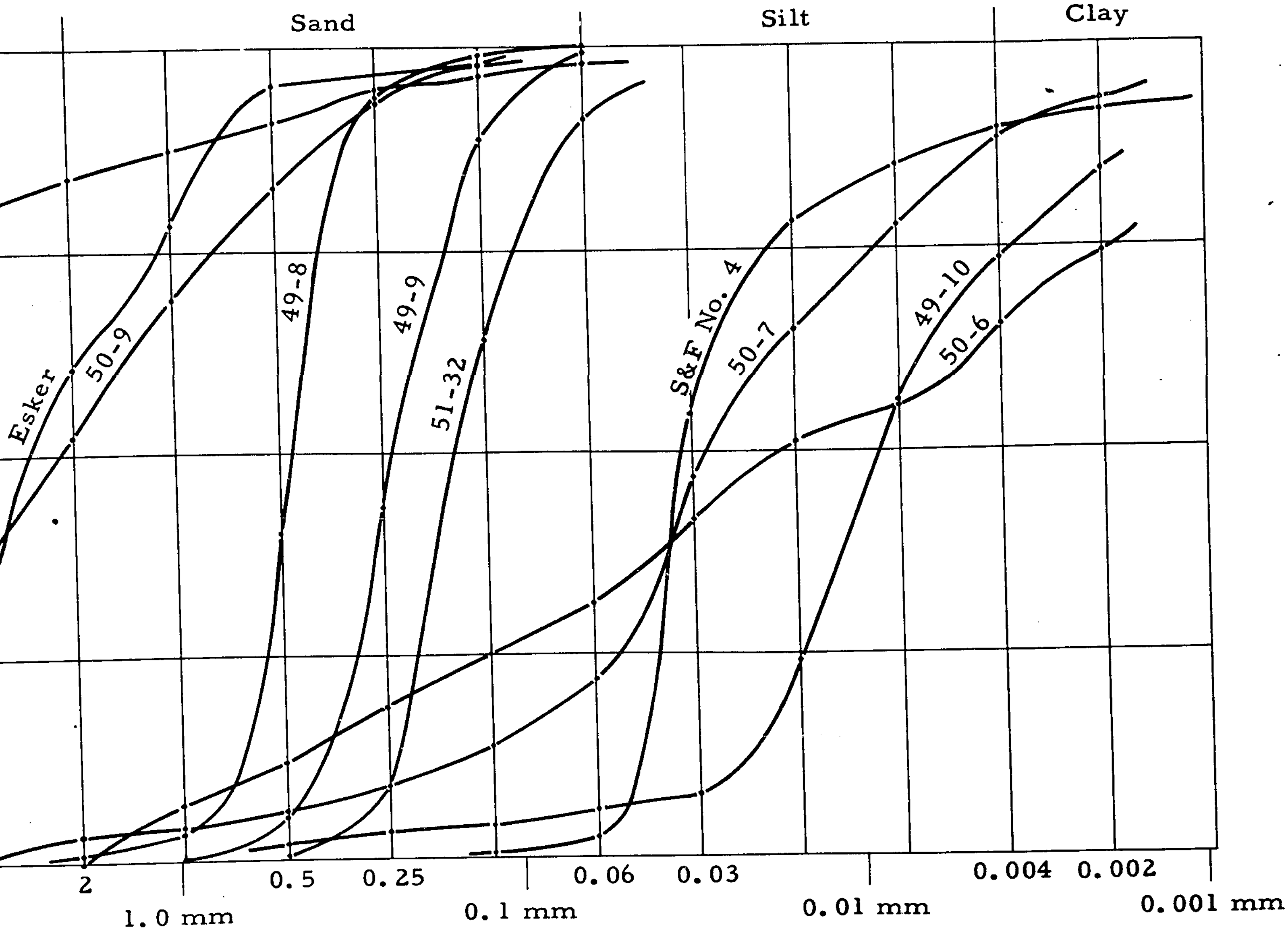
Note: The first four samples were analysed by the writer.



Sample number	Location	Se
51-67	SE 2-7-8 W. Prin.	Beach ridge of
Esker (field analysis)	NW 23-2-8	Small esker
50-9	SW 4-2-7	Alluvial fill in
49-8	NE 33-7-16	Assiniboine de
49-9	SE 21-7-15	Dune sand
51-32	NE 24-8-5	Sand 6 feet bel
S&F No. 4	....	Swineford and
50-7	SW 22-1-14	Problematical
49-10	NW 15-7-17	Silt from the I
50-6	NE 32-1-11	Outwash silt

Figure 3-16.

Cumulative grain-size distribution of sediments in th



Location	Sediment
.......SE 2-7-8 W. Prin.............	Beach ridge of Lake Agassiz
.......NW 23-2-8......................	Small esker
.......SW 4-2-7.......................	Alluvial fill in Pembina trench
.......NE 33-7-16.....................	Assiniboine delta sand 30 feet below surface
.......SE 21-7-15.....................	Dune sand
.......NE 24-8-5......................	Sand 6 feet below crest of Lake Agassiz beach ridge
....	Swineford and Frye (1945) typical loess
.......SW 22-1-14.....................	Problematical silt (loess ?)
.......NW 15-7-17.....................	Silt from the Brandon lake deposits
.......NE 32-1-11.....................	Outwash silt

Figure 3-16.
ative grain-size distribution of sediments in the Tiger Hills region.

The first three samples are from the Tiger Hills region. Sample no. 4 (51-27) is silt from a thrust plane near the terminus of Saskatchewan Glacier; the silt may have been blown onto the glacier and redeposited by meltwater streams. Specimen nos. 5 to 10, except no. 7, are loess specimens described in geological literature (mainly Swineford and Frye, 1945, p. 250). The median diameter of loess ranges from .0066 to .035 mm. Sample no. 7 was collected by Swineford and Frye during a dust storm. A low sorting coefficient (Krumbein and Pettijohn, 1938, pp. 230-233) indicates a well-sorted sediment. The sorting coefficient (so) of windblown sediments (nos. 4 to 9) ranges from 1.21 to 1.64. The problematical silt (no. 1, So 2.47) is not as well sorted as loess, but shows much more sorting than silty outwash (no. 2, So 8.33) which is very poorly sorted. The specimen of lake silt (no. 3, So 2.02) shows better sorting than does the problematical silt, The median diameter of the problematical silt (.028 mm.) is within the range of windblown sediments (.066 to .035 mm.).

The boundaries of the silt, (Pl. 3) are approximate because deposit thins out on ground moraine in the south side and grades into outwash in the north. The outwash boundary is arbitrary and is accurate only within a mile. Where exposed in ditches, the silt is generally 2 to 3 feet thick and contains widely scattered small pebbles. Locally, these form small, gravelly, horizontal lenses as long as two feet. If the silt is a wind deposit the pebbles may have been distributed through it by frost heaving them up from the silty till below; subsequently the pebbles may have been concentrated into lenses by runoff.

Although the silt is slightly thicker in some low areas, it generally covers hills as thickly as hollows. There is no height of land against which a lake could have been ponded by the glacier, although a narrow, temporary, discontinuous belt of shallow water in which silt could have been deposited, may have followed the retreating ice margin.

Where the silt is thin, in level areas, a speckled pattern appears on airphotographs (Fig. 3-17). Each speckle (light-toned) represents a low knoll, almost imperceptible from ground level. Some of the speckles are aligned in rows that are parallel to nearby moraine ridges; others have a random distribution. Road cuts crossing the knolls expose cores of sandy till; hence, pattern of speckles is believed to be the expression of buried moraine topography.

To summarize, the problematical silt has a median grain size comparable to loess, but it is not as well sorted as loess. On the other hand, it is very well sorted for a waterlaid sediment in the same grade-size range. The silt deposit thickens towards its apparent source (outwash) and blankets hills and hollows alike, but tends to be slightly thicker in low areas.

No loess of the classical type has been recognized in the Tiger Hills region. The writer has travelled extensively across the Canadian Prairies without finding any

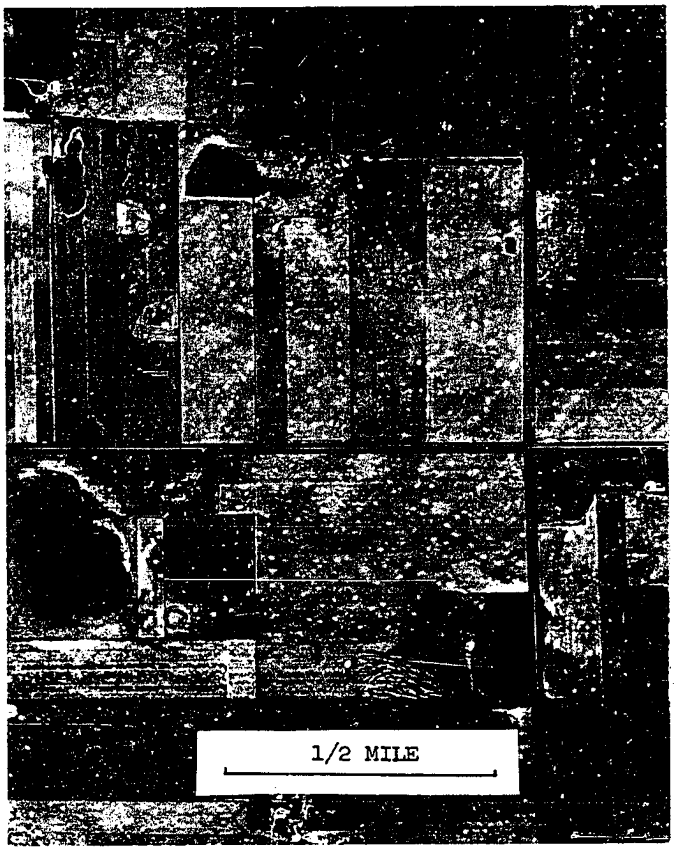


Figure 3-17. Portion of RCAF vertical airphoto showing speckled pattern in an area of problematical silt. Each speckle represents a low knoll of till that projects through the silt. The light tone of the speckles is due to removal of topsoil by erosion. Local relief is generally less than 3 feet, and the knolls are barely perceptible from ground level. The crossroad is at NE 31-1-11 W. Prin. The streaked area above the word "Mile" is a flaw in the photograph.

sections showing the porous, flour-like loess common in South Dakota. Three possible reasons are:(1) a cool, seasonally moist, periglacial climate may result in a more poorly-sorted type of loess than is produced in warm, dry climates farther south. This suggests that loesses in the south were formed at greater distances from the glacier margin. (2) The problematical silt in Manitoba may have been deposited in a narrow, discontinuous belt of ponded water that followed an ice margin retreating down a very gentle slope. (3) The accumulation of dust and englacial silt on the margin of the ice, both by melting and by wind action, may have formed a very silty ablation drift that was lowered by ice melting with some transportation by small meltwater streams.

This silt deposit remains enigmatic; perhaps co-workers in Montana and North Dakota touch as much on the truth as humor when they facetiously apply the term "glaciofluvial eolian lacustrine silt".

WATER-WORKED (REDEPOSITED) DRIFT

Map symbol wt; color azure blue.

The symbol wt derives from the term "waterworked till" but in at least two localities, northeast of Hilton and west of Roseisle, the deposit consists of a residual lag concentrate of pebbles, cobbles and boulders on stratified drift. Where water action has removed all the fines, a few erratics remain on the bedrock surface and there is no clue as to what the original drift may have been.

This lag concentrate may form by current action in streams, as did the belt extending northwest from Margaret through township 5, ranges 18 and 19, and township 6 range 19, where from 0.5 to 2.0 feet of sand and gravel are boulders overly till; waterworked drift on a terrace north of Pembina trench at Ninette consists mainly of boulders resting on bedrock (see also Fig. 1-13). More commonly, waterworked drift is the result of wave action; belts of wave-concentrated stones occur in townships 6 and 7, ranges 14 to 16, and along the Manitoba Escarpment from Holland to the International Boundary. These belts are wave-cut terraces and in most cases the surfaces are covered by a layer of boulders that overlie till, stratified drift, or bedrock. The boulder fields northwest of Morden are particularly impressive.

Not all waterworked drift is exposed. Wherever the depth of water in a lake formed on till was less than the effective wave base, wav e action removed the sand, silt, and clay and left a residuum of pebbles, cobbles, and boulders upon which the sand, silt, and clay later settled (Fig. 3-18). The coarse residuum is rarely more than one or two stones thick because the accumulating stones defend the material below from further wave action. Presumably, this type of concentrate underlies lake deposits formed in shallow water but do not occur below lake deposits formed in deep water.

LAKE AND DELTA DEPOSITS

Map symbols: Coarse sediments (sand and non-plastic silt)lc; color yellow ochre. Fine sediments (clay and plastic silt)lf; color orange.

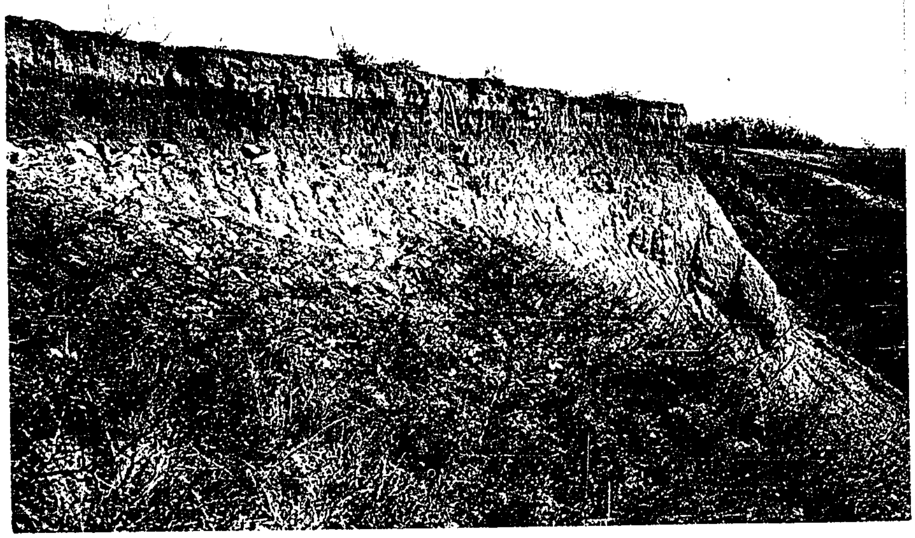


Figure 3-18. Vertical section showing lake sediment (sandy silt) with a lag concentrate of pebbles, cobbles and boulders at the base, overlying till. The lag concentrate was formed by wave action in shallow water. The section is on the west side of the Souris River valley 8 miles southwest of Wawanesa.

General Remarks

No distinction between glacial and non-glacial deposits is made on the map (Pl. 3). The term glacial lake generally suggests a glacial source of sediment and the formation of varves. Although most of the lake sediments in the Tiger Hills region were deposited in lakes either fed by glacial meltwater or ponded by a glacier margin, most of the sediment was not glacial but was from the land to the south and west, and may be termed inwash. Upham (1896, p. 189-190) thought that half the sediment in the Assiniboine delta had been eroded from the Upper Assiniboine valley and its tributaries, and that the other half was glacial sediment transported by streams from glacier lobe occupying the upper Assiniboine watershed. The sediments were deposited in the landward side of glacial Lake Agassiz and are similar to deposits in a non-glacial lake. The terms lake and delta both are used in the heading because delta deposits are distinguished from sediments derived by wave erosion of the shore and from sediments entering the lake directly from the glacier.

Most small lakes in the Tiger Hills region began as glacial lakes and later became independent of their glacial sources. Several small, dry lake basins occur in sections 13, 14, 23, 24; 19, 20; and 29, 30 township 6, range 18, W. Prin. Steel's lake (Chapter 5, p.268), 1 mile north of Glenora (section 4-4-13 W. Prin.), is surrounded by small beach ridges and scarps which indicate that the lake was formerly broader and deeper. L izard Lake, 7 miles northeast of Manitou, has been drained within historical time. Numerous other small lakes (Pl. 3) have deposits too small to map. More than 95 percent of the lake deposits in the Tiger Hills region are those of glacial Lake Agassiz and its high-level predecessor north of the Tiger Hills, the Brandon glacial lake (Chapter 5, p. 235).

To keep map symbols to a minimum, only two types of lake sediment were differentiated: coarse (mainly sand) and fine (mainly clay). The modifying symbols (s) and (cl) indicate that the deposits are well-sorted sand and clay, respectively. Where silt is abundant the symbol (si) is used to modify lc or lf (p. 116). Where silt occurs in lf it is fine-grained and plastic because of its clay content; silt shown in lc is coarse. The general paucity of silt facilitated delineation of sand-clay boundaries (Figs. 3-19 (a) and (b)).

Near-shore Deposits

Beach ridges (bars) are nearly horizontal ridges of well-sorted sand and fine pebble gravel from 3 to 15 feet high, and from 100 to 300 feet wide that represent former lake margins. Most bars on slopes of about 60 feet per mile are about 6 feet thick. The thickest bar is at the base of the Campbell scarp: near Miami and Roseisle gravel pits indicate that it is thicker than 12 feet. The upper 2 feet of many bars are dominantly well-sorted gravel (Fig. 3-20), comprised mainly of medium to small pebbles and rare large pebbles (sample 51-67, Fig. 3-16).

Figure 3-19(a). Unimproved sand road in the Lake Agassiz basin. Tire marks disappear rapidly due to small-scale slumping and wind activity. Ruts rarely develop and are not long preserved.

Figure 3-19(b). Unimproved road in clay alluvium near Rose-isle. Lake clay produces the same type of road but is generally black instead of grey. Tire marks and ruts are well preserved and mud cracks are abundant.

Beach ridges are especially common west of Morden (Fig. 3-21) and near Treherne, where the slope of the shore and the supply of sand and gravel are favourable for their formation. Till forming the shore of Lake Agassiz near Morden was an adequate source of sand and gravel, and the slope (50 to 65 feet per mile) apparently was ideal for bar formation. In general, abundant, well-developed beach ridges occur on slopes ranging from 30 to 80 feet per mile; they are less common on slopes of less than 30 feet per mile and on slopes of more than 80 feet per mile which are characterized by wave-cut scarps. Presumably the waves are weakened by the bottom drag of gently-sloping shores and are not powerful enough to build a bar, whereas on the steep slopes the material that might form bars is carried away into deeper water. Where sources of sand and gravel are lacking on slopes that are otherwise favourable for bar formation, low wave-cut scarps occur; most bars cover a scarp of about half their height. The beach ridges west of Morden are in groups that correlate with single bars and scarps elsewhere in the Lake Agassiz basin (Upham, 1896; Johnston, 1946).

King and Williams (1949) showed that offshore "break point" bars are generally destroyed when water level falls; hence, it is inferred that the beach ridges (bars) of Lake Agassiz are all onshore or storm bars (Chapter 5, p. 252). Subaerial beach ridges are built by waves dropping their load of sediment when their velocity is reduced at the shore. Sorting is accomplished by this change in velocity of waves,

Figure 3-20. Cross-section of a bar northwest of Morden, showining medium to fine gravel overlying coarse sand. The bedding dips gently lakeward (to the right); to the left of the photograph it dips left toward a former lagoon. The visible part of the shovel is about 3 feet long.

and by sheet wash and rills which flow both lakeward and landward over the saturated bar. Sections through bars near Morden show cross-bedding dipping in both directions. Pebbles in any part of a bar indicate that more powerful waves were active when that part was formed. The problem of using beach ridges (bars) for data in studies of former water planes is discussed in Chapter 5 (p. 252-254).

Fine sediments derived from shore erosion are deposited offshore; silt and fine sand south of Rosebank in ranges 5 and 6 are mainly of this origin. They generally form massive beds, and their mean grain size decreases eastward toward the center of the lake basin. A clay faction is not exposed in this part of the Tiger Hills region; clay was undoubtedly deposited when the lake was deep and is believed to be overlapped by younger, shallow-water sediments.

Deep-Water Deposits

Data from the Tiger Hills Region

The clay belt centered around Rathwell (township 8, ranges 8 and 9) probably represents bottomset beds of the early Assiniboine delta. Some of the clay was derived from the shaly Cretaceous rocks in the Manitoba Escarpment, and the remainder is the fine fraction of reworked glacial deposits.

A small triangular area shown as clay in the northeast corner of the map is believed to comprise deep-water sediments of Lake Agassiz. The deposit is a massive, well-sorted clay, on the surface of which are sparse ice-rafted cobbles and boulders that distinguish it from clayey alluvium

Figure 3-21. Mosaic of RCAF vertical airphotos southwest of Morden (upper right-hand corner). Beach ridges (bars) cross the area from northwest to southeast. The scarp of the Campbell strandline is seen 1 mile south of Morden; between it and the main belt of beach ridges is a terrace about 1 mile wide covered with waterworked till. A small esker is seen in the center of the left side of the illustration. The altitudes of the beach ridges range from about 1,130 to 1,250 feet.

which is invariably boulder-free. The few well-logs available indicate that this clay is several tens of feet thick (p. 62-63).

Much of the clay in the marginal belt of the Lake Agassiz basin is alluvium derived from Cretaceous shales, and is difficult to distinguish from lake clay, except for the lack of cobbles and boulders. The alluvium forms fans that overlie lake sediments and are generally no thicker than about 15 feet.

Evidence from North Dakota

The foregoing meagre data are the result of the writer's reconnaisance survey of the Tiger Hills region. Detailed studies in connection with ground-water projects (Paulson, 1951; Dennis, Akin, and Worts, 1949, p. 17-21) in the Lake Agassiz basin in North Dakota yielded subsurface information from test wells as follows:

An upper silt unit, 15 to 35 feet thick, is buff to yellow to gray in color, and locally contains sand or clay. The unit has uniformly laminated bedding and is coarser-grained near the base than it is near the surface; locally it is entirely clay. The silt unit is believed to have been deposited in shallow water in a transgressing lake. Sand and gravel at the base suggest fluvial deposition before the lake formed.

Below the silt unit is a clay unit comprising 15 to 85 feet of blue-gray lake clay containing scattered stones and sand. This clay overlies till and glaciofluvial deposits. It is inferred that the clay unit formed in a body of deep water that persisted for many years.

Rominger and Rutledge (1952) used physical properties (liquid limit, plastic limit, plasticity index, relative water content, natural water content, and preconsolidation stress) to subdivide the sediments at Grand Forks and Fargo, North Dakota, and at Crookston, Minnesota. The uppermost unit (no. 5) is silt and clay and at Grand Forks is separated from unit no. 4 (clay) by an unconformity which Laird (1944, p. 22) suggested may correlate with a similar unconformity in the Lake of the Woods region (Johnston, 1916). At Fargo, the lower half of unit no. 4 contains organic matter, including fossil shell fragments. It is separated from unit no. 3 (clay) by a drying surface indicated by preconsolidation stress data. At Grand Forks and Crookston the drying surface has altitudes of 795 and 811 feet, respectively. Probably the drying surface (unconformity) between units no. 3 and 4 at Grand Forks correlates with erosional unconformities near Rainy River (Johnston, 1915), near Lake of the Woods (Johnston, 1916), and in the Assiniboine delta. Rominger and Rutledge used one of two possible correlations suggested by Laird; Rominger (personal communication, April 26, 1954) subsequently thought the writer's correlation might be correct. If so, the unconformity between units 4 and 5 at Grand Forks is local or is present in the south part of the Lake Agassiz basin only, and the drying surface between units

3 and 4 is the widespread erosional unconformity formed during the interval between Lakes Agassiz I and II. The latter unconformity and drying surface antedates, or is contemporaneous with, the entrance of a gastropod fauna into the Lake Agassiz basin. The Grand Forks drying surface should occur at an altitude of from about 870 to 895 feet near Portage La Prairie, if the Campbell strandline is used as an index of crustal warping. This datum represents the maximum altitude for the level of Lake Agassiz (if it was not drained) during the interval between Lake Agassiz I and II.

Conclusion

The sediments in the Lake Agassiz basin, as known in several areas, show the following stratographic sequence:

Near the International Boundary (Paulson; Dennis et al; Elson)		Grand Forks, N.D. and southward (Rominger and Rutledge)	
Unit	**Description**	**Unit**	**Description**
6	Recent alluvium near the lake margin		
5	Silt unit of variable composition (silt and clay) deposited in transgressing lake.	5	Silt
			-----------unconformity-----
		4	Clay with fossil shells and organic matter in lower half
4	Fluvial (?) sand and gravel (erosional unconformity)		Old drying surface
3	Clay unit deposited in deep water	3	Clay
		2	Clay
		1	Clay
2	Sand and gravel (glacio-fluvial?)		-----------unconformity-----
1	Till		Drift

The following succession of events is inferred from the stratigraphic sequence:

1. Glaciation and the deposition of till.
2. Ice recession under subaerial conditions and deposition of glaciofluvial gravels.
3. Deposition of clay in a deep lake of long duration.
4. Draining of the lake and entry of a gastropod fauna into the lake basin.
5. Formation of a second, shallower lake and a fluctuation in level that briefly exposed the southern part of the lake basin.
6. Draining of the second lake, and deposition of alluvial fans in marginal areas of the lake basin.

Assiniboine Delta in Lake Agassiz

Upham (1890, figs. 2 and 3, facing p. 38E; 1896, fig. 16, p. 373) drew very generalized sections of the Assiniboine delta. Data from river and road cuts are still sparse; because water supply is not a serious problem over most of the delta there are as yet few data from deep wells. Upham inferred that about 120 feet of deltaic sediments overlie about 90 feet of till south of Carberry. A test well drilled in this area by the California Standard Company (p.62) penetrated 225 feet of delta deposits, comprising 85 feet of sand overlying 170 feet of silty clay which are underlain by 70 feet of till. Because the Assiniboine valley contains an alluvial fill, river cuts that expose the lower sediments of the delta are rare. A cut bank at an altitude of about 1040 feet in NW 2-8-14 W. Prin. showed 10 feet of poorly-sorted silty sand (alluvium?) overlying a horizon of thin lenses of fine gravel which overlies massive, blue-grey, stone-free clay. The alluvial fill is generally fossiliferous, hence clays that do not contain fossils are probably the lower beds of the delta. Farther downstream, north and northwest of Treherne, bedrock exposures in the bottom of the valley at an altitude of about 1,000 feet indicate that the delta is probably 200 feet thick 45 miles east of Brandon.

In Plate 5(a) (in pocket), a profile along the axial line (talweg) of the Assiniboine valley, the general surface of the delta constitutes the upland shown in the east (right) half of the profile. The main delta surface has an altitude of about 1,200 feet; the distal portion is 25 to 40 feet lower than the apex, near Brandon. East of the 1,200-foot contour (Pl. 1), the surface of the delta declines about 150 feet in 11 miles; this slope probably represents the dip of foreset beds, modified by wave-cut scarps formed during a subsiding phase of Lake Agassiz. East of this the delta surface slopes about 150 feet in 25 miles. This gentle slope represents the dip of bottomset beds, modified by strandline scarps and a deposit of sand. Some of the sand may be younger deltaic sediment deposited in Lake Agassiz II; however, most of it was eroded from wave-cut scarps during the subsidence of Lake Agassiz I; it was reworked during the subsequent rise and fall of Lake Agassiz II.

A vertical section from the apex to the margin of

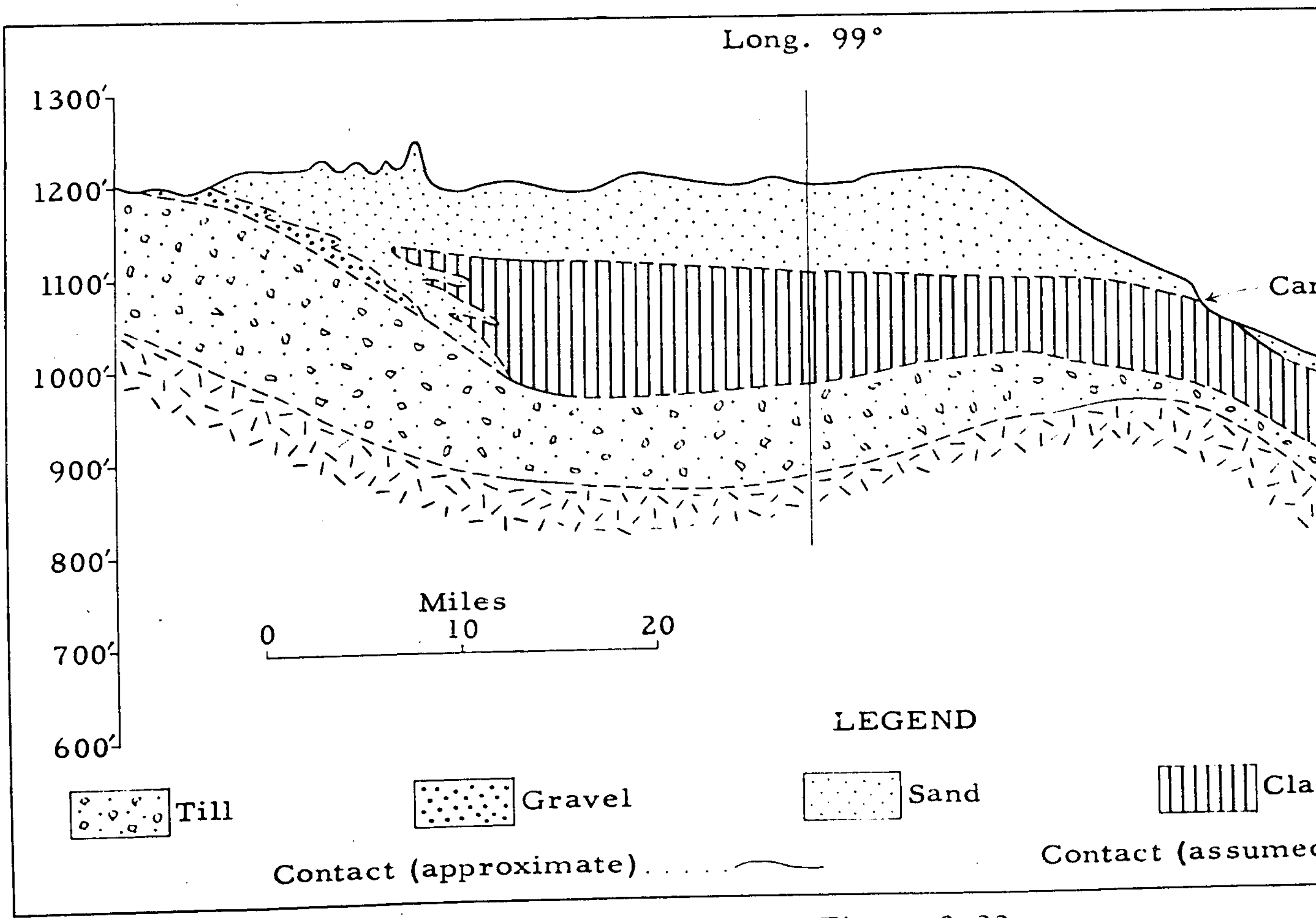


Figure 3-22.

Idealized section of Assiniboine delta in vicinity of Latitud with profiles of present Assiniboine valley omitted. The slope at 1050 feet is the Campbell scarp and marks the tra zone between the younger and older delta deposits.

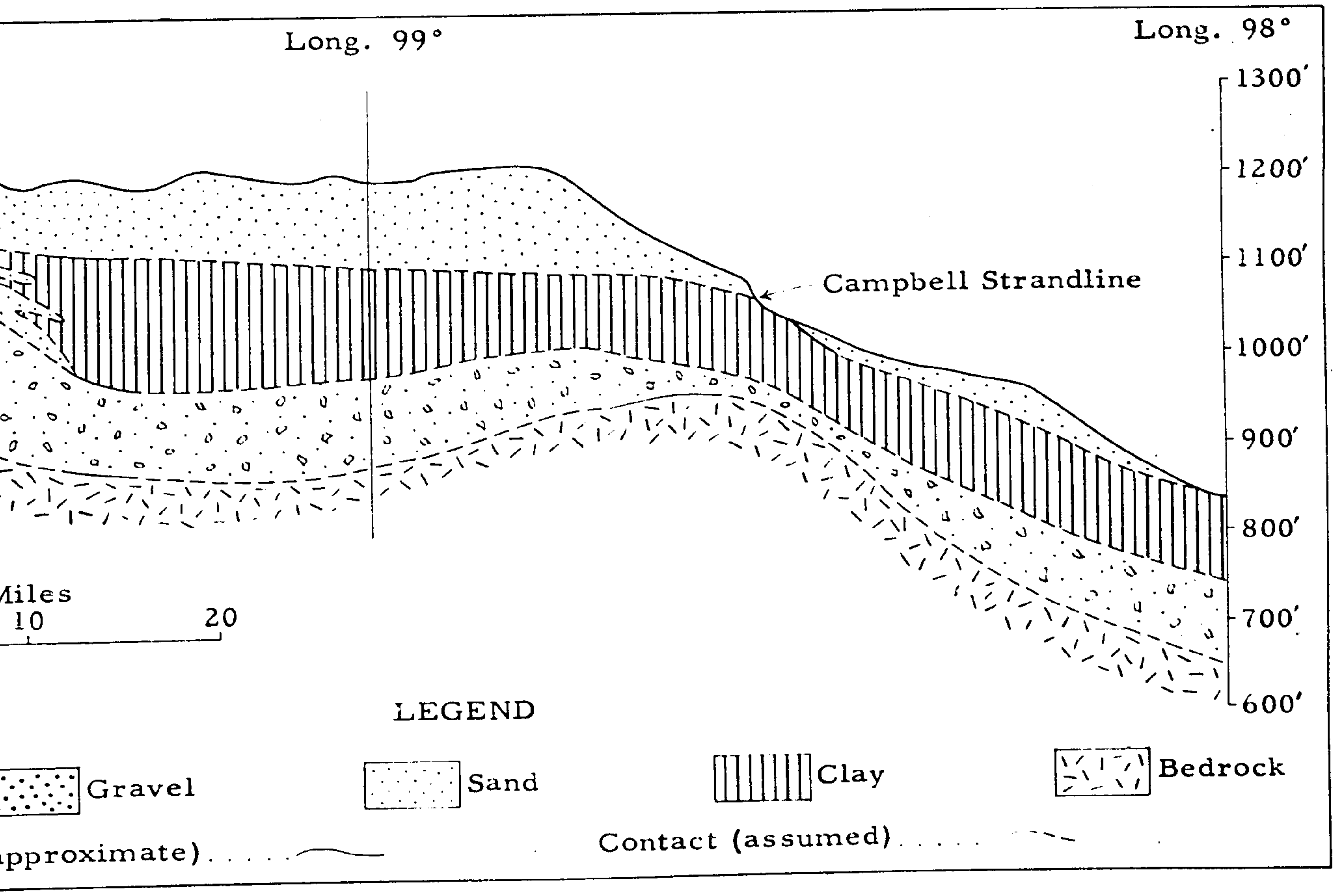


Figure 3-22.

lized section of Assiniboine delta in vicinity of Latitude 49°45'. profiles of present Assiniboine valley omitted. The steep e at 1050 feet is the Campbell scarp and marks the transition between the younger and older delta deposits.

the Assiniboine delta (Fig. 3-22) can be compared with similar sections of deltas produced experimentally by Nevin and Trainer (1927, figs. 4 and 5). The upper beds of the Assiniboine delta are generally horizontally-bedded sands with shallow channels (Fig. 3-23). The structure of the delta is similar to that of a delta deposited in rising water (Nevin and Trainer, 1927, fig. 4). Formation of the Assiniboine delta, with its 1,200 square miles of thick topset beds on which the general slope is only 50 feet in 28 miles, can be explained as deposition in rising water. If the lake level was constant during delta deposition, the gradient of the delta surface should have been greater than it is now to make possible the transportation of well-sorted, medium-grained sand to the foreset slope. In fact, the slope of the delta surface has been reduced as much as 40 feet in 28 miles by crustal warping since deposition, and the stream gradient could have been as great as 3 feet per mile during deposition. Also, the great discharge of the early Assiniboine River gave it a large sediment-transporting capacity in spite of the low gradient.

In conclusion, the broad, simple form of the Assiniboine delta indicates that it was deposited in a lake having a rising or a stationary water level, but not a subsiding water level. Sections of the uppermost delta sediments show thick topset beds which suggest that the baselevel of the river was rising during delta deposition. The great discharge of the early Assiniboine River, owing to glacial sources and a gradient of as much as 3 feet per mile on the delta, probably

Figure 3-23. Exposure of sand in the Assiniboine delta 3 miles east of Carberry (SW 33-10-14 W. Prin.) showing channels in horizontally-bedded medium-grained sand. The upper 6 feet of the section is partly windblown sand and has been modified by soil-forming processes. The man is pointing to a thin clayey bed.

was adequate to transport medium-grained sand as far as the present foreset slope if the lake level was stationary. Hence, it is not possible to decide from the present data whether Lake Agassiz was rising or had a stationary level during delta deposition; the former seems more probable.

ALLUVIUM

General Discussion

Alluvium in the Tiger Hills region occurs on valley terraces and floodplains and as alluvial fans; on the map some colluvium is included. The short time available prevented complete subdivision of the alluvial units, which, therefore were classified as younger or older alluvium. In general, younger alluvium is deposited as a normal high-water or flood phenomena at the present time, whereas older alluvium was deposited in climatic and topographic situations that ranged from modern conditions to a nearly-glacial environment; some older alluvium grades into glacial outwash.

Younger Alluvium

Map symbol ya; color emerald green.

Younger alluvium forms flood plains in the Pembina, Souris, and Assiniboine valleys, and alluvial fans located south of the village of Cypress River and along the base of Pembina Mountain. Most younger alluvium is poorly-sorted silty sand with minor amounts of clay and contains channel fillings and lenses of poorly-sorted sand and gravel. Alluvial fans east of Pembina Mountain are mainly sandy silty clay.

In Pembina trench younger alluvium comprises several alluvial fans, deposited by tributary streams (upper Pembina River, Badger Creek, Long River, Crystal Creek, and minor gullies), that obstruct the trench and form Pelican Lake, Lake Lorne, Lake Louise, Rock Lake, Pembina Lake, and two marshes that were formerly lakes; between Pembina Lake and La Riviere a floodplain forms most of the valley floor. Several alluvial fans downstream from Pembina Lake are shown as older alluvium because they formed before the floodplain. Typical floodplain features, between Rock Lake and section 29-4-10 W. Prin., include well-developed natural levees and backswamps. These deposits filled a lake northwest of Pilot Mound and are filling one south of Swan Lake. The floodplain downstream from La Riviere is narrow and contains abundant oxbows and abandoned channels.

In the Souris and Assiniboine valleys, younger alluvium includes all slip-off slopes and terraces below the surface of the alluvial fill that was deposited during the Campbell phase of Lake Agassiz (see below). It was not feasible to classify these lower terraces into units; several of them may be parts of paired terrace systems.

Deposition of alluvium on the Cypress River fan occurs occasionally where the stream has not been artificially straightened, but most of the fan is no longer subject to alluviation. The fan comprises about 4 feet of poorly sorted sand, silt, and clay, overlying a soil-gyttja-peat zone formed on older alluvium consisting ofsilty sand and fine gravel (Fig. 4-2). The base of the fan is generally medium to fine pebble gravel composed of Odanah shale. Channel fillings of shaly sand and gravel cut through the fan and represent comparatively recent, but prehistoric courses of Cypress River.

The alluvial fans along the Manitoba Escarpment are mainly clay derived from soft Cretaceous shale that underlies the Escarpment. Silty sand occurs locally, but most of the alluvium within the Lake Agassiz basin (in the map-area) is clay that is distinguished from lake clay with difficulty only. The criteria for this distinction are: continuity with known alluvial fans near the base of the Escarpment, superposition on sand and gravel beach ridges, the presence of stream channels, and the general lack of ice-rafted stones that occur in the deep-water clays. One can readily understand why Upham (1896, p. 202) considered the upper unit of the Lake Agassiz deposits to be of fluvial origin.

In general, deposition of younger alluvium occurs on a wide scale at the present time. Two or more periods of moist climate separated by drier interval are indicated by: (1) the valley of Morris River north of Stephenfield, where the stream cut a broad shallow valley, filled it with alluvium and is now eroding the alluvium, (2) alluvial fans in Pembina trench that have been eroded by a stream now depositing a flood plain, and (3) a buried soil zone in the Cypress River alluvial fan, where alluviation was interrupted by an interval of non-deposition and seems to be less intense at present than it was in the geologically recent past. It is inferred that the younger alluvium records a moist climatic interval that was followed by a relatively dry interval which was succeeded by a moist climate that is becoming less moist.

Older Alluvium

Map symbol oa; color olive green.

Older alluvium was mapped on high-level terraces in the Pembina and Assiniboine valleys, and on the floor of Pembina trench west of Ninette. Minor alluvial bodies, many too small to map, occur in small valleys on Pembina Mountain, and on the bottoms of some dry channels (e.g. west of Thornhill and west of Treherne). Much of the older alluvium forms the surfaces of terrace remnants of former valley floors cut on older deposits, but there are also two significant valley fills, one in the Assiniboine valley and the other in the lower part of Pembina trench. The latter is older and is discussed first.

Alluvial fill in Pembina trench

Broad terraces above an altitude of 1,300 feet in the wide parts of Pembina trench west of Kaleida, north and northeast of Mowbray, and north of Windygates, are covered with shale gravel ranging from medium-sized pebbles to small cobbles described as outwash (valley trains) earlier in this chapter (p. 111-112). On the small scale map (Pl. 3) the outwash was not differentiated from a younger valley (alluvial) fill. This valley fill forms a prominent set of paired terraces whose altitude increases from about 1,150 feet near

Walhalla, North Dakota, to about 1,200 feet at the International Boundary, and about 1,230 feet north of Windygates (Pl. 5(b)). The fill extends upstream to La Riviere, where the present gradient of Pembina River changes from less than 1 foot per mile upstream to more than 5 feet per mile downstream. Between Mowbray and La Riviere the surface of the fill is contiguous with a cut terrace. The surface of the valley fill would extend the gentle gradient of the upper part of Pembina trench downstream from La Riviere to an altitude of 1,150 feet near Walhalla (Pl. 5(b)); from this it may be inferred that the Norcross or upper Tintah phase of Lake Agassiz formed the baselevel of Pembina River at the close of the interval of alluviation in Pembina trench.

The valley fill is a sandy shaly pebble gravel (Fig. 3-16, sample 50-9) about 120 feet thick north of Windygates, and it thickens downstream. The gravel is finer than the outwash gravel of the high terraces and comprises medium to small shale pebbles and sand composed of shale fragments and about 15 percent of quartz grains; pebbles other than shale were not observed. North of Windygates the basal part of the alluvial fill (SW 5-2-7 W. Prin.) is poorly sorted silty sand 1/ situated between altitudes of 1,110 and 1,140 feet, and may have been deposited in standing water.

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1. Mr. Kenneth Lambe, Engineer, Prairie Farm Rehabilitation Act, oral communication.

The valley fill is believed to have been derived from the Odanah shale forming the floor of Pembina trench above La Riviere, and was deposited downstream from La Riviere when a rise in the level of Lake Agassiz elevated the baselevel of Pembina River to about 1,150 feet. This valley fill antedates the valley fill in the Assiniboine valley (see below) and represents a rise in the level of early Lake Agassiz.

Alluvial fill in the Assiniboine valley

Paired terraces forming the surfaces of an alluvial fill extend upstream at least 45 miles from section 18-9-8 W. Prin. (Pl. 1), where Assiniboine River flowed into the Campbell phase of Lake Agassiz (1,050 feet altitude), to beyond Glenboro Ferry (Pl. 5(a)). In this distance the surface of the fill rises from an altitude of 1,050 feet at the Campbell strandline to about 1,080 feet north of Glenboro. The valley fill comprises fossiliferous sand, silt, and clay that gradually changes from a fluvial deposit (Fig. 3-24) north of Glenboro to an estuarine-like facies, north of Treherne.

Gullies in the fill north of Treherne and Rathwell expose about 10 feet of laminated clay overlying about 10 feet of laminated silt and sand which are inderlain by 40 feet or more of medium-grained sand. The laminae in the silt and clay are uniform and range from 2 to 4 inches in thickness. Fossils, including freshwater and terrestrial snails, clam shells, and rare tamarack cones, are abundant near the top of the sand and at the base of the silt beds. Higher in the silt beds the fauna comprises clams and a few snails; the clay contains a few clams only. The clam shells in the clay are a large delicate species and could not be collected (Chapter 4).

Near the bridge north of Holland, about 12 miles upstream from the sequence just described, about 10 feet of fossiliferous laminated silt and sand overlie about 18 feet of coarse pebbly sand containing a few clam shells. The sand is underlain by 6 feet of brown clayey silt, below which is silty clay that may be more than 40 feet thick. The lower silt and clay contain no fossils and may be basal beds of the Assiniboine delta.

In SE 25-8-14 W. Prin., about 24 miles upstream from the Campbell strandline near Glenboro Ferry (Pl. 5(a)), the valley fill (Fig. 3-24) resembles the alluvium of a flood-plain. The section is as follows:

Depth in feet	Lithology
0-2	Clayey sandy silt rich in snail shells; probably a fluvial fauna.
2-10	Sandy and silty clay in beds 0.5 to 2.0 inches thick with lenses of well-sorted medium to coarse sand; several clay laminae about 0.5 inch thick show fossil mud cracks; contains a gastropod fauna (lacustrine) similar to that in the silt beds downstream. This unit thins (eroded) toward the center of the valley.
10-12	Medium-grained sand to fine pebble gravel with variable sorting, containing a few small clam shells.
12-20	Clayey silt containing no fossils; lower beds of the Assiniboine delta?

The upper fossiliferous silt and clay increase in thickness from 10 feet north of Glenboro to 20 feet 30 miles

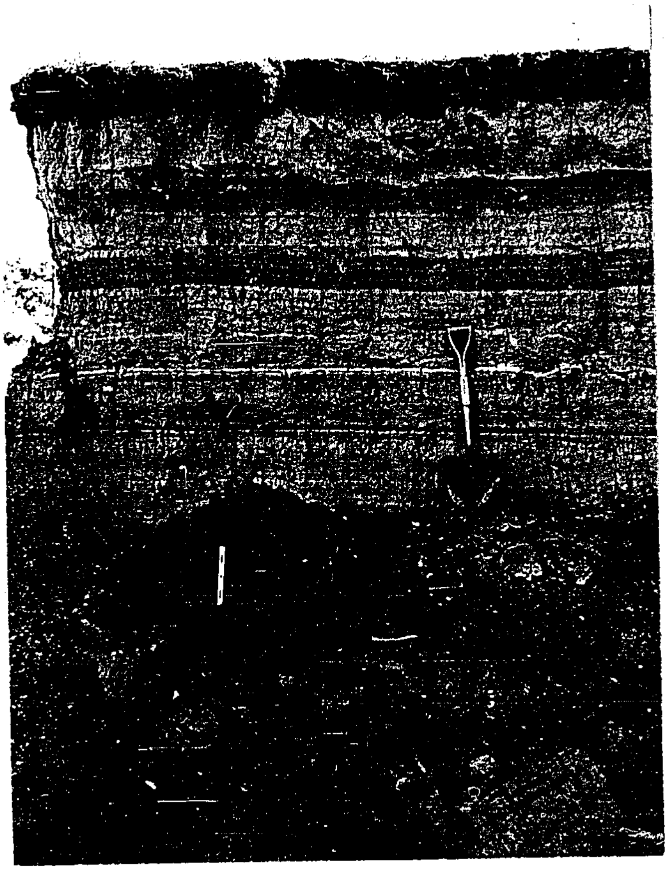

Figure 3-24. Vertical section in SE 25-8-14 W. Prin. (near the Glenboro Ferry) showing fluvial facies of the valley fill in the Assiniboine valley. The 1-foot scale rests against medium to coarse sand overlain by clayey silt and sand in beds 0.5 to 2.0 inches thick.

downstream; in the same distance the underlying sand increases from about 2 feet to probably more than 40 feet in thickness.

It is inferred that Assiniboine River eroded its valley to an altitude of 1,055 feet or lower near Glenboro Ferry, and to 990 feet or lower at Rossendale Ferry, during subsidence of Lake Agassiz. A molluscan fauna entered the lake basin during a low-water phase or while the lake was drained. The lake level subsequently rose to an altitude of 1,050 feet, raising the baselevel of Assiniboine River so that it deposited alluvium in the lower part of its valley. Alluviation did not keep pace with the rising water level, hence, the valley was inundated by the lake and the sediments and fauna have lacustrine characteristics. About 35 miles upstream from the Campbell (1,050-foot) strandline the valley floor was above lake level and the sediments and fauna are characteristic of fluvial environment.

Higher terraces in the Assiniboine valley and its tributaries are mapped as older alluvium, but do not constitute valley fills. These terraces are discussed in Chapter 5 (p.222-226).

EOLIAN SEDIMENTS

Windblown sand

Map symbol es; color canary yellow.

Windblown sands of the Tiger Hills region have a median grain size ranging from 0.25 to 0.5 mm., and are well-sorted but not more so than some of the undisturbed delta sands (Fig. 3-16). The topographic expression of windblown sand varies from gentle undulations to ridges more than 50 feet high and several miles long. Many small areas of eolian sand with less than 3 feet of relief were not mapped. Most of the deposits have topography comprising low dunes and blowouts with from 5 to 15 feet relief (Fig. 1-15). However, extensive areas are occupied by dunes 20 to 30 feet high (Fig. 1-14).

Windblown sand occupies about 400 square miles of the Tiger Hills region. Extensive tracts occur on the Upper Assiniboine delta in townships 7 and 8, ranges 11 to 16, and smaller areas are in townships 6 to 8, ranges 5 to 8 on the lower delta. Dunes occur on paired terraces in the Assiniboine valley, in sections 31 to 33-7-14 W. Prin., and in sections 4, 14, 26 and 35-8-14 W. Prin. The terraces have an altitude of about 1,150 feet and probably represent a lower Norcross or upper Tintah phase of Lake Agassiz. Extensive dunes have not been observed on lower terraces.

Most of the sand is anchored by vegetation except for small areas (blowouts) and several square miles of active dunes, known as the Bald Headed Hills, in sections 21, 22, 27, 28 and 33-8-14 W. Prin. (Pl. 3, outlined by dotted lines). In general, blowouts are only widespread a few acres in extent, although residents report widespread drifting of sand in drought years.

Dune ridges, in township 8, ranges 12 to 15, comprise series of dunes from 30 to 60 feet high trending southeast and east-southeast, and are as long as 9 miles. The northeast slopes, mainly bound by vegetation, are as steep as 45°, whereas the southwest sides slope at about 15°, and, though generally anchored by vegetation, bear numerous blowouts. The ridges present a confused pattern of dune crests rather than a smooth whale-back surface. They may be seif dunes (Bagnold, 1942, p. 222-235), in which case they should be aligned in the effective wind direction. Boughner and Thomas (1948, p. 60-61) show that at selected stations (Winnipeg, Rivers, and Melita) in southern Manitoba the winds with high frequencies and high average velocities are west and northwest. These evidently are the winds effective in dune ridge construction. Hence, the wind conditions during the formation of the dune ridges were essentially the same as at present.

Belts of windblown sand mark former strandlines at Jobin and west of Jobin in township 8, range 8; similar belts are in the north half of township 8, ranges 5, 9, and 10. Evidently the removal of the fine sand fraction by wave action along a strandline results in sand succeptible to wind action.

Buried soils appear in the sides and form the floors or parts of the floors of many blowouts (Fig. 3-25) and are exposed in road cuts (Fig. 3-26). The boles of trees, 6 to 10 inches in diameter, growing on the surface of the sand overlying the buried soil in NW 27-6-7 W. Prin. are not covered by drifted sand, which inidicates that there probably has been little drifting there for at least 40 years. The present soil has little humus whereas the buried humus zone is

Figure 3-25. Blowout about 6 feet deep on the Assiniboine delta in SW 31-10-12 W. Prin., 2 miles south of Sidney. Much of the blowout is floored with a resistant humified layer of sand representing a former soil.

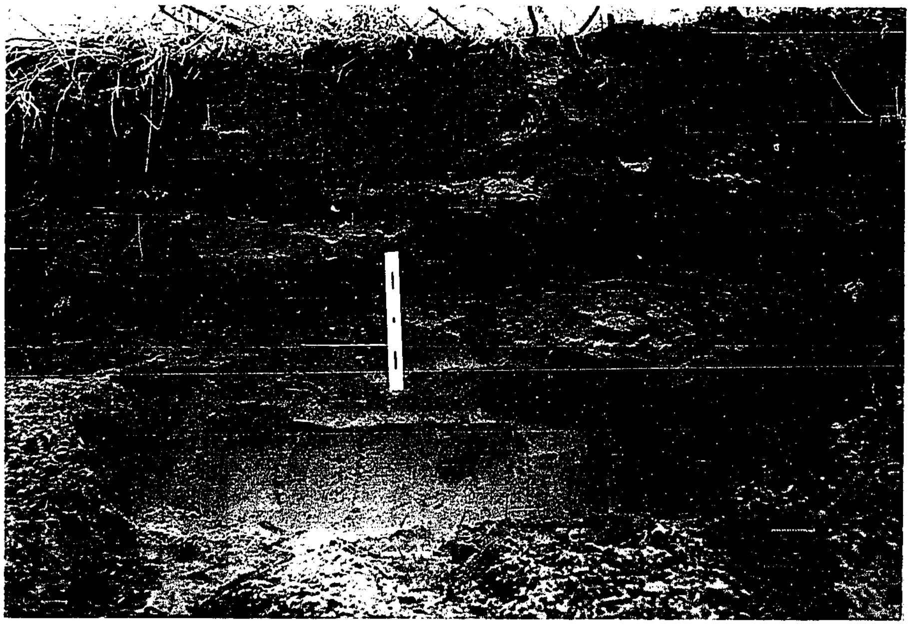

Figure 3-26. Vertical cut in sand dune in NW 27-6-7 W. Prin., near Roseisle, showing humified zone about 4 inches thick overlain by about 18 inches of sand. Oak trees 6 inches in diameter grow on the upper sand which is stabilized by sod, but shows no appreciable humification.

4 to 6 inches thick, which suggests that the latter represents a fairly long period of soil formation.

From the foregoing data it is inferred that an interval of eolian activity followed deposition of the Assiniboine delta and continued through the upper Tintah phase of Lake Agassiz. Inception of a humid climate, before Assiniboine River eroded the valley fill deposited during the second Campbell phase of Lake Agassiz, ended the interval of eolian sedimentation. A long interval of dune stability followed, during which a soil profile, more fully developed than the present one, was formed. Subsequently, there have been minor periods of general and localized eolian activity.

Loess

Deposits that fit the usual concept of loess (Flint, 1947, p. 175-177) have not been observed in the Tiger Hills region. Problematical silt in the south part of the Tiger Hills region has some of the properties of loess (see proglacial sediments, p. 112 - 115).

In many places from 0.5 to 1.5 feet of windblown very fine sand and silt overlie other sediments (till, etc.); locally this eolian deposit is underlain by minor concentrations of pebbles which, however, do not include ventifacts. These windblown deposits are generally leeward of possible sources of eolian sediment (e.g. flood plains and intermittent lakes).

Ventifacts

With a few rare exceptions on the Assiniboine delta, ventifacts have not been observed in the Tiger Hills region. Those observed are composed of soft dolomitic rock. It is inferred that even the major periods of eolian activity in the Tiger Hills region were relatively brief.

PERIGLACIAL FEATURES

Features indicating modification of the deposits in the Tiger Hills region while they were perennially frozen are inconspicuous. Some of the modifying processes generally considered as periglacial are active on a small scale under present climatic conditions 1/. Fossil ice wedges, polygons and involutions have been observed.

Fossil Ice Wedges

Fossil ice wedges (Fig. 3-27) in which shattered bedrock is upturned adjacent to the former ice zone (Smith, 1949, p. 1503) and the space once occupied by the ice wedge is filled with debris (soil and rock fragments) fallen from above, are common where the drift is less than a foot thick on the Purves plain. These wedges probably form polygonal patterns. Some wedges in the Odanah shale are as wide as 2 feet near the surface and extend to a depth of 8 feet; these probably represent a climate much colder than the present one. No evidence that ice wedges of this size are still forming in bedrock was observed. Fossil ice wedges are rare where the

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1. R.S. MacNeish (oral communication) reported that Mr. Stuart Criddle, a farmer north of Treesbank, watched the formation of several ice wedges 2 to 3 feet long in the earth wall of a root cellar during a recent winter.

Figure 3-27. Vertical section of Odanah shale in a pit 1 mile northwest of Manitou (SW 31-3-8 W. Prin.) showing a medium-sized fossil ice wedge; the scale is one foot long.

Figure 3-28(a). Till overlying sand, with a "fossil" ice wedge projecting through the till into the sand. Pavement boulders not in the photograph are embedded in the sand with their faceted upper surfaces in the plane of the till-sand contact. Located 4.5 miles northeast of Neelin (in NW 2-4-14 W. Prin.).

Figure 3-28(b). Shallow cut showing polygons in silt; the digging tool is 20 inches long. The dark "A" horizon of the soil projects downward in the form of wedges about 2 feet long that form a polygonal pattern.

drift is more than 2 feet thick, probably owing to the insulating and water-retaining ability of the soil. It seems unlikely that they are a result of plant root action. Fossil ice wedges were observed also in drift (Fig. 3-28(a)).

Polygons formed by ice wedges or by the desiccation of the soil (J.H. Ellis, oral communication) are visible where the topsoil was stripped from silt during road construction in the Lake Agassiz basin. Dark (humified) soil bands from 2 to 6 inches wide form polygons 1 to 8 feet in diameter (Fig. 3-28(b)). The dark bands have no surface expression (e.g. ridges or depressions) in the sod; in vertical cross-section they are wedges that pinch out from 1.0 to 2.5 feet below the surface. These features are most common in silty deposits and probably are still being formed either as ground ice wedges (Smith, 1949, p. 1498) as desiccation cracks or as solution structures (Yehle, 1954). It seems doubtful that they are evidence of former perennially frozen ground.

Involutions

Involutions, in which humified soil is enclosed in well-sorted fine to medium-grained sand have been reported in the Lake Agassiz basin by Horberg (1951, p. 9-14, Pl. 4) and were observed by the writer (Fig. 3-29) on the lower Assiniboine delta. Horberg (1951, p. 11) attributes them to

> "plastic deformation produced by differential freezing and thawing and growth and melting of masses of ground ice above perennially frozen ground."

Involutions are too scarce in the Tiger Hills region to form the subject of a special study; they are evidence of former

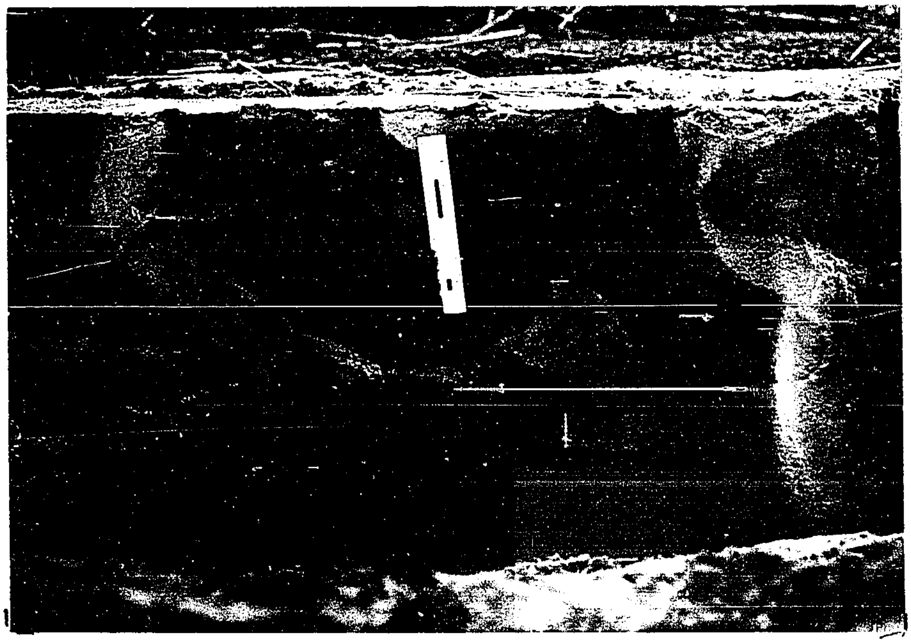

Figure 3-29. Vertical section in a ditch (NE 33-9-7 W. Prin.) showing soil involutions in sand on the lower Assiniboine delta. Organic matter and clayey silty sand are enclosed in well-sorted medium to coarse sand. From 6 inches to 1 foot of surface soil has been removed; the scale is about 7.25 inches long. These involutions may be perennially-frozen ground phenomena.

perennially frozen ground. It is inferred, from their occurrence at an altitude below fossiliferous sands of the Campbell phase of Lake Agassiz, that the climate in the Lake Agassiz basin was very cold during or after final subsidence of the lake from the Campbell strandline.

Thaw Depressions (Lakes)

Fossil ice wedges and soil involutions in the Tiger Hills region represent an interval during which the ground was perennially frozen; some of the closed depressions in southwest Manitoba may be the result of ground ice melting during this interval. The mode of origin of thaw lakes in areas of frozen ground is described by Hopkins (1949, p. 124-127) as a process of enlargment by shore erosion (by thawing as well as wave action) of depressions formed by the melting of a large number of ice wedges. This may be the origin of many of the sub-circular depressions on the Prairies. Most of the irregular closed depressions in the Pelican Lake Area (Pl. 4) are due to the intersection of the low ridges of drumlinized ground moraine and washboard moraines.

Several depressions, as much as 300 feet in diameter and as deep as 5 feet, contain one large boulder in the center. It is suggested that the boulder initiated formation of a thaw lake because its heat absorption and conduction is high compared to that of ice.

Conclusion

Fossil ice wedges and soil involutions indicate that there was at least one interval of perennially frozen ground in the Tiger Hills region. The small size of these features suggests that the interval (s) was (were) brief, and the occurrence of involutions on the lower Assiniboine delta indicates that such an interval occurred during or after the final subsidence of Lake Agassiz II from the Campbell strandline. Many of the depressions in ground moraine on the Prairies may have originated as thaw lakes in perennially frozen ground.

SEDIMENTATION STUDIES

INTRODUCTION

Several problems not solved by mapping were approached through sedimentation studies that included pebble counts (provenance), roundness of pebbles, and till-fabric analyses. Mechanical and mineralogical analyses were used in routine description.

An attempt to determine the directions of ice movement by provenance gave negative results. Till-fabric analyses showed the direction of glacier movement and yielded data on the constitution of a till sheet and on the structure of washboard moraines. Roundness studies proved to be mainly of descriptive value and were discussed earlier (p. 57-58).

PROVENANCE

Scope of the problem

Drumlinoids, till-fabric analyses, and striations on boulder pavements indicate that the last ice sheet in the Tiger Hills region flowed southeastward. However, these represent the last ice movement only, and their evidence contrasts with the southwestward flow generally attributed to the last ice sheet (McConnell, 1882-3, 1884; Alden, 1931; Johnston and Wickenden, 1931, p. 40). J.B. Tyrrell (1890, p. 401) inferred from drumlins and striated boulder pavements that the glacier moved southeastward over much of the Prairies; other workers inferred southwestward movement from the southeast trend of end moraines (including the Altamont (Max) moraine on the Missouri Coteau) and from the drift stones, the lithology of which resembles an assemblage from the Canadian (Precambrian) shield. However, the significance of the Max moraine is uncertain (Townsend and Jenke, 1951) and the Precambrian shield and a belt of Paleozoic rocks border most of the Prairies on the north as well as on the east. A rapid study of about 25,000 vertical airphotos of the Prairies selected on a sampling basis revealed much evidence of southeastward flow (drumlinoids, grooves, washboard moraines, eskers) south of latitude 52°, and cast doubt on several of the moraines mapped by Johnston and Wickenden.

For a working hypothesis it was assumed that the lithologic composition of an assemblage of stones from north of the Prairies would differ from that of an assemblage from the east. It proved impossible to determine the difference between northern and eastern assemblages by ordinary field methods of pebble counting; hence, the results of this work were negative and it was abandoned after about 30 samples totalling more than 7,000 pebbles had been studied. The failure prompted an analysis of the pebble-counting method to determine its accuracy and limitations; the results of this analysis are presented below.

Early studies

G.M. Dawson (1875, p. 221-243) made nine pebble counts along the International Boundary between the Manitoba Escarpment and the Rocky Mountains, a distance of 700 miles. Apparently, each pebble count included from 85 to 300 pebbles; boulders and very small pebbles were omitted. The pebbles were subdivided into seven to 12 categories, which, apparently, generally excluded the local bedrock. Dawson's analyses revealed two types of drift, one of which he termed " northeastern" after the presumed Precambrian source of most of its pebbles; the other he termed "quartzite drift" after its relatively high proportion of quartzite stones. The quartzite drift is mainly west of the Missouri Coteau (longitude 105°).

Stones of the northeastern drift have a wide size range and generally have glacial facets and striations. The rock types in the northeastern drift are: limestone 48-63 percent, granites and gneisses 18-38 percent, dark aphanitic rocks 4-8 percent, and quartzites 0-7 percent.

Quartzite pebbles of the quartzite drift are well-rounded and have no glacial facets or striations. The mean size of stones in this drift is smaller than that of the stones in the northeastern drift, and the size distribution is more uniform. The rock types in the quartzite drift are: limestone 33 percent at Wood Mountain decreasing to 6 percent near the Rocky Mountains; granite and gneissic rocks 22-25 percent; dark aphanitic rocks 0-7 percent, least near the mountains; and quartzite 24-55 percent, increasing toward the mountains. From later work (Fraser, McLearn, Russell, Warren and Wickenden, 1935) it is apparent that the quartzite drift occurs near and on Cenozoic quartzite gravels (Swift Current formation, Cypress Hills formation, Wood Mountain formation); hence, its distribution probably depends on local bedrock and has little significance for the direction of ice movement.

G.M. Dawson is apparently the only person to have published data concerning the provenance of the drift on the southern Prairies.

Pebble Counts

Introduction

Pebble-count studies passed through three phases: first, the Tiger Hills region was sampled on a grid basis and isopleths of different rock types were drawn in the expectation that patterns similar to the fan-shape of a boulder train would appear; preliminary work failed to reveal such a pattern. Secondly, pebbles were collected at intervals of 40 miles along a traverse west along the International Boundary from Turtle Mountain to Wood Mountain (longitude 106°), north to Humbolt (latitude 52°), then east and southeast approximately along the crest of the Manitoba Escarpment to the Tiger Hills region. These samples were expected to yield data on lithologic assemblies from different parts of the Canadian Shield, and to show the effect of dispersion as the distance from the source area increased; the results of this study were negative. Thirdly, the pebble-count method was carefully evaluated: the importance of pebble size, the number of pebbles in a sample, and the methods of applying the data were examined. It was concluded that the method requires refinement before having more than descriptive application on the Prairies.

Method

Each sample comprised 200 or more pebbles from 8 to 64 mm. in size (long axes) collected from a rectangular area of 6 or 8 square feet on a fresh cut, generally in till; it was usually necessary to remove about 2 inches of material to obtain enough pebbles. Decomposed gneisses and granitic stones could not always be collected but were noted; in some localities where local bedrock formed most of the drift it was omitted from the sample. Ordinarily the pebbles were not sorted into grade size (see below) but were simply broken to obtain a fresh surface and one large piece retained for examination. Limestone was distinguished from dolomite (dolostone) by the application of dilute hydrochloric acid. The pebbles were classified as follows: quartz, quartzite, and chert; shale (often omitted); limestone; dolomite; granitoid rocks, including granite, syenite, gneiss, and other sialic phanerites; mafic aphanites (mostly altered Pre-cambrian volcanics); and "others", including all rocks (mainly sandstones and coarse-grained basic igneous rocks) that did not fit into the previous categories. The percentage composition was generally calculated with the shale fraction (local bedrock) omitted.

Importance of pebble size

The relative scarcity (less than 1 percent by weight) of stones in the till on the Prairies made necessary the use of all pebbles available, with the result that the samples include a wide range in pebble sizes. That lithologic characteristics (jointing, parting, fractures, concretions etc.) have important effects on the size of glacial stones was established by Udden (1912, p. 54-55), and is to be expected when the crushing strengths of rocks are considered (Birch, 1942, p. 116). If Birch's average crushing strengths are compared with Udden's data a rough correlation between pebble size and crushing strength is apparent: diabase and gabbro, with an average crushing strength of 1,800 kg/cm^2, are most common in the 27-inch size group (boulders); granites, with an average crushing strength of 1,480 kg/cm^2, are most common in the 9-inch size group (cobbles); limestones and dolomites, with average crushing strengths of 960 kg/cm^2, are most abundant in the 1 to 1/3 inch size group (medium-sized pebbles). Hence, if the size distribution of stones by number (rather than by weight) are plotted as a histogram there would be several modes, each one corresponding to a different lithology 1/. In Udden's smallest size groups (1 inch and 1/3 inch)

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1. If this principle is applied to the smaller grade sizes in till, the more abundant mineral constituents such as quartz, feldspar and calcite should each have their own modes that should appear in mechanical analyses of the sand, silt, and clay fraction.

the lithologic proportions are fairly constant. Holmes (1952, p. 1,000) restricted his "index grade size" to 0.25 and to 0.5 inch pebbles. K.S. Knox 1/ found unimportant variations when he subdivided a grade size similar to Holmes' into three units. However, the grade size range of pebbles collected on the Prairies (8 to 64 mm) is greater than the sizes studied by Udden, Holmes or Knox; therefore, to determine the effect of pebble size on the lithologic composition of a given size group, six samples were each sorted into three grade sizes (8 to 16 mm, 16 to 32 mm, and 32-64 mm) and the results compared with the results for the whole sample; the results of two samples follow:

Table 3-3. Variation in rock types of medium, large, and very large pebbles in till.

Sample 50-24: Total 263 pebbles; the individual size groups contain from 33 to 124 pebbles.

Rock types	Range in percent in three size groups	Whole sample (percent)
1. Quartzite	4-13	8
2. Shale	0-5	4
3. Limestone	8-30	23
4. Dolomite	31-39	33
5. Granitoids	20-39	25
6. Mafic aphanites	0-2	2
7. Others	2-8	5

Sample 50-31: Total 285 pebbles; the individual size groups contain from 42 to 107 pebbles.

Rock types	Range in percent in three size groups.	Whole sample (percent)
1. Quartzite	3-5	4
2. Shale	0-5	1

1. Unpublished M.Sc. thesis, "The differentiation of the glacial tills along the north shore of Lake Erie", 1952. (Personal communication from A. Dreimanis, Univeristy of Western Ontario, April 24, 1952.).

	Rock types	Range in percent in three size groups	Whole sample (percent)
3.	Limestone	3-15	9
4.	Dolomite	40-58	48
5.	Granitoids	18-31	24
6.	Mafic aphanites	0-11	7
7.	Others	4-14	7

Granitoids are common in the 32 to 64 mm range whereas mafic aphanites are absent; the reverse is true in the 8 to 16 mm range. Number of pebbles varies inversely with size; hence, there is an unbalance in favour of the rock types that form small pebbles. Calculation of percentages by weight instead of by number of stones would offset this skewness, but is impractical as a field method. With this in mind and with the knowledge that each lithology has a statistically preferred pebble size, it is possible to compare pebbles of the whole 8 to 64 mm size range if all size grades within this range are fully represented in each sample.

Size of the sample

One test of the reliability of data is whether or not it reproduces itself. This test can be used to determine the minimum practical size of samples for pebble counts. A sample, collected in a gravel pit, totalling 457 pebbles consisted of four groups of 100 or more pebbles, taken at intervals of a few feet. Each group of 100 was analysed separately and the results compounded to form samples of different sizes. Departures of any lithologic category in any of the 100-pebble samples did not exceed 28 percent of that category in the total sample. All departures in the 200-pebble samples were less than 16 percent. Pebbles in gravel are sorted both as to specific gravity (governed by lithology) and size, and may show more variation in lithology than pebbles from till, which are unsorted. After this evaluation of sample size and supporting opinions (unpublished) of other workers on the Great Plains, 30 analyses were made without obtaining useful results. Further examination of the method seemed warranted.

Variance in lithologic representation

A fresh road cut in sandy till on Turtle Mountain afforded an opportunity for a rigorous examination of the pebble-count method. A rectangular area of 15 square feet was subdivided into units of 1 square foot each. From 21 to 33 pebbles were collected from each unit, the gross sample amounting to 383 pebbles. The pebbles from each unit were sorted into the seven rock types already listed, and the results compounded to give samples of approximately 25, 50, 100, 200, 300, and 400 (383) pebbles within the 8 to 64 mm size range. The largest sample was assumed to be as accurate as field methods permit, and formed the standard from which the maximum departures of each rock type in each of the smaller samples was calculated (Table 3-4).

Table 3-4. Maximum departures (percent) of smaller samples from data derived from gross sample (383 pebbles).

Rock types	Composition of gross sample (%)	Maximum departures from gross sample				
		25 pebbles	50 pebbles	100 pebbles	200 pebbles	300 pebbles
1. Qtz.	3.9	525	200	200	75	25
2. Shale	17.2	88	30	25	6	6
3. Ls.	21.2	90	50	45	15	0
4. Dol.	31.3	52	40	20	6	6

Rock types	Composition of gross sample (%)	Maximum departures from gross sample 25 pebbles	50 pebbles	100 pebbles	200 pebbles	300 pebbles
5. Gran.	9.8	130	60	20	20	0
6. M. Aph.	3.4	360	300	200	35	35
7. Others	9.7	100	80	60	20	10

The expectable meaningless variation in any category in any size of sample may be obtained by plotting the numerical size of each category in Table 3-4 against its maximum departures from the "perfect" sample (400 pebbles), and smoothing the resulting curves. Significant variations of lithology in a suite of samples must be much greater than the expectable meaningless variations, especially when even a sample containing 400 pebbles is imperfect. Meaningless variations for a series of 200-pebble samples are given in Table 3-5. As anticipated, the categories with the smallest representation show the greatest variations: in Table 3-5 it is shown that, in a set of 200-pebble samples, variations in quartzite of less than 100 percent are insignificant, whereas variations of as little as 25 percent in the dolomite category may be important.

Table 3-5. Expectable meaningless variations in a series of samples comprising 200 pebbles each.

Rock types	Meaningless variation
1. Quartzite	80 percent
2. Shale	20
3. Limestone	15
4. Dolomite	10
5. Granitoids	20
6. Mafic aphanites	120
7. Others	30

Application of raw data

The common practice is to compute the percentage forms of the total sample, a procedure that gives distorted results if local bedrock is abundant and varies greatly from sample to sample, as commonly happens. In one set of calculations the effect of local bedrock was eliminated by giving the granitoid category an arbitrary index value of 100, and calculating all other rock types as proportions of this datum. The granitoid category was chosen because granitoid stones appear to be widely dispersed on the Prairies and are common enough to be statistically important. The problem of variance is more complicated when such a system is used. As with the percentage calculations, the results were negative.

In a third attempt to interpret the data the ratios of limestone to dolomite (always less than 1.0) were computed. More is known about the source areas of these pebbles than is known about the sources of Precambrian stones, and it was hoped that limestone and dolomite would be present in the same proportions as the areas of their sources. Unfortunately, maps and other data proved inadequate for this approach.

In every attempt at interpretation the data were plotted on maps and lines of equal values were drawn; graphs representing traverses parallel and transverse to the supposed directions of ice movement were plotted. Variations are generally insignificant, and it is concluded that larger samples subdivided into more rock type categories are required to make the pebble-count method work on the Prairies.

Eskola (1933, reviewed in Flint, 1947, p. 115-116) showed that in a sample comprising 1,000 stones from glacial drift south of Finland the lithologic proportions corresponded to the areas of the rock types in Finland, with deviations as follows:

Rock types	Difference in percent of each category between proportion of rock type in sample and proportion of source area in Finland.
Granite	12.5 percent more in sample than in Finland
Migmatite	11.5 " less " " " " "
Schists	44 " " " " " " "
Quartzite	44 " " " " " " "
Sandstone	44 " " " " " " "
Calcareous rocks	no difference
Basic igneous rocks	5 percent more in sample than in Finland

Quartzite and sandstone together represent less than 5 percent of the area of Finland. As expected, rocks of the three categories with the greatest deviations are all weak types.

Restated, Eskola's principle is that the proportions of various rock types in a stone sample from glacial drift vary directly with the proportions of the rock types in the area over which the glacier passed. The writer attempted to calculate the proportion of rock types in the source areas from drift pebbles in the Tiger Hills region. Pebbles southwest of the Darlingford moraine represent ice that flowed southeastward, and pebbles east of the moraine may represent ice that flowed southward. The results of the calculations were inconclusive, but gave the general impression that a northern source was more probable than a northeastern source.

Conclusions

Because of repeated glaciations and the remotness of source areas, the pebble types in the glacial drift on the Prairies are too widely dispersed to yield data on the direction of ice movement by ordinary field pebble-counting methods. Probably the picture is complicated by the operation of several centers of glacial outflow during the Pleistocene epoch. The principal differences in the rock types in the drift are due to differences in local bedrock. Heavy mineral analyses and pebble counts based on samples of 1,000 or more pebbles may yield significant results.

Erratics

Erratics in the Tiger Hills region that are believed distinctive were collected and submitted for identification to officers of the Geological Survey of Canada who have worked in Precambrian areas of Manitoba and Saskatchewan. The method is necessarily haphazard, fortuitous and subject to all the vagaries of stratigraphic correlation based on physical properties alone. As most "distinctive" erratics prove to be rock types common throughout the Precambrian shield, the results of this project have been disappointing.

To date (March, 1954) one rock type, a generally pebbly whitish quartzite with local brown staining, has been identified with confidence by D.A.W. Blake, M.J. Frarey, and others, as from the Athabasca series. Extensive areas of this late Precambrian or Cambrian formation are known about 550 miles northwest of the Tiger Hills region; no closer sources are known. These stones are not common in the Tiger Hills region but several specimens have been collected. Although Dawson (1875, p. 225) found in the drift a whitish sandstone that resembles rocks in the Rocky Mountains near the

International Boundary, his description is inadequate for comparison with the quartzite erratics in the Tiger Hills region. Quartzite stones that have been in transport from the Cordillera across the Prairies throughout Cenozoic time are fouhd in glacial sediments; however, most of these quartzites are fine-grained rather than pebbly, and the stones from them are well rounded and commonly show crescentric percussion marks resulting from stream action, even after being incorporated into till. The quartzite stones of the Tiger Hills regions are not well rounded and are shaped like glaciated stones. Hence, it is inferred that they were glacially transported southeastward from northern Saskatchewan.

Evidence of southeastward glacier movement in the Peter Pond Lake area in northern Saskatchewan was reported by Kupsch (1954, p. 33-34). The provenance of glacial gravels (from an area underlain by Athabasca sandstone rather than by Precambrian rocks) indicates a north to northwesterly source of ice. The south to southeastward glacier movement is believed to have preceded a later movement from the northeast. Peter Pond Lake is about 540 miles northwest of Brandon.

TILL-FABRIC ANALYSES

Introduction

A comprehensive study of till-fabric analysis was published by Holmes (1941). He ascribed the first critical observations on till-stone orientation to Hugh Miller (1884), a Scot who noticed that the stones in a boulder-pavement near Edinburgh generally were aligned in the direction of ice movement with their narrow ends pointing toward the former source of the ice. The writer found an earlier reference to till-stone orientation by H.Y. Hind (1859, pp. 119-122), a former professor of Chemistry and Geology at what is now the University of Toronto. At the time of his observations, the glacial theory was still debated in Canada, and Hind used the orientation of stones in till (being impressed by the 60° dip of tabular blocks rather than their azimuthal position) as an argument against the hypothesis of deposition by dropping from melting icebergs and in favour of deposition from moving glacier ice.

Apart from the finding of Hind's work the writer has nothing to add to Holmes' "Historical Statement" (1941, pp. 1301-1303). As he stated the early work was selective and qualitative, and till-fabric studies had their useful beginning with Richter (1932) who published statistical data on the directions of the optic axes of quartz grains in till, and on the azimuths of the horizontal projections of the long axes of pebbles in till. His data were presented as histograms and rose diagrams and depended on personal judgment for interpretation. Later (1936) he extended his studies to include englacial stones in Norwegian glaciers and was able to verify his earlier work.

Holmes made an intensive study under laboratory conditions, of the shapes and orientations of pebbles in till. The directions of ice movement were known from other evidence, and Holmes was able to show that pebbles of certain shapes have statistically preferred orientations in the direction of ice movement or transverse to it, and that certain shapes also have a tendency to point up or downstream, depending upon their vertical position. He plotted three-dimensional data on equal-area stereoscopic nets in the usual manner of petrofabric studies, and presented two-dimensional data on rose diagrams. Statistical criteria such as median measures, standard deviations and probable errors (Krumbein, 1939) were not applied to his data and Scott Simpson (1949) has questioned the validity of Holmes' conclusions for the small shape-groups.

Holmes' technique requires time-consuming use of a wire frame to mark the orientation of pebbles in till so that they can be set up in exactly the same position in the laboratory. His method is impractical for field application; a more convenient technique was applied by Hyyppa (1948) when prospecting for copper by tracing erratics in Finland: he measured the only azimuths of the long axes of pebbles projected on a horizontal plane. The till stones were exposed by carefully excavating horizontal surface. It was found earlier that the azimuth of the face had a decided influence on the results when pebbles projecting from a vertical surface were studied. 1/ The method used by the writer follows that of Hyyppa rather than that of Holmes.

The writer's original purpose in making till-fabric analyses was to strengthen the evidence of the direction of

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1. Heikki Ignatius; Oral communication.

ice movement from striated boulder pavements, and to extend these data away from the boulder-pavement areas. Subsequently, the recognition of washboard moraines, drumlinoids and eskers made the tedious and subjective fabric studies generally unnecessary.

Till-fabric analyses also were used to ascertain the nature of the till in washboard moraines, to determine if they were deposited by lodgment or by some other process. It was anticipated that something might be learned about the process of till deposition through the following circumstances: there is strong evidence of southeast ice movement in the Tiger Hills region and there is also evidence of a southwest movement in the eastern part of the area. In the south-central section a southward movement resulted from splitting of the ice margin into sublobes during retreat. In the Cartwright area this sequence is suggested: a general southeast movement of ice was followed by a gradual change to a southward flow and then a gradual change back to southeast movement. If till is carried as drift in the basal part of the ice, and is deposited all at once when this ice ceases to move, then the pebble orientations should reflect one direction of movement throughout the vertical section of the till sheet; if till is derived from a relatively thin layer of basal drift deposited by lodgment on the underlying surface (Chamberlin, 1894, p. 525) the till sheet should reflect the movements outlined above by systematic changes of preferred orientation throughout the vertical section. If till is deposited only at or near the ice margin there would be a period of non-deposition separating two periods of deposition by southeast-moving ice, and one might expect the till sheet to have a uniform till fabric with a hiatus in the middle. The two sections examined seemed to support the last two hypotheses; they are discussed later in this chapter.

The writer made fabric analyses of widely scattered glacial features on the Prairies, of englacial pebbles and in freshly deposited drift at Victoria, Athabasca and Dome Glaciers in Alberta. The results verified Richter's work and provided a background of experience with the statistical measures. Although a quantity (300 to date) of oriented pebbles ~~were~~ was collected from glacier ice for shape studies, the number is as yet too small for sound statistical analysis (Figs. 3-30, 3-31).

Method

In developing a method of fabric analysis suited to the pebble-lean tills of the Tiger Hills region the writer tried to retain the better qualities of Hyyppa's technique, while striving for greater objectivity in interpretation. The best methods combine three-dimensional analysis with studies of shape and roundness. Time prevented such detail, especially because medium and small pebbles are not suited to the wire-frame technique used by Holmes. Encouraged by the results of Richter and Hyyppa, the writer used the two-dimensional approach. Early in the work the stones were studied on vertical, sloping and horizontal surfaces of cuts where

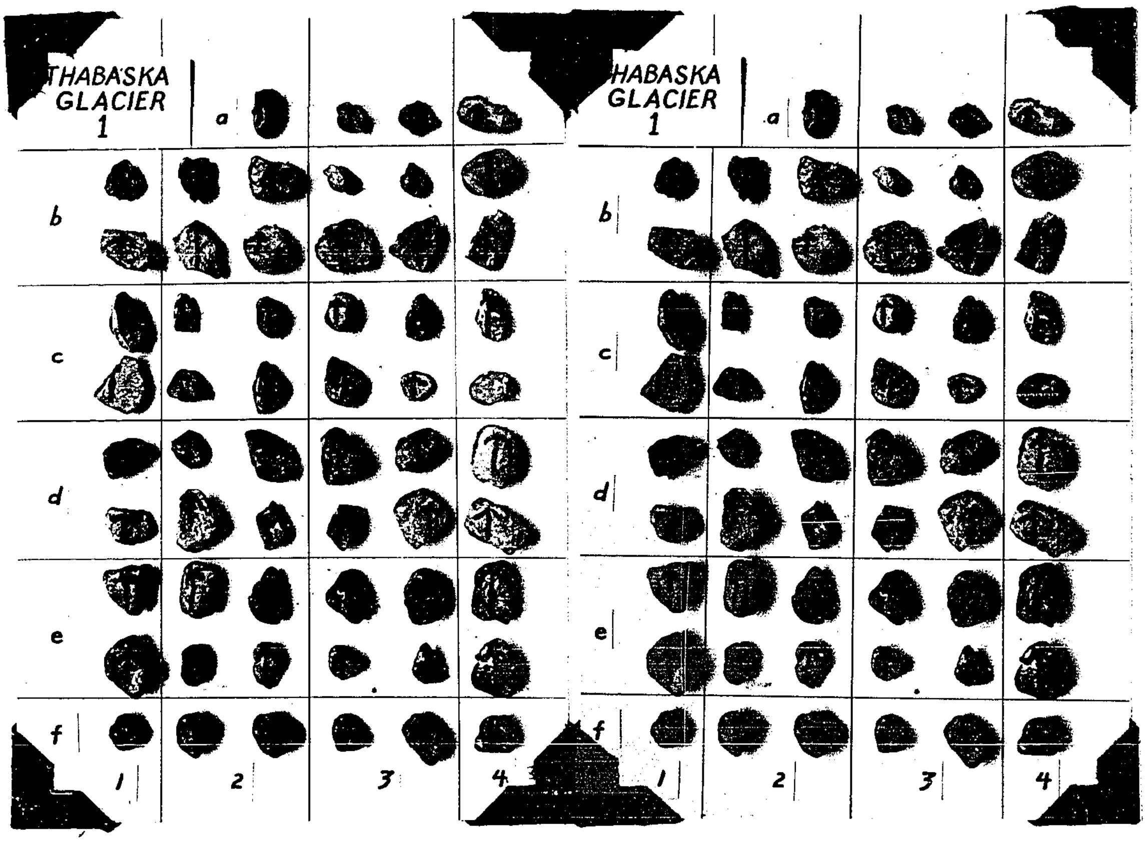

Figure 3-30. Stereoscopic photographs of pebbles collected from Athabasca Glacier mounted in the position they were found in the ice. The squares are 2.5 inches to the side and the arrow points north. By coincidence the direction of flow is also north.

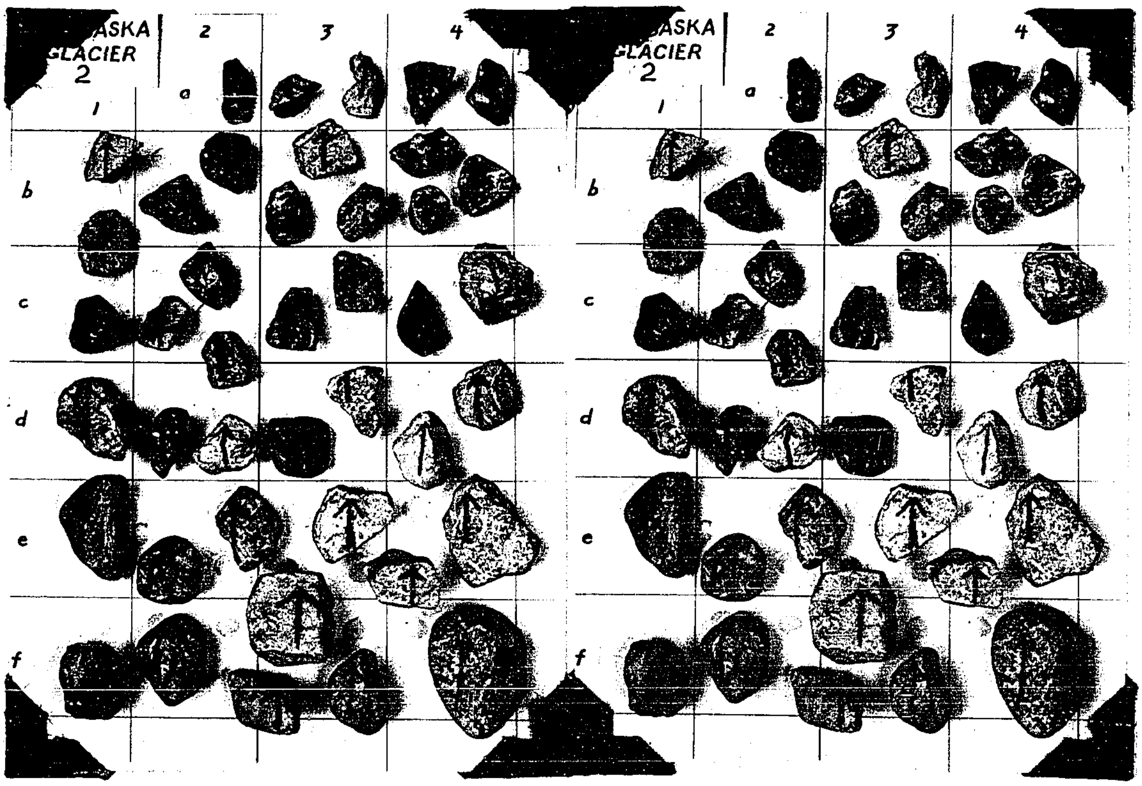

Figure 3-31. Stereoscopic photographs of pebbles collected from the terminus of Athabasca Glacier, mounted in the position they were found in the ice. The squares are 2.5 inches to the side and the arrow points north, which, by coincidence, is also the direction of ice movement.

the structure and texture of the till was undisturbed by plant roots and frost action. Later, all analyses were made on horizontal surfaces, thus reducing the vertical range of the measurements from 2 feet to about 2 or 3 inches.

An analysis is made as follows: a horizontal surface of about 6 square feet is cut in undisturbed till. By means of a penknife and whisk-broom one man carefully exposes all pebbles on or near the surface, and measures the azimuth of the long axis of each in its undisturbed position. A Brunton compass may be used for azimuth readings, which are taken to the nearest 5 degrees. The writer found that a dust-proof, liquid-filled compass modified from a U.S. Army marching compass was satisfactory. To avoid repetition, each pebble is discarded after measuring. The sizes of the pebbles range from 1 cm. to 10 cm., but small sizes predominate; in some localities pebbles are so sparse that sizes smaller than 1 cm. have to be used. Pebbles with long axes less than 1.5 times the intermediate axes are discarded, as are pebbles that stand so nearly vertical that there is doubt as to the azimuth of the long axis. An assistant records the data.

Bruno Sander, a leading researcher in petrofabric analysis, pointed out 1/ that a very useful criterion in the determination of significant preferred orientations is the reproducibility of data. For this reason two men worked together whenever possible, one measuring and one recording.

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1. In an unpublished personal communication to Dr. E.B. Knopf.

When 25 measurements were made the observer and recorder changed positions, until either the record sheet showed no evidence of any preferred orientation after 50 measurements, or until 100 pebbles had been recorded. Rarely do the data reproduce themselves so well in groups of 25 that only 75 measurements need be made. The switch from observing to recording and vice versa tends to destory preconcieved notions the observer may develop and thus maintains more objectivity. Two or three hours are generally required for a set of observations.

Presentation of data

The matter of objective interpretation of the results is difficult unless a high proportion of the analyses are to be rejected as meaningless. The common method is to plot a rose diagram in which the length of each radius is proportional to the number of pebbles having that azimuth, and then to select the longest radius as the direction of preferred orientation (Fig. 3-32(b)). Whether the orientation is transverse or parallel to ice movement must depend on outside evidence, until Holmes' data concerning the tendencies of certain shapes to lie parallel with or transverse to the direction of movement become more firmly established.

In this unavoidably subjective method the writer found many instances in which the longest radius of the rose diagram did not coincide with, or even approach, the direction which obviously represented the main bulk of the measurements, hence the statistical method devised by Krumbein (1939) was utilized. 1/ The arithmetic mean of the distribution, (a

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1. The writer is indebted to Professor C.I. Bliss and Mr. R.B. Smith of Yale University for advice on statistical analysis.

measure that is generally parallel or transverse to the direction of ice movement) and the standard deviation (a measure of the spread of the data and hence the degree of perfection of the orientation) are calculated. Any investigator will arrive at the same results from a set of data; thus the subjective element in fabric analysis is reduced to the decision by the observer as to what is the long axis of the pebble. As described later, the statistical measures may give a false impression of random orientation, as in the case of bimodal and trimodal distributions. Here personal interpretation is unavoidable and histograms (Fig. 3-32(a)) provide the best basis for it. Histograms can be drawn quickly from the raw data and one is prepared for each analysis as a matter of course.

Statistical Analysis

Throughout the following discussion the reader should refer to Table 3-5 and Figure 3-32. The raw data, originally in 5-degree groups, are compounded into 9 classes each comprising an arc of 20° designated by its central point. The class (d) having the highest frequency (f) is usually selected as the center of the distribution (d = 0, the modal class or mode). Those classes that fall to the left of the modal class (Fig. 2-32(a)) are given negative numbers indicating their distance from the mode, and those classes falling to the right are given positive numbers 1/. Thus, the greater

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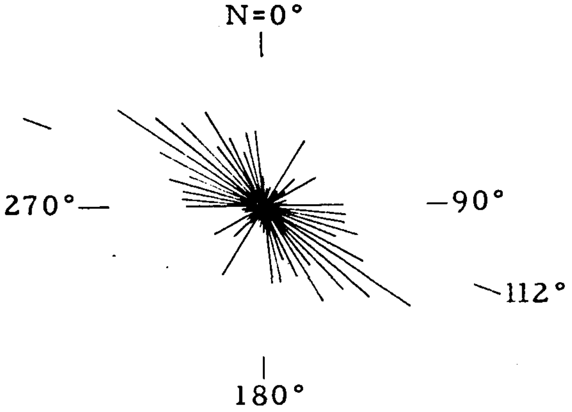
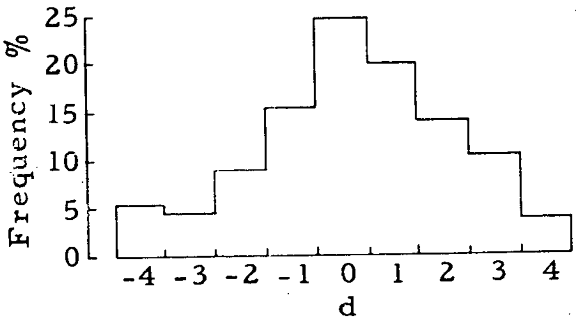
1. In the discussion of the general cases later in the text the (d) numbers are used to designate classes, because the modes of all the different analyses combined here do not have the same



0.1 inch = 1 pebble

(b)



d = 0 = 107.5°

Ma = 112°

$\sigma = \pm 38°$

(a)

Figure 3-32.
Histogram and rose diagram for Analysis II at NW 14-5-17 W. Prin. meridian.

d is numerically, the farther it lies from the modal class 1/. The data from an analysis in a washboard moraine at NW 14-5-17 W. Prin., are shown in Table 3-6. The central point of each class is in column 1, the frequency (f) in column 2 and the distance (d) from the central class in column 3. In column 4, the first moment of each class (fd) is recorded with their algebraic sum (Σfd). This is the first moment of the distribution and it is used to calculate the arithmetic mean (Ma). To obtain this measure Σfd is divided by the total population (n, column 2), giving n_1 (see equation 1, Table 3-5). Then Ma equals the mid-point of the central class (d = 0) plus n_1 times the class interval (20°) (see equation 3, Table 3-5).

The standard deviation, σ, is a measure of the average spread of the data about the arithmetic mean and is calculated from the second moment of the distribution. In column 5 is (d^2), and in column 6 is (fd^2) which is summed (Σfd^2). This sum divided by the total population, n, gives the second moment (n_2). The formula for the standard deviation is:

$$\sigma = k\sqrt{n_2 - (n_1)^2}$$

where k is the class interval (see equation 4, Table 3-6).

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azimuth. The same system of class identification has been used habitually by the writer as it aids the interpreter to view the distribution as it is and not as he might like to see it.
1. In the example given, and in a majority of analyses, the central class is also the modal class. However, a number of distributions have two modes and the central class is a smaller one between them; hence, the (d) = (0) class is referred to as the central class rather than the modal class.

Table 3-6

Statistical measurements of fabric analysis, NW 14-5-17 W. Prin., analysis 2 of the series; determination of Ma and σ.

Class (1)		(2) f	(3) d	(4) fd	(5) d^2	(6) fd^2
7.5°	(177.5-17.5°)	3	4	12	16	48
27.5		5	-4	-20	16	80
47.5		4	-3	-12	9	36
67.5		8	-2	-16	4	32
87.5		15	-1	-15	1	15
107.5		24	0	0	0	0
127.5		19	1	19	1	19
147.5		13	2	26	4	52
167.5		10	3	30	9	90
	Sums	n = 101		$\Sigma fd = 24$		$\Sigma fd^2 = 372$

Equation (1) $n_1 = 24/101 = 0.24$

(2) $n_2 = 372/101 = 3.72$

(3) $Ma = 107.5^\circ + (20^\circ \times 0.24) = 112^\circ$

(4) $\sigma = \pm 20^\circ \sqrt{3.72 - (0.24)^2} = \pm 38^\circ$

(5) Error $Ma = 38/\sqrt{101} = \pm 3.8^\circ$

(6) Error $\sigma = 38/\sqrt{202} = \pm 2.7^\circ$

A standard deviation of less than $\pm 45^\circ$ indicates a definite tendency toward a preferred orientation; less than $\pm 42.5^\circ$ indicates a fairly well developed preferred orientation, and less than $\pm 40^\circ$ indicates a strong preferred orinetation. The writer has found that distributions having standard deviations greater than $\pm 45^\circ$ are not necessarily random orientations, but may have a pattern that contains two, three or even four modes and hence gives random results if analysed statistically; these can be judged on the basis of symmetry.

The probable error of Ma and σ are discussed by

Chayes (in Fairbairn, 1949, p. 304). The estimated errors of these measures are given by the formulae:

$$\text{Estimated error Ma} = \sigma / \sqrt{n}$$

$$\text{Estimated error } \sigma = \sigma / \sqrt{2n}$$

It is evident that the error decreases as the population increases. The error of Ma is usually about $\pm 4.5^{\circ}$ in studies of 100 pebbles which show a reasonable degree of preferred orientation, while the error of σ is of the order of $\pm 3.5^{\circ}$. The analysis given in Table 3-5 is considered to show a strong preferred orientation. The direction of preferred orientation that would be chosen by inspection of the rose diagram, Figure 3-32b, is 115°, so close to the arithmetic mean (Ma) that it lies within the estimated error.

The histograms of some analyses indicate that there is preferred orientation but two or three classes of almost equal size separated by smaller classes or pronounced asymmetry make the selection of the central ($d = 0$) class difficult. In these cases, the first moments of the distributions around each of the suspected modal classes, are calculated and the true mode will give the lowest numerical result.

Some distributions should be tested for reproducibility of data. Arithmetic means and standard deviations can be calculated for the measurements in groups of 50, the smallest set of data that will give reliable results. One calculation can be made on the first 50, a second on the middle 50, and a third on the last 50. If the means agree within 10°, or so preferred orientation is present.

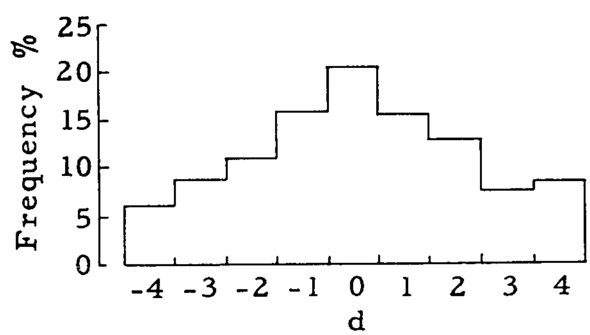
General Observations

A composite distribution based on 3,121 measurements was established by setting up the data from 32 till-fabric analyses studies so that the $d = 0$ classes coincided, and all corresponding classes could be summed. The result (Fig. 3-33) gives an average for all the analyses in the Tiger Hills region, and forms a standard on which individual analyses can be judged. The composite distribution is mono-modal 1/ even though a substantial number of bi-modal distributions are incorporated into it. A regional asymmetry is shown by the arithmetic mean which falls 1.8° to the right of the center of the distribution (clockwise on the rose diagram). The standard deviation is $\pm 45^{\circ}$.

Three other composite curves (Fig. 3-34) are generalized examples of the three main distribution types. The histograms were compounded by superimposing the central classes and arbitrarily using north (0° azimuth) as the middle of the central class.

Figure 3-34(a) represents the common mono-modal distribution and was compounded from 12 selected studies totalling 1,214 measurements. The arithmetic mean lies about 2° to the right of the center, and the standard deviation is $\pm 40.6^{\circ}$. The standard deviation of this type of distribution is generally less than $\pm 45^{\circ}$ and commonly less than $\pm 40^{\circ}$. When plotted on

1. The terms mono-modal, bi-modal and tri-modal refer to the histogram rather than the rose diagram. Plotted on a circular basis these distributions would have 1, 4 and 5 or 6 modes, respectively.



Ma = center of d-0 group + 1.8°
$\sigma = \pm 45°$

Figure 3-33.
Frequency distribution compounded from 32 orientation studies, including 3,121 pebbles.

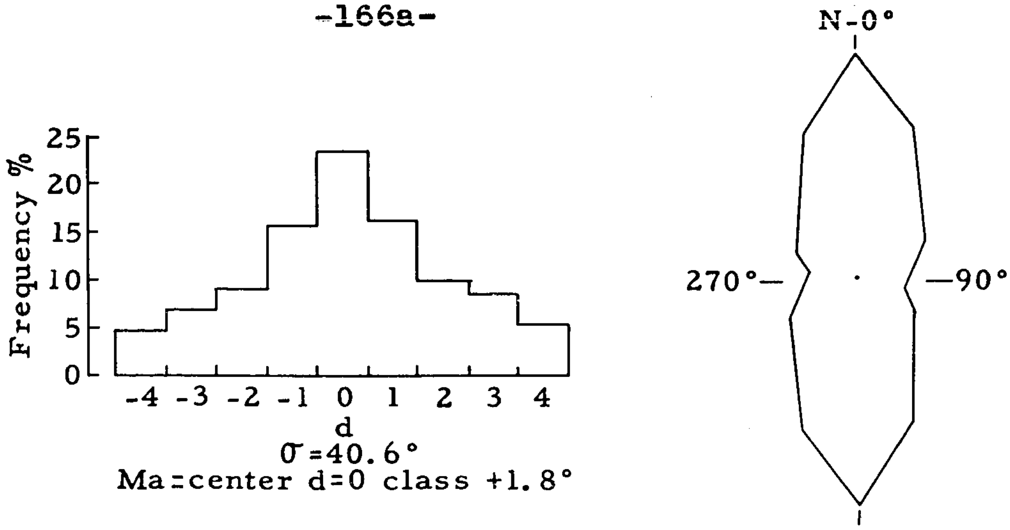
probability paper[1] (Fig. 3-35(a)), this distribution approximates a straight line, hence is almost a normal distribution.

The best-developed till fabrice might be expected at their source, namely active or formerly active glacier ice. A statistical treatment by the writer of englacial stones studied by Richter (1936, p.27) gave a standard deviation of ±28.9°. A composite distribution of the orientation of 242 englacial stones in glaciers in the Rocky Mountains studied by the writer has a standard deviation of ±33.7°. Individual orientation analyses of englacial stones gave standard deviations as follows: Dome Glacier, 51 stones, ±27°; Athabasca Glacier, 100 stones (Figs. 3-30, 3-31), ±32°; Victoria Glacier, 99 stones, ±39°. These standard deviations represent highly developed preferred orientations; all the distributions are mono-modal.

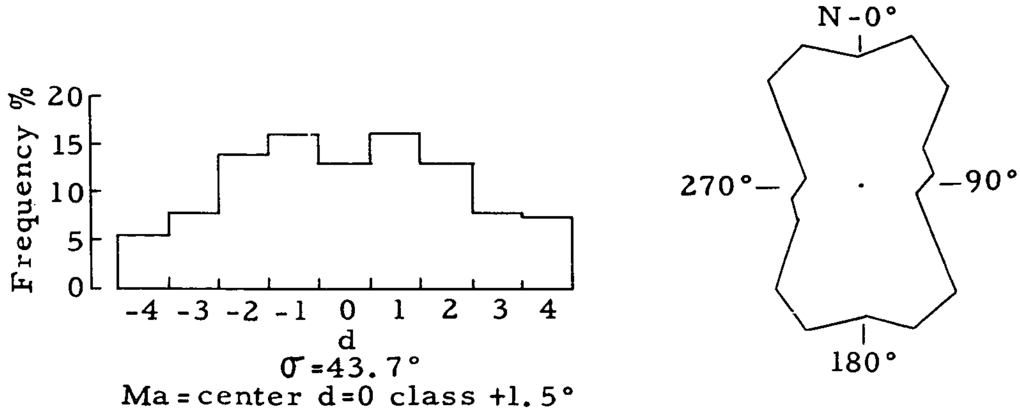
The second type of distribution (Fig. 3-34 (b)) is bi-modal and the data for the generalized curve were compounded from seven separate studies totalling 673 measurements. Although the general curve is nearly a normal curve (Fig. 3-35 (b)), some individual cases diverge widely from normal. The angle between the two modes ranges from 30° to 80°. The modes of some distributions are indistinct and may appear on the histograms as the sides of a central "plateau". There may be a lack of symmetry between the modes, one having a greater population grouped around it than the other.

There are two hypotheses of origin of bi-modal

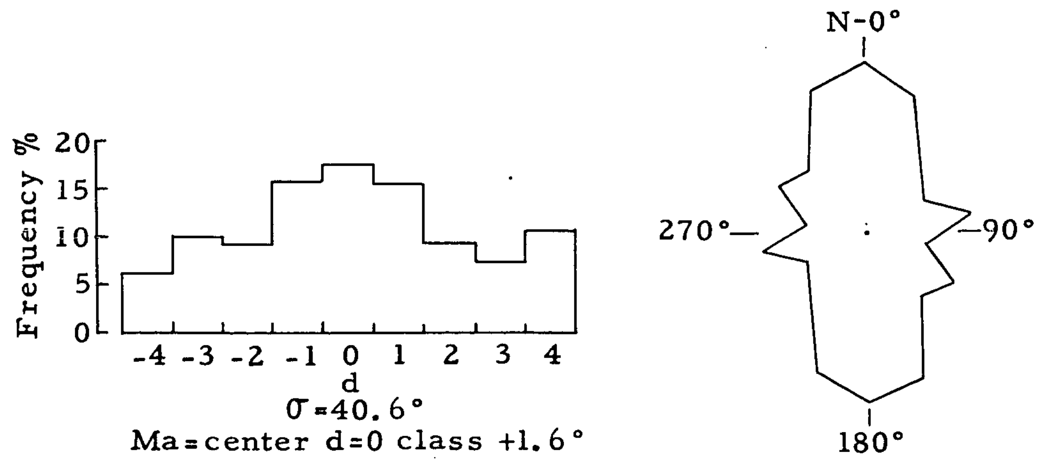
1. Probability paper can be used for rapid graphic determinations of Ma, σ. and skewness (Otto, 1939, pp. 67-69).



(a) Generalized mono-modal (normal) distribution, based on 12 examples totalling 1,214 pebbles.



(b) Generalized bi-modal distribution, based on 7 examples totalling 673 pebbles.



(c) Generalized tri-modal distribution, based on 9 examples totalling 894 pebbles.

Figure 3-34.
Histograms and rose diagrams for the three general types of distribution. In the rose diagrams, 0.1 inch radius=2%

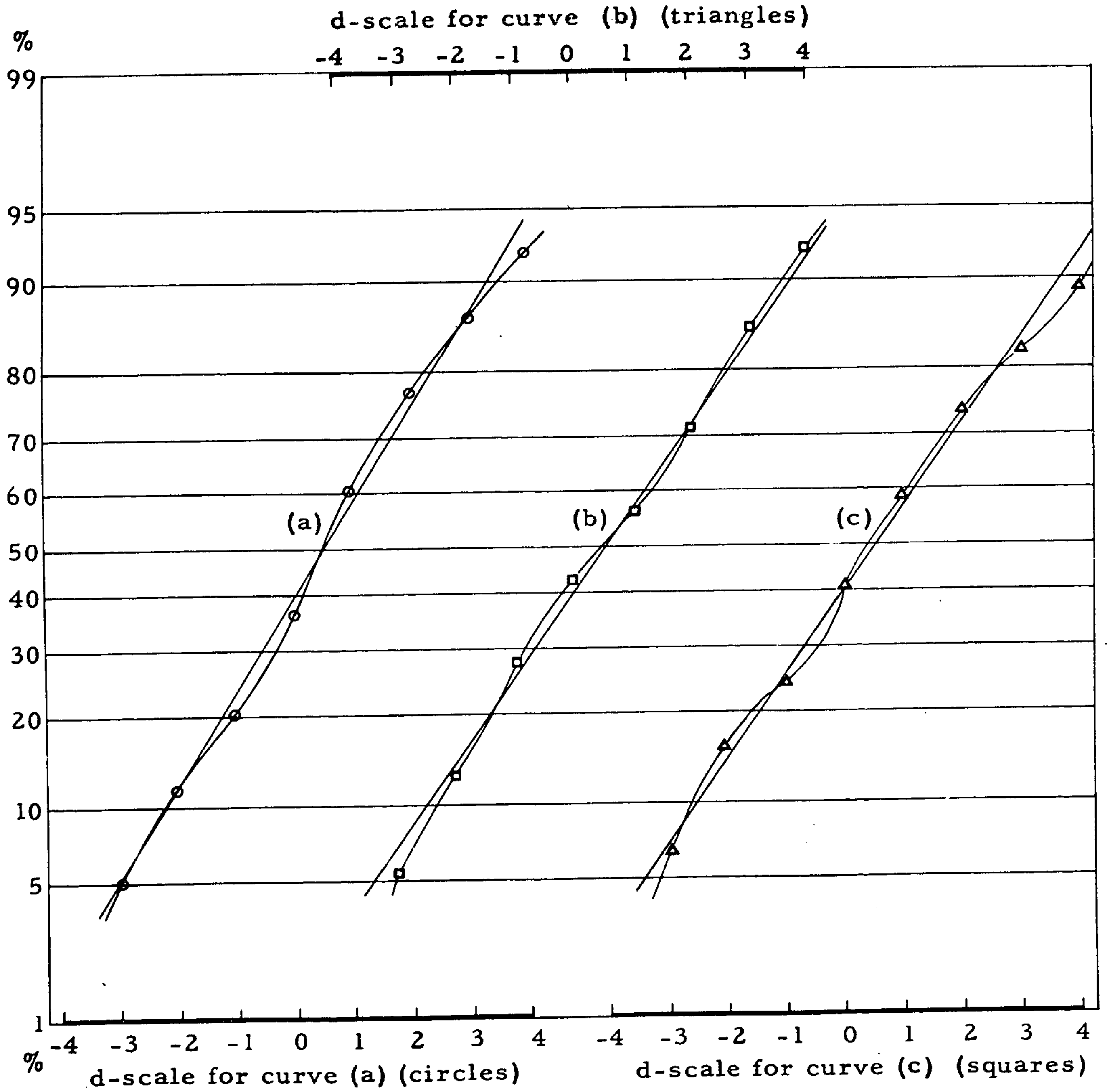


Figure 3-35.

The three generalized types of distribution are plotted on probability paper. The sinuous curves through the circles, triangles and squares are the mono-modal, tri-modal and bi-modal distributions, respectively. The straight line through each curve is the normal curve having the closest fit, and is shown for comparison only.

distributions in till. Several workers 1/ have observed them, and commonly interpret them as representing two successive directions of ice movement, the second movement imposing a fabric upon the till deposited during the first movement, so that the bi-modal distribution is really two normal mono-modal distributions out of phase. This reasoning might apply where one mode dominates the other, but seems unlikely where the two modes are about equal in size. Two normal curves out of phase should have greater departure from single normal curves (the straight lines in Fig. 3-35) than the generalized bi-modal curve displays. A fairly strong preferred orientation with a bi-modal distribution having modes spaced about 40° apart was found by the writer in fresh ground moraine in front of Athabasca Glacier, Alberta, where there was definitely only one direction of ice movement. If the bi-modal distribution represents two directions of movement it should be found only in till that has been subjected to two directions of movement. According to the concept of till accumulation by lodgment (H. Miller, 1884, p. 172) only a thin layer of till, perhaps 1 to 2 feet, should be affected by the two movements (Fig. 3-36). Hence, bi-modal orientations should be found only in zones affected by two directions of ice movement. It would be mere coincidence if an observer happened to select many of these zones (few are as obvious as the one in Fig. 3-36) for study, yet bi-modal distributions are fairly common. As they are common near the surface of washboard moraines, factors other

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1. A. Dreimanis, C.D. Holmes, H.G. Ignatius and others; unpublished oral communications.

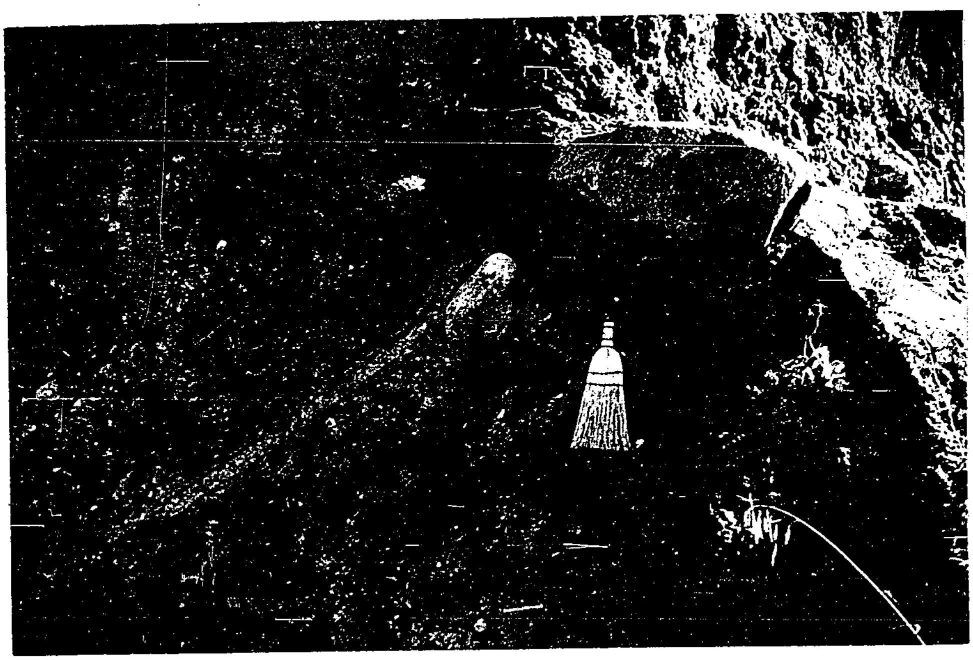
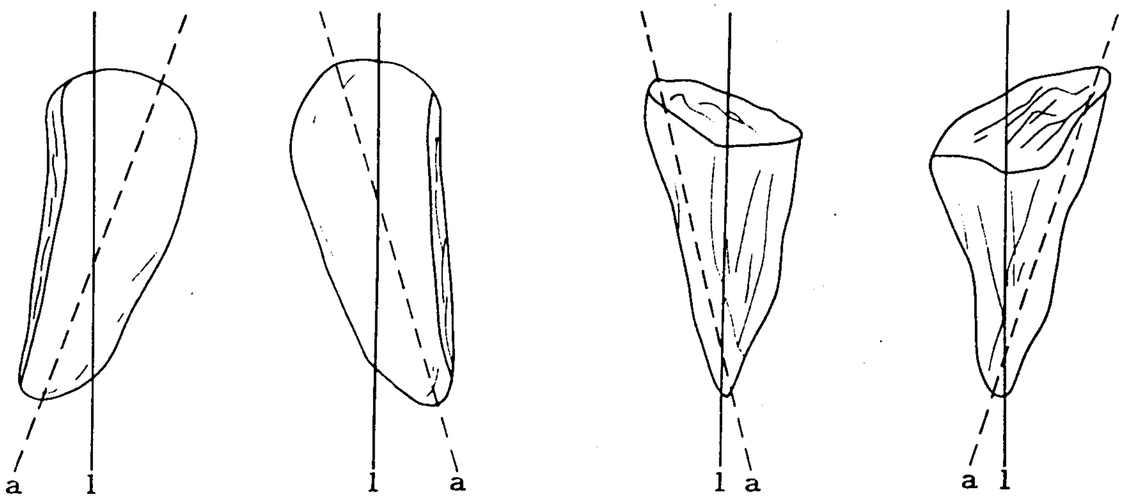


Figure 3-36. Vertical section of till showing a striated boulder pavement in a road cut at NE 34-1-17 W. Prin. The till above the two large stones (pavement boulders) is sandy-silty till whereas that below is sandy-clayey till (Fig. 3-2, sample nox. 50-3 and 50-4 respectively). Till-fabric analyses (p. 91-92) were made on the vertical faces above and below the pavement. The structures resembling bedding dipping to the left are thin layers of poorly sorted sand; R.F. Flint (oral communication) suggested that the thick (2 inches) layer may be a clastic dike. The sand layers are deformed below the pavement boulders, having been dragged in the direction of the last ice movement (southeast); the disruption does not extend more than 1.5 feet below the surface of the striated boulder pavement. The whisk-broom is about 12 inches long.

than change in direction of ice movement must be important. In one fabric analysis made at SW 34-2-15 W. Prin., where there is know to have been a change in direction of movement, a bi-modal distribution is present and one mode is subordinate to the other, as suggested above.

Pebble shapes are believed to be important causes of bi-modal distributions. The direction of movement does not necessarily correspond to the long axis of a pebble; different observers often disagree in their interpretations of the direction on the pebble that should be measured. Where there are a large number of pebbles of one rock type, similarly shaped pebbles are common. The long axes of pebbles are measured rather than the assumed direction of movement which, pending further research is still fairly subjective. Similarly shaped pebbles whose axes of movement differ from their long axes (Fig 3-37) picked up at random by a glacier, should align their long axes in two directions on either side of the direction of movement, one mode being the mirror image of the other (Fig. 3-37; see also Figures 3-30 and 3-31). The problem depends upon the observer's conception of the long axis of each pebble. In a till that contains a large number of pebbles of these divergent types, the center of symmetry of the till-fabric distribution is the criterion of the direction of ice movement. This principle of symmetry is further borne out by tri-modal distributions, described next.

The general case for tri-modal distributions is presented in Figures 3-34(c) and 3-35(c). It is based on 9



l = direction of ice movement a = long axis of pebble

Figure 3-37.
Long axes of similarly shaped pebbles reflected around the direction of ice movement.

studies totalling 894 pebbles. One of these analyses showed a bi-modal tendency at the center (4 modes altogether), but was included because basically the histogram was composed of a central mass with subordinate modes at each end. Actually, the small modes at the ends of a tri-modal distribution are close together, as the histogram represents half of a circular distribution and one end should be adjacent to the other (Fig. 3-34). This type of distribution is actually a mono-modal fabric upon which a widely divergent bi-modal fabric is superimposed. The principles of symmetry applied to irregularly shaped pebbles in the preceding paragraph can be applied to pebbles oriented transverse to the direction of ice movement, to explain the minor modes at the ends of the histogram.

As an index of degree of preferred orientation, the standard deviation loses much of its value in tri-modal distributions, and to a lesser extend in the bi-modal type. An example is a till-fabric analysis made on a vertical face above a boulder pavement at NE 34-1-17 W. Prin. The standard deviation is $\pm 48^{\circ}$, suggesting a low degree of preferred orientation, but an examination of the histogram shows that there is a definite trimodal distribution. In this analysis, the vertical range (1.5 feet) of the analysis may be responsible for the tri-modal distribution.

The three general cases just presented do not show the tendency towards asymmetry displayed by many pebble fabrics. Commonly the weight falls slightly to the right (clockwise) of the arithmetic mean. This may be due to an undiscovered systematic error in observation or interpretation or it may be an expression of the postulated change in direction of ice movement from south to southeast, during the waning stage of the glacier.

Although statistical measures greatly aid objective interpretation of fabric analyses they do not entirely eliminate the need to consider each analysis on other bases, such as symmetry of distribution.

Specific problems attacked by till-fabric analyses

(1) Structure of washboard moraines.

A number of till-fabric analyses were made in the crests of washboard moraines, and a comprehensive study of a cross section exposed in a new road cut was carried out. These analyses were discussed in the section on washboard moraines (p. 74-75).

(2) Structure of a till sheet.

Two studies were made to determine whether pebble orientations are homogeneous from top to bottom of a till sheet, or whether changes in direction of ice flow during deposition are reflected in the preferred orientations of pebbles at various stratigraphic positions in the till.

The first study, at SW 34-2-15 W. Prin., was made on a section of sandy till 16 feet thick, lying on a striated boulder pavement underlain by more sandy till. The mean azimuth of striations on 52 stones in the pavement was about 140°. Fabric analyses were made at intervals of 3, 6, 9 and 12 feet above the boulder pavement, giving 5 directional measurements of ice movement including striations. Preferred orientations were moderately well developed (Fig. 3-38). The mean directions of preferred orientation from the bottom up, including the boulder pavement, are 140°, 142°, 163°, 138°, and 146°. Standard deviations range from ±39° to ±46°; the only analysis of dubious interpretation is the second from the top, an asymmetric bi-modal distribution. Probable errors are of the order of ±5°. There is a significant anomaly 6 feet above the boulder pavement where the direction of movement is about 20° clockwise from the upper and lower movements. This is in keeping with the shift of ice flow from southeast to south and back again as suggested earlier (p. 3-86). Several more analyses might show that this anomalous zone is 2 or 3 feet thick, and that at one level the orientations are even more nearly true south than the present analyses indicate. In fact, the alternative interpretation of the analysis 9 feet above the boulder pavement (mode of about 160°) agrees with the anomaly. However, it is probable that the ice was thicker during its period of southward movement than during the periods of southeast movement, and because of the energy relationships involved it may have eroded till or at least failed to deposit any during the phase of southward flow. Hence, the southward flow would have little or no expression in the till fabric; on the other hand, the duration of the southward movement may have been short, resulting in little deposition.

In summary, this study suggests that till is deposited by lodgment of thin layers and that each layer reflects the direction of ice movement during its deposition.

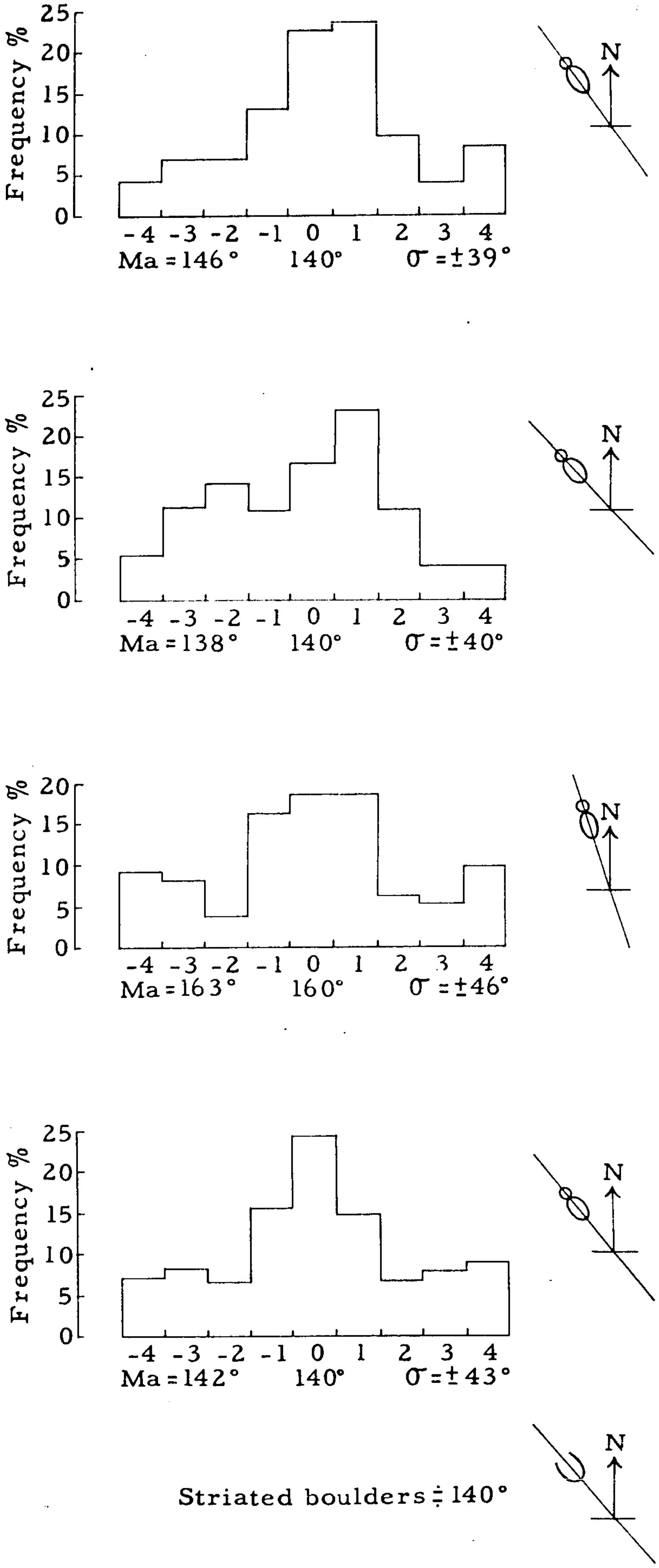


Figure 3-38.
Histograms for fabric analyses at Sw 34-2-14 arranged in proper order of superposition.

The second till-sheet study was made at NW 14-5-17 W. Prin. and supports the conclusions based on the first. In a new cut on the east side of a ravine and on the south side of the road about 4 feet of silt overlies, successively, 16 feet of sandy fissile till which is sandier at the top than at the base, and undisturbed Odanah shale. In the middle of the till a horizontal zone about 2 feet thick contains contorted lenses of compact silty sand as thick as 6 inches and as long as 10 feet. Some till may have been eroded from the surface by glacial meltwater, but the lack of a concentration of stones at the base of the silt or on the surface of the ground and the gently undulating topography suggest that the erosion was less than 5 feet. Till-fabric analyses (Table 3-7) were made on horizontal surfaces cut into the 30° to 60° face of the exposure at vertical intervals ranging from 1.5 to 4.5 feet.

Table 3-7 Results of a vertical series of till-fabric analyses in till sheet at NW 14-5-17 W. Prin. (1.5 miles west of Ninette).

Height above bedrock	Ma	σ	Number of modes	Comments
14.0 feet	110°	±45.8°	3	Secondary modes at about 90° from Ma.
11.5	106	46.0	3	May be 5 modes, center one is dominant.
9.5	102	41.5	2 or 3	Asymmetric, low population 90° from Ma.
8.0	170	48.0	3	Outer modes strong.
7.0	113	36.1	1	Secondary mode 60° clockwise from Ma.
5.0	112	38	1	Very strong preference, asymmetric clockwise.
0.5	86	73.6	2	Asymmetric to left of central plateau.

Although this series of analyses shows considerable irregularity, with three very high standard deviations and bi-modal and tri-modal distributions, the central tendencies are strong enough to indicate preferred orientations. The estimated errors of the arithmetic means range from $\pm3.6^\circ$ to $\pm7.4^\circ$.

The nearest washboard moraines, about 1.5 miles south or west, trend north (Pl. 4). These represent the trend of the glacier margin, and presumably the last ice movement was nearly transverse to the margin (eastward). It is inferred from eskers, drumlins and washboard moraines that earlier the ice moved southeastward. Probably when the ice sheet extended southward into North Dakota it was thick enough to flow over Riding Mountain so that southwest-flowing ice coalesced with southeast-flowing ice and formed a southward-moving tongue that crossed the Tiger Hills region. If the sequence of directions of ice flow during glacier advance was the reverse of the sequence during retreat, the following succession of glacier movement occurred at Ninette: first the ice flowed east-southeast, as shown by striations on the boulder pavement (p. 91), then it shifted southeastward, and then, during the maximum extent of this glaciation, it flowed south; when the ice sheet waned the flow shifted to southeastward and finally eastward. If till deposition was continuous, this shift in direction of ice flow should be apparent in the till fabric. If deposition was not continuous, or if subglacial erosion occurred, there should be a hiatus in the continuity of the till fabric. Such a hiatus may be represented by the anomalous 170° orientation and the lenses of sand at the 8.0-foot level. The sand may be redeposited material transported southward from a proglacial lake north of the Tiger Hills during the maximum extent of the glacier.

In both series of till-fabric analyses the anomalous orientations of till stones near the centers of the sections have tri-modal distributions. The sequence of till fabrics is similar in both sections, except that the change in direction is greater at Ninette than at the first locality.

A third series of till-fabric analyses showing an anomaly in the middle of a till sheet would prove that the two anomalies described above are not the result of coincidence. However, the meagre data do justify the hypothesis that the till was deposited by accretion of thin layers having a fabric formed by moving ice. Probably till is deposited beneath the marginal zone of a glacier during advance and retreat, whereas there is little or no deposition under the thicker ice behind the marginal zone, where erosion (abrasion) may occur. It appears doubtful that more than a few inches of till become attached to the ice so that the original fabric is obliterated and replaced by a new one.

(3) Directions of ice movement.

Till-fabric analyses may be used to determine direction of ice movement where other criteria are lacking, provided several analyses are used in a single area so that any transverse orientations can be recognized. If possible, fabric study should start near a feature such as a drumlin, striated boulder pavement, or esker, that indicates direction of ice movement, and should extend progressively into unknown territory. Analyses to determine the direction of ice movement (Table 3-8) were made early in the study of the Tiger Hills region but were later rendered unnecessary by other lines of evidence. Several analyses were made on vertical rather than on horizontal surfaces.

CONCLUSION

Two main types of deposits, glacial and lacustrine, occur in the Tiger Hills region. Their thickness ranges from a knife edge along the Manitoba Escarpment to more than 300 feet in preglacial valleys.

In the southwest part of the map-area two tills are separated by a striated boulder pavement having no associated weathered zone. If the pavement stones accumulated during an interval of subaerial erosion it must have been brief; probably the pavement formed as a result of selective subglacial erosion during till deposition, and there was no subaerial exposure; the pavement may be the subglacial expression of a distant ice-margin fluctuation of substage magnitude.

Glacial sediments in the southern half of the region were deposited by ice that flowed southeastward. North of the Darlingford-Tiger Hills moraine, which trends sinuously across the map-area from the southeast to the northwest corner, the glacial sediments were deposited by a southwest and south-flowing sublobe of an ice tongue in the Lake Agassiz basin.

The glacial deposits include normal end moraine, ground moraine, and washboard moraine.

Table 3-8. Miscellaneous till-fabric analyses in the Tiger Hills region.

No.	Location (W. Prin.)	Ma	σ	Number of modes	Comments
1.	NW 2-4-14	16°	±44°	2 or 4	Analysis on vertical face above boulder pavement with striations from 115° to 165°; strong preference.
2.	NE 11-6-14	164	49	2	Analysis on vertical face; very weak preference.
3.	SE 12-1-15	104	39	1	Analysis on vertical face; strong preference; rose diagram mode is 116°.
4.	SE 31-3-16	91	43	3	Vertical face above boulder pavement with striations from 97° to 143°; minor modes about 60° from Ma.
5.	SW 19-6-16	93	40	1	On vertical face; strong preference, minor mode 60° right of Ma; rose diagram 95°.
6.	SE 5-8-16	69	41	1	On vertical face; rose diagram 75° to 80° . central "tower".
7.	SE 7-1-17	4	49	3	On vertical face; rose diagram mode 23°; nearly random distribution.
8.	NE 34-1-17	158	40	1	On vertical face 2 feet below boulder pavement; rose diagram mode 145°; strong preference.
9.	NE 34-1-17	129	48	3	On vertical face above boulder pavement with striations at 135° to 150°; rose diagram mode 140° ; fair preference.
10.	SW 6-3-17	72	43	2 or 3	On vertical face; strong preference, weighed to right; rose diagram mode 65°.
11.	NW 15-7-17	81	39	1	On vertical face; rose diagram mode 80°; strong preference.
12.	NW 15-7-17	108	48	3?	On vertical face; rose diagram mode 100°; weak preference.
13.	NW 15-7-17	167	52	3	On vertical face; very weak preference - random distribution.
14.	NW 5-3-7	30	46	2 or 3	On horizontal surface in Darlingford moraine; weighed to right of Ma; fair preference.
15.	NW 16-3-6	157	47	3	Strong preference, weighed to left of Ma.
16.	W/2 25-5-7	147	47	2	Very weak preference.
17.	SE 3-6-15	142	48	2 or 3	Horizontal surface in drumlin; secondary mode 90° from Ma; strong preference.
18.	SW 31-2-14	45	44	2	Weighed to left of Ma; weak distribution.

Washboard moraines are believed to have formed subglacially at the zone of thrusting between flowing and stagnant ice; they may be cyclical phenomena, but they also depend upon the supply of drift and the amount of thrusting in the glacier. Moraines are the response of a slowly shrinking ice sheet to climatic fluctuations. Various types of maraine, ranging from ground moraine to massive terminal moraines result from the effect of climatic variation on the "metabolic rate" of the glacier, and each type of moraine may represent a specific climatic cycle (e.g. annual and 11-year sunspot cycles) whose expression depends upon the general rate of ice-margin recession.

Eskers in the Tiger Hills region are commonly 10 to 20 feet high and comprise ridges as long as 1 mile that are aligned to form eskers as long as 12 miles. Eskers south of the Darlingford-Tiger Hills moraine generally trend southeast; north of the moraine their trends are variable and some are transverse to the inferred direction of ice movement. Two types of eskers are associated with washboard moraines: massive eskers, termed "dominant eskers", form the axes of reentrants between lobes in the pattern of moraines, whereas small eskers, termed "subordinate eskers", change direction or are offset at each moraine ridge. It is inferred that the dominant eskers formed before the moraines were deposited and that the subordinate eskers formed in stagnant ice overlying washboard moraines. The length of eskers and esker segments as compared to the spacing of washboard moraines suggests that the esker segments may represent ice recession during an 11-year cycle, and that washboard moraines may be annual phenomena.

Outwash sand and gravel forms extensive plains south of the Darlingford-Tiger Hills moraine, and forms the surface of several high-level terraces in Pembina Trench. Clayey silt covering large areas in the Purves plain may be partly outwash and partly eolian in origin.

Glaciofluvial sand and gravel overlying the till underneath lake deposits in the Lake Agassiz basin indicate that there was an interval of subaerial exposure as the ice withdrew. Finely laminated clay above the sand and gravel was deposited in a body of deep water (Lake Agassiz I). A drying surface on the clay correlates with an erosional unconformity that resulted when the lake was drained; subsequently the lake basin was flooded a second time (Lake Agassiz II) and fossiliferous silt and clay were deposited. Beach ridges (bars) and scarps mark phases of the final drainage of the lake.

The thick topset beds of the Assiniboine delta suggest that it was deposited at least partly in a rising lake; an alluvial fill in Pembina trench indicates that Lake Agassiz I rose from an altitude of 1,050 feet or lower to 1,150 feet or higher near Walhalla, North Dakota. The Pembina "delta" (Chapter 5) may be an alluvial fan deposited in a reentrant between the Manitoba Escarpment and the ice margin and later modified by wave action. An estuarine-like alluvial fill in the Assiniboine valley indicates that that valley was excavated to an altitude of 1,000 feet or lower and then flooded by a lake (Lake Agassiz II) which contained a molluscan fauna and rose to an altitude of at least 1,050 feet.

From the structure of the Assiniboine delta, the sequence of sediments in the Lake Agassiz basin, the alluvial fills in Pembina trench and the Assiniboine valley, and strand-line features, it is inferred that the basin of Lake Agassiz was dry when the southeastward-flowing ice receeded from it; Lake Agassiz I formed when an ice advance north of Lake Superior blocked drainage to the east and caused the basin to fill to an altitude of 1,250 feet. At this time the Assiniboine delta and an alluvial fill in Pembina trnech were deposited. Lake Agassiz I was partly or wholly drained when glacier recession north of Lake Superior opened an eastern outlet. Lake Agassiz II formed when the eastern outlet was again blocked by an ice advance, and the lake level rose to the Campbell strandline (about 1,050 feet near Treherne).

Extensive redeposition of delta sand by wind occurred after the Norcross phase (altitude about 1,150 feet) of Lake Agassiz I. Soil zones buried by windblown sand indicate that one or more comparatively humid periods of stability were followed by intervals of eolian deposition.

Modifications of the deposits of the Tiger Hills region by intense frost action include fossil ice wedges, polygons, and convolutions. Small ice wedges are forming during the winter seasons at present, hence only the largest fossil ice wedges may be considered as evidence of perenially frozen ground. The evidence for an interval with a periglacial climate is inconclusive.

Alluvium is being deposited at present in alluvial fans and on flood plains. A buried soil in the Cypress River alluvial fan indicates that two intervals with humid climates were separated by a relatively dry interval.

Attempts to solve the problem of the general direction of ice movement by provenance studies (pebble counts) were fruitless. Till-fabric analyses indicate that the last ice sheet flowed southeastward, that washboard moraines are composed mainly of lodgment till, and that ground moraine is deposited by lodgment of thin layers of drift that have a fabric reflecting the direction of ice movement at the time of deposition.

Chapter 4

PLEISTOCENE FOSSILS

INTRODUCTION

Pleistocene fossils from the Tiger Hills region include mollusks, poorly preserved plant matter, and a few vertebrates (bison and mammoth). Except for mammoth, all species collected are living, and many of the mollusks range throughout the northeastern half of North America. Also, except for mammoth, all the fossils were collected from post-glacial deposits, mainly alluvium. The writer's data 1/ augment the work of Mozley (1934) on the fauna of glacial Lake Agassiz and provide information on the stratigraphic and geographic distribution of mollusks in more recent alluvial bodies. The writer attempts to correlate archaeological data, very kindly made available by Dr. R.S. MacNeish of the National Museum of Canada, with the geological history of southern Manitoba. The Yale Geochronometric Laboratory assayed several specimens from the area for radiocarbon, but unfortunately most of them proved to be chemically peculiar and the resulting data are not reliable.

FOSSILS IN GLACIAL DEPOSITS

Foraminifera and sponge spicules from Cretaceous rocks are common in the till of the Tiger Hills region, and Foraminifera are also found in the sand of the Assiniboine

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1. The writer is indebted to Drs. L.S. Russell and A.B. Leonard for identifying mollusks; and to Mr. H.G. Ignatius, Drs. E.S. Deevey Jr. and A.E. Porsild for studying plant matter; to Dr. J. T. Gregory for identifying vertebrate remains, and to the Ottawa Forest Products Laboratory of the Department of Resources and Development for identifying fossil wood.

delta. These fossils have little significance in local Pleistocene stratigraphy, but could be used in the same manner as heavy minerals to study the provenance of drift on the Prairies.

Through the kindness of Dr. R.S. MacNeish, the writer acquired a small mammoth tooth found in glacial gravel (outwash?) on the farm of Mr. M. Hunter, near Crystal City. The tooth, identified by Dr. L.S. Russell of the National Museum, was about 20 feet below the surface of the upland on the south side of a ravine, nearly at the center of the north boundary of SW 35-2-15 W. Prin; no other remains were found. The tooth survived reworking by ice and water because relatively soft Odanah shale forms the gravel in which it was deposited. The tooth indicates only that mammoth was present before the last glaciation.

Two occurrences of plant matter within the drift were reported from the southwest part of the Tiger Hills region:

One occurrence (Elson and Halstead, 1949, p. 11) is on Turtle Mountain at the northeast corner of Lake William (SW 21-1-19 W. Prin.) where a well penetrated 90 feet of drift, mainly till, and ended in a "nest" of spruce cones. These cones, now in the posession of Mr. C.B. Gill of the Forestry Branch of the Manitoba Department of Lands and Forests at Winnipeg, were identified as <u>Picea</u> <u>mariana</u> (Black spruce), a species that does not grow in the area at present. It is inferred that the climate was moister and perhaps cooler during the interglacial interval that the cones represent. The cones may be correlated tentatively with the Bronson, and Jackson, Minnesota, interglacial deposits (Rosendahl, 1948, p. 290-296) that are believed to represent the Peorian interval.

The second occurrence was reported by a farmer, near SW 12-2-14 W. Prin., who encountered a log in the drift at a depth of about 30 feet while digging a well. This is in about the same position as a striated boulder pavement reported in several other wells in the neighbourhood (p. 97). The wood was not identified or preserved; its presence near the striated boulder pavement suggests that both may represent an interglacial interval, but the occurrence is too poorly documented to prove such an interval.

FOSSILS IN POSTGLACIAL DEPOSITS

INTRODUCTION

Localities at which mollusks were collected are described in the Appendix following Chapter 6. Mollusk shells were collected from shallow cuts in alluvium to determine their present geographic distribution, and from vertical sections to determine their stratigraphic distribution. The stratigraphy of the localities is described below, and organic matter other than mollusk shells is discussed; the mollusks are considered later in the chapter.

FOSSILS OF LAKE AGASSIZ II

Rossendale alluvium

On the farm of Mr. E. Buchholz in SW 35-9-9 W. Prin., 3 miles south and 1 mile east of the village of Rossendale (Pl. 1), is a flat-bottomed ravine that contains peat and molluscs representing fauna and flora of Lake Agassiz II. The ravine was formed during the interval between Lakes Agassiz I and II, and was alluviated when Lake Agassiz II rose to the Campbell strandline. A reservoir 16 feet deep exposed peat and snails which were collected from the spoil pile because the excavation was full of water when visited; an auger hole was put down at one end of it to check the stratigraphy. The alluvium is clay at the surface and grades downward into silty and sandy clay below a depth of 10 feet. Snail shells are abundant and wood fragments are common 10 to 11 feet below the surface; a piece of charcoal was found at 11.5 feet. The auger ceased to function at 13.5 feet because of water entering the hole; it is inferred that the bed of peat is between 13.5 and 15 feet below the surface. The altitude of the top of the auger hole, as determined by several barometric traverses, is 1,065 5 feet; the altitude of the peat is about 1,050 feet.

The snail collection from the spoil pile may represent all post-Lake Agassiz II time, although the snails occurred in material that was encountered below 10 feet in the auger hole, and there does not appear to have been recent alluviation in the ravine. The mollusks from the alluvium are listed in the Appendix (locality 1). The writer identified the following genera within the peat: _Pisidium_, _Lymnaea_, _Gyraulus_, and _Valvata_.

Samples of the peat were submitted to Dr. A.E. Porsild of the National Museum of Canada, to Dr. E.S. Deevey Jr. of Yale University, and to the Yale Geochronometric Laboratory. Dr. Porsild identified the peat as mainly sphagnum moss with other mosses, and noted the presence of Larix (Tamarack) cones, but was unable to list all the plants present. Dr. Deevey found that pollen was too sparse for a detailed study without the use of special methods, but he observed some pollen of grasses and conifers. The Yale Geochronometric Laboratory assayed the peat (Y165) for radiocarbon both by the Libby elemental carbon method and by the acetylene method, and arrived at ages of 13,163 ± 1,200 years and 13,200 years respectively 1/.

Assiniboine valley fill

The alluvial fill in the Assiniboine valley was described in Chapter 3 (p. 132-135); a generalized section that represents fossil localities 4 and 6 (Appendix) is shown graphically in Fig. 4-1. A section in a gully about 60 feet deep in SW 13-9-9 W. Prin. (locality 4) is as follows:

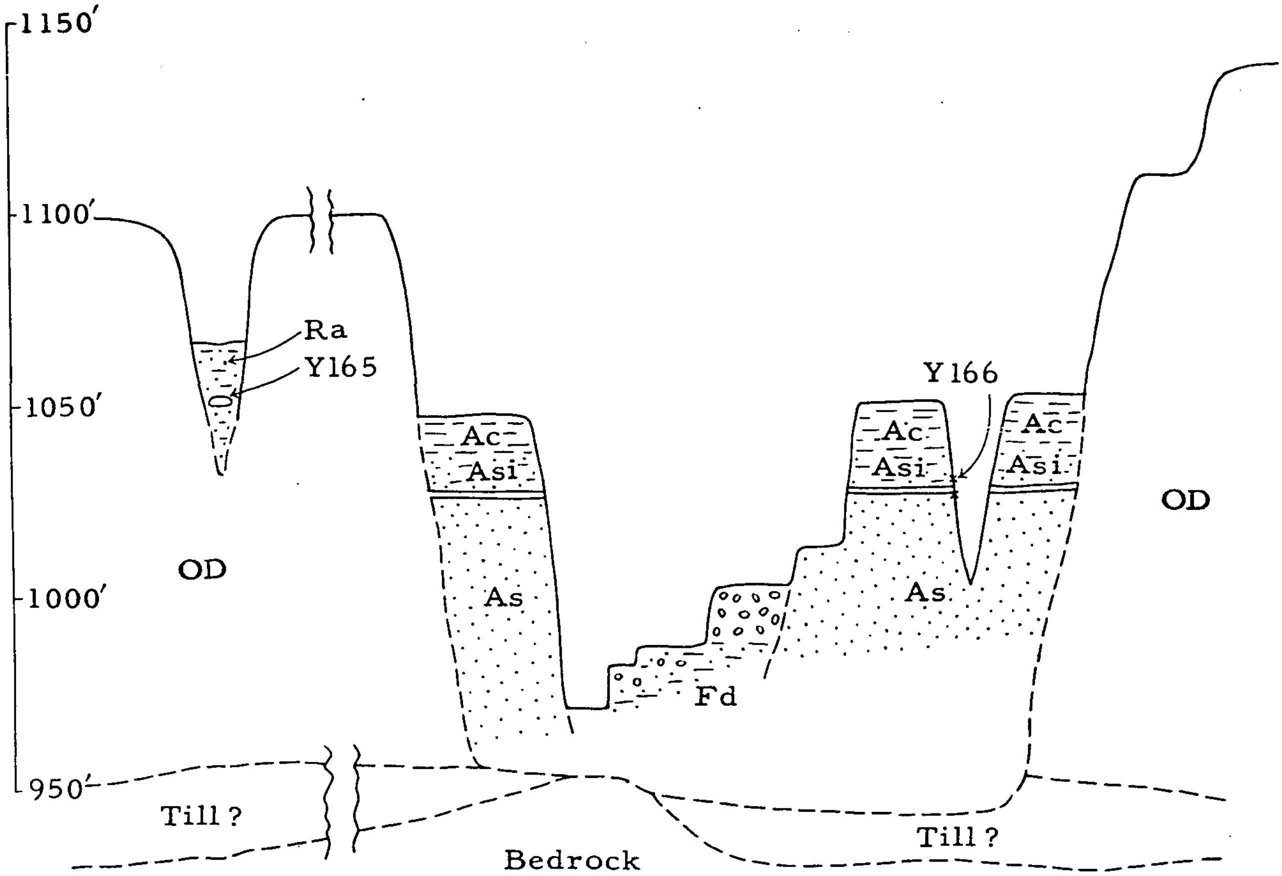
Surface: A flat terrace, altitude about 1,045 feet, with a surface possibly depositional but probably wave-or current washed.

Depth in feet	Description
0-10	Clay, silty gray, weathering buff, with brownish silty partings at intervals of 1-5 to 5 inches; partings thicken toward base of clay, which grades into silt in the basal foot; fragmental grass leaves and stems between some laminae; clay contains two species of clam shells (Anodonta and Sphaerium), both generally

1. Personal communications dated March 16, 1954 and April 6, 1955.

Depth in feet	Description (Cont'd)
	articulated and commonly in positions of growth; clams sparse and thin-shelled in upper part of clay, but common in lower silty part.
10-19	Silt, weathering buff, in beds 2 to 6 inches thick with sand partings that are thin at the top of the silt and as thick as 1 inch at the base; silt is finely crossbedded and grades into sand at base; snail and clam shells common throughout, abundant at the base; clams include Sphaerium and Lampsilis; grass leaf and stem fragments common in basal foot, and cone of spruce or tamarack also found.
19-23	Sand, medium to fine, crossbedded; at 22 feet is a bed of silt 1 foot thick; snail and clam (Lampsilis) shells abundant.
23- ?	Sand, medium, slumped.

The gradation from sand to silt to clay from the base to the top of the section indicates a depositional environment of deepening water and increasing distance from the source of the sediments. The sequence of clams indicates that the water became progressively quieter. Snails, which generally prefer relatively shallow, quiet water, are common in the top of the sand and the base of the silt; they are missing from the upper part of the silt and the clay because, presumably the water was too deep, and from the sand because the current was too rapid. Pelecypods in the deposit include: (1) Pisidium, clams 2 to 4 mm long with a wide range of habitats, found only with the snails in the silt beds; (2) Sphaerium, clams 7 to 20 mm long that generally prefer shallow, clear water, are abundant in the silt and common in the basal part of the clay but are not found above the middle of the clay; in the clay the shells are thinner than they are in the silt, suggesting an inadequate supply of carbonate, perhaps due to reduced water circulation; (3) Lampsilis, a thick-shelled clam generally 7 to 10 cm long, that prefers a stream



Older Assiniboine delta (unfossiliferous)		OD
Lake Agassiz II (or III?)	clay, laminated	Ac
do.	silt, laminated	Asi
do.	sand	As
Young Assiniboine River alluvium		Fd
Alluvium in gully near Rossendale		Ra
Rossendale peat sample		Y165
Assiniboine valley shell sample		Y166

Note: The Rossendale peat and alluvium is in a gully about 1 mile west of the Campbell scarp.

Figure 4-1
Diagramatic cross section of part of Assiniboine delta showing relationship of Rossendale and Assiniboine Valley fossil localities.

Horizontal scale about 2 inches to 1 mile habitat is common in the sand and also occurs in the lower half of the silt. Shells from the sand were submitted to the Yale Geochronometric Laboratory for radiocarbon assay (Y166) by the Libby method, and gave an age of 11,160 ±940 years. (4) <u>Anodonta</u>, a clam 10 to 15 cm long with a very thin shell and having a preference for a quiet lacustrine habitat, is found only in the clay. The sequence of mollusks indicates that there were fairly strong currents when the sand was deposited and that the water became quieter and possibly, though not necessarily, deeper as the silt and clay were deposited. The general paucity and thinness of the shells in the clay may be due partly to colder water as well as to reduced circulation.

The collections from localities 2, 4 and 5 each represent the whole sequence described above.

<u>Radiocarbon dates</u>

The relative positions (Fig. 4-1) of the peat (Y165) and shells (Y166) indicate that the peat represents the erosion interval between Lakes Agassiz I and II, whereas the shells represent the rising phase of Lake Agassiz II. This difference is reflected in their ages, about 13,200 years for the peat and about 11,200 years for the shells. These dates may be compared with a radiocarbon date of 11,283 ±700 years on wood found in shell-bearing Lake Agassiz (II) sediments at Moorhead, Minnesota (Rosendahl, 1948, p. 289-290; Libby, 1952, p. 87, no. C497). The Moorhead wood and the Rossendale shells represent the rising phase of Lake Agassiz II whereas the Rossendale peat may represent an interval when the lake basin was dry or nearly dry.

The radiocarbon dates appear to leave insufficient time for ice retreat from Iowa, where radiocarbon dates representing the late Cary ice advance range from 12,120 ±530 to 13,300 ±900 years ago (Ruhe and Scholtes, 1955, p. 91, nos. C912 and C913), formation and drainage of Lake Agassiz I and formation of Lake Agassiz II, all by 11,200 years ago. If full advantage is taken of the possible error in the assay of the Rossendale peat, the erosional interval between Lakes Agassiz I and II occurred about 12,000 years ago. If full advantage is taken of the possible errors of the dates in Iowa, the late Cary advance may be placed at about 12,600 years ago. This allows 600 years for the history of Lake Agassiz I, which involved an initial ice recession of about 650 miles and a minor advance and retreat of, probably, less than 100 miles (Chapter 6, Fig. 6-2).

Flint (1955) showed that in Alaska ice-margin retreat by calving have been as great as 1 mile per year; he calculated overland retreats of continental glaciers at rates of from about 250 to 500 feet per year. Advances of as much as 1 mile per year have been observed in Alaska but it is doubtful if advances of outlet glaciers from ice fields can be compared to advances of ice sheets. If all the retreats and advances of glaciers in the Lake Agassiz basin occurred at the fastest rates mentioned by Flint, 850 years would be required for events that radiocarbon dates show to have taken place in 600 years; this does not take into consideration overland retreat which is generally about 10 times slower than retreat by calving. Clearly, more data are needed.

FOSSILS IN YOUNGER ALLUVIUM

General occurrences

Gastropods collected from recent alluvial deposits (localities 18 to 28) are discussed later in this chapter.

Locality 26 (NW 24-8-9 W. Prin.) is in a shallow abandoned channel that may have been in use during the Campbell phase(s) of Lake Agassiz and now contains at least 3.5 feet of Carex peat. Mr. H.G. Ignatius examined the peat but found the content of inorganic matter too high for pollen studies without the use of special methods; he found the following forms by cursory inspection:

Pollen: *Pinus* (*banksiana*?), *Picea*, *Graminae*, and *Cyperaceae* (?).
Diatoms: *Epithemia turgida*
Sponge spicules: *Ephydatia*?

This locality has been a marsh within historical time. Unfortunately it was not possible to have the vertical sequence of peat specimens studied.

Locality 23 (SW 31-6-6 W. Prin.) is alluvium 12 feet below the surface of the flood plain of Boyne (Morris) River, and is connected to locality 26 by the river. There is little similarity in the fauna because locality 26 represents a shallow lake or marsh whereas locality 23 represents a stream environment. Fragments of wood at locality 23 were not identified; one fragment bore tooth marks, probably of beaver. Specimens of *Lampsilis* and *Sphaerium* collected here were inadvertently omitted from the faunal lists (Appendix).

Pembina trench

The fossil localities in Pembina trench (nos. 7 to 12) are described in the Appendix and discussed later in this chapter. It should be emphasized that localities 7, 8 and 9 are in a single river cut and represent the stratigraphy of an alluvium older than the present flood plain deposits (localities 10, 11, and 12) and younger than the "older" alluvium (valley fill, p. 130-132). Only gastropods were collected; but fragments of bone, probably Bison bison, are common.

Cypress River alluvial fan

The alluvial fan of Cypress River (p. 128-129) forms an equilateral triangle about 27 square miles in area located mostly in township 6, range 13. The fan slopes north and west from an altitude of about 1,300 feet at the apex, in section 18-6-12 W. Prin., to about 1,230 feet at the distal margin, and is mostly higher than the strandlines of Lake Agassiz I. Cypress River flows northward just east of the western boundary of range 12, in a channel that has been artificially straightened. The channel is from 4 to 12 feet deep, and the alluvium of the fan are well displayed in its banks (Fig. 4-2). These sediments vary greatly, but have the following general stratigraphy:

Thickness in feet.	Description
1-6	Silt, sandy, poorly sorted, containing abundant snail shells (localities 16 and 17); humified soil zone on surface is 15 to 20 inches thick, leached to a depth of about 12 inches; silt locally overlies

Figure 4-2. Bank of Cypress River on south side of road at NE 18-6-12 W. Prin., showing buried soil zone in sandy silty alluvium. The present soil, indicated by a yard-stick, is overlain by about 3 feet of backfill, and is leached about 12 inches. A lower soil zone, indicated by a foot-rule, is leached 3 to 8 inches. Fine sand and gravel are seen below the trenching tool at the base of the lower silty alluvium.

Thickness in feet.	Description (cont'd)
	medium to fine shale pebble gravel that forms channel fillings and locally contains logs and clam shells.
0-2	Horizontal lenses of sandy silty clay containing snail shells and small lenses of charcoal less than 5 mm thick; clay lenses commonly replaced by lenses of gyttja as thick as 6 inches or of Carex peat as thick as 1.5 feet; peat is rich in inorganic matter and snail shells; clay also replaced by humified soil zone 6 to 8 inches thick, leached 3 to 8 inches, formed on underlying alluvium; snail shells abundant except in soil (localities 14 and 15); bones of Bison bison common.
2-6	Sand, clayey silty, poorly sorted, containing sparse snail shells (locality 13) and bison bones; locally cut by gravel-filled channels of same age as upper alluvium.
2-?	Gravel, fine pebble (shale), and sand, poorly sorted; north-dipping crossbedding; not observed throughout fan.

At three places the alluvium below the buried soil-gyttja-peat horizon rests on lenses of till as thick as 6 feet that overlie proglacial (?) sand and gravel. Elsewhere the basal beds are buff-colored laminated silt, probably of glacio-lacustrine origin.

The gastropods in the alluvial fan are listed in the Appendix following Chapter 6 and are discussed later in the present chapter. Bones in and above the buried soil horizon were identified as Bison bison by Dr. J.T. Gregory of Yale University, Mr. H. Schwartz, of the Ottawa Forest Products Laboratory, identified wood from the base of the gravel channels as oak, and from the buried soil-gyttja-peat horizon as oak, willow, and poplar or willow. The peat contains much inorganic matter; Dr. Deevey observed pollen of pine, grasses, sedges, artemisia, achenopod, cat-tail, and Ericaceae in it and inferred that the flora represent a climate that was no colder than the present one.

The following sequence of events is inferred from the sediments and fauna in the Cypress River alluvial fan (the gastropod fauna are discussed below): (1) Formation of a small glacial lake in which there were minor advances of a retreating ice margin. (2) Rapid deposition of fine gravel and sand during a very humid interval after the glacial lake drained but before clams populated the region. (3) Deposition of sandy silty alluvium during a humid interval when snails and bison populated the area. (4) A dry interval, with little or no deposition of alluvium, during which a soil formed, and snails and bison lived in the area; the climate may have been warmer than at present. This interval may have been the altithermal. (5) A moist interval during which the upper sandy silty alluvium was deposited; the climate may have been slightly more humid than it is at present.

MOLLUSKS OF THE TIGER HILLS REGION

Introduction

Early studies

The only work on Pleistocene fossils near the Tiger Hills region is that of Mozley (1934). He observed no fossils in the immediately-postglacial deposits, but found that the region was populated by mollusks from the Mississippi River. The southern mollusks were trapped in the Lake Agassiz drainage basin when Lake Agassiz abandoned its southern (Lake Traverse) outlet and broke the connection with the Mississippi River system. The gastropoda in Lake Agassiz deposits represent a mixture of terrestrial and freshwater habitats. Although early Lake Agassiz contained no mollusks, a later phase of the lake (Lake Agassiz II) contained the full assemblage now living in the region.

Mozley presented the most complete list of Lake Agassiz fauna to date, but unfortunately his descriptions of the fossil localities are inadequate to establish their exact stratigraphic positions. His theory of the isolation of the northern fauna apparently does not take into account that spring freshets in the Lake Traverse area often make a water connection from the Gulf of Mexico to Hudson Bay (Dawson, 1875, p. 252).

Present studies

The mollusks in and near the Tiger Hills region are listed in the Appendix (following Chapter 6); the faunal tables are preceded by descriptions of the fossil localities. The mollusks are listed alphabetically by genera; although most convenient for the present discussion, this listing is undesirable in that closely related genera may be separated as are *Menetus* and *Promenetus*, and *Armiger* and *Gyraulus*. The last two are grouped under *Gyraulus* by some workers.

Because the collections are small and the localities few the inferences that follow are only working hypotheses. None of the mollusks are extinct, and all should be represented somewhere in sediments deposited since their arrival in the area. That they are not is a matter of ecology: some of the snails in Lake Agassiz II sediments (*Amnicola*) are absent from younger deposits because they require the shallow, open water conditions of large lakes (e.g. Lake Manitoba). The apparent lack of certain earlier genera in younger sediments suggests that the collections are inadequate; hence, the writer has not attempted to make several correlations that at first sight may seem obvious to the reader.

The zoologists who identified the fossils applied different species names to genera collected in similar localities, so the writer chose to base his conclusions on genera rather than on species. It is hoped that future work will make possible correlations based on species.

Pelecypoda

Pelecypods (clams) without their soft parts are very difficult to identify, so little effort was made to collect these shells. However, four genera comprising at least 5 species were identified; the collections are inadequate as a basis for inferences.

Gastropoda

There are 24 genera of gastropods in the Tiger Hills region, comprising at least 56 species. Of these genera 13 are freshwater types and 11 are terrestrial types. The terrestrial snails proved to have stratigraphic value whereas the freshwater snails did not.

Freshwater gastropods

The 13 genera of freshwater gastropods comprise at least 35 species (Appendix following Chapter 6). They are discussed below in groups of occurrences arranged in chronological order as far as possible.

Lake Agassiz II fauna:

Deposits of Lake Agassiz II in the Assiniboine valley (Localities 2 to 6) contain seven genera of freshwater snails, represented by at least 14 species. This fauna differs from others in the Tiger Hills region in that it contains an abundance of individuals of the genus *Amnicola*, not found in other deposits; at least four species of this genus are present. *Amnicola* generally prefers fairly shallow, quiet but not stagnant water such as occupied the flooded Assiniboine valley; it lives in Lake Manitoba at present. *Amnicola* does not occur in the younger alluvium in the Tiger Hills region because there have been no suitable habitats since the draining of Lake Agassiz II.

Genera found in younger alluvium but missing from Lake Agassiz II deposits are mainly stagnant-water types, and include *Aplexa*, *Ferrissia*, *Menetus*, *Promenetus*, and *Physa*.

Transitional fauna following Lake Agassiz II:

The alluvium at locality 1 resulted from the rise of Lake Agassiz II to the Campbell strandline; the gully in which it was deposited has no alluvial fan at the Campbell scarp, which indicates that alluviation probably ceased before Lake Agassiz subsided from the Campbell scarp: however there is no conclusive evidence that minor deposition has not occurred in the gully during more recent humid intervals. The collection may partly represent fauna younger than that of localities 2 to 6.

Eight genera comprising 10 species have been identified. The only genus at locality 1 that is absent in the Assiniboine valley fill is Promenetus, a pond snail. Locality 1 contains fewer species of Amnicola, Lymnaea, Planorbula and Valvata than the other Lake Agassiz deposits, and more species of Stagnicola. These differences are the result of differing habitat requirements of the snails.

Pembina trench, younger alluvium:

Localities 7 to 10 represent progressively younger deposits of "younger" alluvium, and contain four genera comprising five species of freshwater gestropods. Locality 7, the oldest, contains one genus, locality 8 one genus, locality 9 three genera and locality 10 two genera. The differences are probably partly due to small collections.

Locality 11 corresponds to locality 10 stratigraphically but contains no freshwater gastropods. Locality 12 is about 60 miles upstream from localities 7 to 10, in an alluvial fan rather than in a flood plain, and it may correlate with either locality 9 or locality 10; three species representing three genera are present.

There appears to have been an increase that was followed by a decrease in the number of species of freshwater gastropods in Pembina trench. This variation may represent a change in stream velocity caused either by climatic variations or by a change in stream gradient.

Cypress River alluvial fan:

Locality 13 represents the lower alluvium of the

Cypress River alluvial fan, and contains two genera comprising two species of freshwater gastropods.

Localities 14 and 15 represent the buried soil-gyttja-peat horizon on the lower alluvium. Three species of freshwater gastropods represent three genera; as might be expected, most of the gastropods in this horizon are terrestrial types.

Localities 16 and 17 represent the upper alluvium and contain six genera represented by at least eight species.

The freshwater snails in the Cypress River fan are all pond or quiet water types, whereas the Lake Agassiz snails are open water types. The increase from two species in the lower alluvium to eight in the upper alluvium suggests a considerable difference in the age of these alluvia. The collections are inadequate for correlation with other deposits.

<u>Recent alluvial fans</u>:

Alluvial fans in the Lake Agassiz basin are represented by localities 18 to 21. The fauna is mainly terrestrial, as might be expected; however, five genera of freshwater gastropods are represented by as many species.

Locality 22, a similar alluvial fan north of Assiniboine River, contains only two genera (and species).

Locality 23 represents alluvium deposited in Morris River valley shortly after its excavation and may be older than the recent alluvial fans. Five genera are represented by as many species.

<u>Assiniboine River, younger alluvium</u>:

Only one freshwater gastropod was obtained from localities 24 and 25, which represent alluvium deposited before the present flood plain of Assiniboine River was established.

<u>Miscellaneous collections</u>:

Locality 26 represents the fauna of a channel that probably was formed during the Campbell phase of Lake Agassiz I and since has been abandoned except for occasional flooding. Eight genera are represented by 10 species, most of which are quiet water or pond types.

Locality 27 is the floor of Lizard Lake, a shallow lake drained within historical time; only one freshwater gastropod was collected.

Locality 28 represents the surface of the lower Assiniboine delta and the two genera (and species) of freshwater gastropods present may have lived in a shallow pond that was later filled with windblown sand.

<u>Conclusions</u>:

Correlation of alluvial bodies in the Tiger Hills region on the basis of freshwater gastropods is not feasible because (1) the collections are too small and too few and (2) a wide range in habitats is represented.

The fauna of Lake Agassiz differs from other younger faunas in that it contains the genus <u>Amnicola</u>; the gastropods of the Lake Agassiz sediments in the Assiniboine valley prefer a shallow lacustrine environment whereas most of the species at other localities prefer quiet or stagnant water. Lake

Agassiz II and its tributaries contained a freshwater gastropod fauna of eight genera comprising at least 19 species. The present freshwater gastropod fauna of the Tiger Hills Region comprises 11 genera including 31 species; the species now lacking are absent because suitable environments are lacking.

There seems to have been an increase in the number of species of freshwater gastropods in Pembina trench during the early phases of recent alluviation, but the number decreased at the time of a comparatively recent increase in stream velocity.

The number of species of freshwater gastropods in the Cypress River alluvial fan shows a substantial increase from the lower alluvium to the upper alluvium. The lower Cypress River alluvium may correlate with alluvium 6 to 12 feet below the surface of a terrace 30 feet above Pembina River (locality 9).

Terrestrial gastropods

The number of terrestrial gastropod genera increased from three, comprising four species, during Lake Agassiz II time to 11, comprising at least 21 species, at present.

Lake Agassiz deposits:

Three genera of terrestrial gastropods are represented by four species in the alluvial fill of Lake Agassiz II in the Assiniboine valley (localities 2 to 6).

Transitional deposit after Lake Agassiz II:

Alluvium overlying peat (locality 1) buried as a result of the rise of Lake Agassiz II contains four genera (and species) of terrestrial gastropods. The genera Gastrocopta and Vallonia, occurring in Lake Agassiz II sediments, are not in the collection from locality 1. If they are present in the alluvium, as might be expected in a larger collection, six genera would be present in late - or post - Lake Agassiz II deposits.

Pembina trench, younger alluvium:

The numbers of genera and species of terrestrial snails in Pembina trench are as follows:

Locality	Genera	Species	Cumulative Genera	Cumulative Species
12 (youngest)	1	1	7	9
10 and 11	6	7	7	9
9	2	2	6	7
8	5	5	6	7
7 (oldest)	3	4	3	4

There is a general increase in the number of genera from three in the oldest to six in the youngest beds of the younger alluvium in Pembina trench. The number of species increases from four to nine. The basal alluvium may be as old as, or slightly younger than, the Lake Agassiz II alluvial fill in the Assiniboine valley. Conditions were apparently unfavourable for the deposition of terrestrial snails when the alluvium of locality 9 was deposited.

Cypress River alluvial fan:

The lower alluvium in the Cypress River fan contains one species of terrestrial gastropod and the upper alluvium contains two species, each of different genera. The buried soil-gyttja-peat horizon contains six genera (six species) a number that might be expected in a non-aquatic depositional environment. The numbers of species in the alluvia are probably not fully representative of the numbers living in the area at the time, and the increase in numbers from older to younger alluvia may be partly accidental. It is assumed that the terrestrial snails in alluvium from much larger watersheds (e.g. the Pembina or Assiniboine watersheds) are more fully representative.

Recent alluvial fans:

Localities 18 to 21 represent the most recent alluvium in the Tiger Hills region, and contain eight genera of terrestrial gastropods composed of 11 species. Locality 22 is primarily aquatic and yielded only one species of terrestrial gastropod. Locality 23, representing alluvium somewhat older than localities 18 to 21, yielded six genera (six species).

Assiniboine River, alluvium (younger):

Locality 25, representing "younger" alluvium older than the present flood plain of the Assiniboine River, yielded seven genera (seven species); this fauna is similar to that of the late recent alluvium in Pembina trench (Localities 10 and 11).

Miscellaneous

Locality 26 is transitional between an aquatic and terrestrial environment and contains one terrestrial gastropod (*Succinea decampii Tyron*).

<u>Conclusion</u>

Because of the small size of the collections and the few localities represented, the following conclusions are working hypotheses rather than facts:

The terrestrial gastropod fauna migrated into the Tiger Hills region more slowly than did the freshwater gastropod fauna. The genera may have arrived in approximately the following order, as inferred from the stratigraphy of the Assiniboine valley alluvial fill, Pembina trench alluvium, and Cypress River alluvium:

1. <u>Discus</u>, <u>Gastrocopta</u>, and <u>Vallonia</u>, all found in the Lake Agassiz II fill in the Assiniboine valley.
2. <u>Zonitoides</u> and <u>Retinella</u>, occurring near the base of "younger" alluvium in Pembina trench, in late-or post-Campbell phase Lake Agassiz II deposits, and in the lower alluvium of the Cypress River fan.
3. <u>Cionella</u>, <u>Deroceras</u>, and <u>Hawaiia</u>, characteristic of the buried soil-gyttja-peat horizon of the Cypress River alluvial fan.
4. <u>Succinea</u>, <u>Carychium</u>, and <u>Helicodiscus</u>, all characteristic of the most recent alluvium.

The basal "younger" alluvium in Pembina trench and the lower alluvium of the Cypress River fan may be contemporary deposits, and both apparently post-date the Campbell phase of Lake Agassiz II; they are characterized by the appearance of <u>Zonitoides</u> and <u>Retinella</u>. Morris River eroded its valley during the deposition of the lower alluvium of the Cypress

River fan, and deposited alluvium during the interval of soil-formation on the Cypress River alluvial fan[1], characterized by the appearance of Cionella and Hawaiia. This may represent an interval of low precipitation, perhaps the altithermal 4,000 to 6,000 years ago (Flint, 1947, p. 487). This apparently was an interval of little or no deposition in Pembina trench, where Cionella, Hawaiia and Deroceras are missing from the section. A more humid climate followed the altithermal and has continued to the present, and is characterized by the appearance of Succinea, Carychium, and Helicodiscus.

In the foregoing discussion no attempt has been made to evaluate the effect of different environments which, as in the case of freshwater fauna, must effect the species represented in the deposits. The effect is less marked in terrestrial than in aquatic species because all terrestrial environments are generally represented somewhere along a river and the terrestrial snails are washed into the alluvium.

HUMAN OCCUPATION OF SOUTHERN MANITOBA

Introduction

The use of artifacts as index fossils is a procedure that makes any archeologist feel ill at ease, because he

1. The apparent anomaly that Cypress River was depositing an alluvial fan while Morris River was cutting its valley deeper is due to the different situations of these features. Cypress River alluvial fan is on a nearly flat area north of the Tiger Hills where the stream gradient decreases rapidly. Morris River has a uniform gradient. The upper part of Cypress River was cutting its valley deeper at the same time as was Morris River. Morris River alluviated its valley when a decrease in precipitation reduced its discharge and, hence, its power to transport sediment.

generally looks to the geologist to determine the stratigraphic positions of cultures, and he prefers to have early cultures better represented than they are in Manitoba. The advent of radiocarbon dating has done much to establish cultural sequences formerly in doubt, and the data from stratified occupation sites, supplemented by less reliable surface finds, are now adequate for tentative application to some geologic problems.

For many years studies of early man (preceramic cultures) in North America centered in southwestern United States. The results of these studies were summarized by Dr. H.M. Wormington (1949) who gave her discussion a geographic organization. MacGowan (1950) published an excellent popular account of the subject and in a similar account Sellards (1952) illustrated the artifacts that form the basic data. Martin, Quimby, and Collier (1947) provided a necessary link between early man and historical times by their treatment of the ceramic cultures. Hurt (1953) applied all the available radiocarbon dates and organized a stratigraphic sequence of human cultures that extends back about 12,000 years.

The writer is indebted to Dr. R.S. MacNeish, of the National Museum of Canada, who introduced him to archeology on the Canadian Prairies and who provided almost all of the information presented here (most of it as yet unpublished). The writer has applied less caution in some of his speculations than was advocated by Dr. MacNeish, and accepts full responsibility for oversimplifications, errors, and misconceptions.

Early man in southern Manitoba

The cultural sequence in southern Manitoba is presented in Table 4-1 and the areal distributions of the significant preceramic cultures are shown in Fig. 4-3. Ceramic cultures and the preceramic Larter focus (culture) are distributed throughout southern Manitoba and have little geological significance.

Pre-Larter cultures, with the exception of one occurrence of a Lake Shore-type culture (Whiteshell focus) on Winnipeg River, all are found outside the basin of Lake Agassiz II (Campbell phase). The Winnipeg River occurrence is at a higher altitude than the lower levels of Lake Agassiz II. It is inferred that Lake Agassiz II (Campbell phase) lasted through the pre-Lake Shore cultures and that the lake was subsiding in Lake Shore time.

Lake Shore culture is poorly represented except at the type locality in Pembina trench at Rock Lake. The main site is on the north side of the valley floor (Vickers, 1949, p. 4), indicating that there was not very much more water in the valley in Lake Shore time than there is at present.

The Agate Basin ("Long") culture is the best represented of the older (preceramic) cultures. Several projectile points were found beside gullies eroded in the Assiniboine delta before and during the Campbell phase of Lake Agassiz II. It is believed that the gullies may have contained streams that provided water for human occupation.

A break in the typological sequence of artifacts

Table 4-1. Human occupation of southern Manitoba.

Culture	Dates: Sample number and age in years	Distribution and remarks
Ceramic cultures		
Selkirk focus	1750 A.D.; beginning not known	Southern Manitoba; equivalent of early Cree and Assiniboine; represents Final Woodland culture.
Winnipeg and Manitoba foci	no dates	Southern Manitoba; represent Late Woodland culture.
Lockport focus	C722 - 2,150; C126, 137, 139 C152 - 2,300 to 1,950	Southern Manitoba; abundant in Lake Agassiz basin; represents Middle Woodland culture.
Preceramic cultures		
Larter focus	C723 - 2,700 C668 - 2,800	Widespread in Manitoba; resembles Signal Butte Ic; represents Early Woodland culture.
Lake Shore	L104A - 3,400	Sparse distribution west of Lake Agassiz II; one occurrence in the lake basin at an altitude of about 960 feet; similar to early Signal Butte Ia
Typological gap	5,000?	Altithermal in early Lake Shore time?
Agate Basin (Long site)	C604 - 7,000 C454 - 7,700	Fairly common west of Lake Agassiz II but not found within the lake basin; also found east of Lake Agassiz II.
Plainview	C604 - 7,000 C454 - 7,700 C471 - 9,500 C470 -10,500	Sparse west of Lake Agassiz II, not found within the lake basin; occurs on middle Lake Algonquin III strandline north of Lake Superior.
Yuma cultures: Scotsbluff and Eden Valley	C471 - 9,500	Sparse sites west of Lake Agassiz II, not known within the lake basin; Eden Valley artifacts rare.
Folsom	C558 - 9,800	One occurrence west of Lake Agassiz II in the basin of glacial Lake Souris.

occurring between the Larter and Agate Basin cultures is only partly filled by the Lake Shore culture. There seems to be a similar gap in eastern North America. In the southwest the gap is filled, in part at least, by the early Signal Butte culture (1a), which MacNeish compares to Lake Shore. The restricted distribution of Lake Shore artifacts in Manitoba suggests that conditions at that time may have been unfavourable for human occupation. The sites are all close to or in valleys whereas other preceramic sites are not so restricted. It is speculated that a dry interval, possibly the altithermal, occurred during Lake Shore time. (Table 4-1).

Dr. MacNeish found Agate Basin artifacts at Fort Laird and Champagne in the Northwest Territories; they are uncommon in Alberta and Saskatchewan. It is speculated that there may have been a migration route along the border of the Canadian Shield and the west side of Lake Agassiz following the spread of _Bison occidentalis_ (see below).

Plainview points were found by MacNeish (1952) on the northwest shore of Lake Superior at an altitude of 832 feet. They were on a beach ridge of Lake Algonquin III, probably part of the Tofte shoreline described by Sharp (1953) although it may be about 30 feet lower in altitude. Flint and Deevey (1951, p. 283) showed that Lake Algonquin III existed more than 4,930 years ago, and Zumberge and Potzger (1955) stated that Lake Algonquin ended 8,000 years ago (M288). Plainview artifacts have been dated by radiocarbon as about 9,500, 7,700, and 7,000 years old (Table 4-1).

Hence, both the artifacts and the radiocarbon dates indicate that Lake Agassiz II (Campbell phase) was at least partly contemporary with Lake Algonquin III. One may speculate that Lake Agassiz II flowed eastward into Lake Chippewa about 5,000 years ago (M290) before finally draining northward into Hudson Bay.

All the preceramic sites in Manitoba indicate that the occupants were hunters of bison. Bison horn cores, now in the Manitoba Museum at Winnipeg, were collected from the Assiniboine delta north of Treesbank and were identified as _Bison occidentalis_, an extinct species, by O.P. Hay. Yuma, Plainview, and Agate Basin projectile points were also found in the vicinity, and suggest that the bison remains may be 7,000 to 10,000 years old. Skinner and Kaisen (1947, p. 157, 171, Map 2, p. 156) stated that _Bison occidentalis_ lived in late Pleistocene time and developed into the present race that occupies the plains, _Bison_ (B.) _bison bison_. All other bison remains associated with artifacts appear to be the latter living species.

Conclusion

Artifacts of preceramic cultures ranging from Folsom to Lake Shore (early Signal Butte?) are found west of but, with the exception of one Lake Shore site, not within the basin of Lake Agassiz II. It is believed that Lake Agassiz II existed throughout these cultures and that it stood at the level of the Campbell strandline until Lake Shore time. The paucity of Lake Shore sites suggests either a short occupation or a small population due to adverse climatic conditions, possibly during the altithermal 4,000 to 6,000 years ago. The preceramic Larter culture post-dates the Lake Shore culture and is distributed throughout southern Manitoba, including the basin of Lake Agassiz II. It is inferred that the lake was drained during Lake Shore time.

Lake Agassiz II is tentatively correlated with Lake Algonquin III on the basis of Plainview cultural material and radiocarbon dates; both lakes existed about 8,000 years ago.

GENERAL CONCLUSIONS

Pleistocene fossils are generally sparse in the Tiger Hills region, but form the basis for the following working hypotheses and the correlations summarized in Table 4-2.

Spruce cones under 90 feet of drift on Turtle Mountain may represent the Peorian interglacial interval; it is not known whether the striated boulder pavement in this area correlates with the Peorian interval or is considerably younger.

Deposits of Lake Agassiz I are barren of fossils; freshwater mollusks from the Mississippi River system entered the area through Lake Agassiz II by way of the Lake Traverse outlet and expanded rapidly. The freshwater molluscan fauna is essentially unchanged at the present time. Terrestrial snails entered the region slowly and form a stratigraphic sequence (Table 4-2).

Table 4-2. Relationships of faunas, human cultures, and geological events in southern Manitoba. The sequence geological events and fauna and flora were established independently of radiocarbon and cultural data; "adj." means probable error of sample was utilized.

Approximate age in years	Geological events	Fauna and flora	Human culture
C723- 2,700 C668- 2,800	Deposition of the upper alluvium of the Cypress River fan	Appearance of: *Succinea*, *Carychium*, and *Helicodiscus*	Larter ?
L104A-3,400 5,000 (guess)	Draining of Lake Agassiz II during altithermal. Soil formed on Cypress River fan	*Pinus*; appearance of: *Cionella*, *Deroceras*, and *Hawaiia*	? Lake Shore ?
C604- 7,000 C454- 7,700 M288- 8,000	Lake Agassiz II, Campbell phase; Lake Algonquin III	Appearance of *Zonitoides* and *Retinella*; *Bison bison*	Agate Basin Plainview
C558- 9,800 C470-10,000	Lake Agassiz II, Campbell phase	*Bison occidentalis* and *Bison bison*	Plainview, Yuma, and Folsom
C497; Y166 -11,200	Lake Agassiz II, Campbell phase. Two Creeks (Valders) ice advance in Wisconsin	*Larix*; most of present fresh-water mollusks; appearance of *Discus*, *Gastrocopta*, and *Vallonia*	Yuma and Folsom??
Y165-12,000 (adj.)	Subaerial erosion in Lake Agassiz basin	Sphagnum and other moss, Larix, grasses; *Pisidium*, *Lymnaea*, *Gyraulus*, and *Valvata*	none known
?	Lake Agassiz I	not known	
	Altamont moraine		
C912 (adj.) 12,600	Cary maximum		
C528-16,300	Tazewell maximum		
?	Peorian inter-glacial	*Picea mariana*	

A soil-gyttja-peat horizon within the alluvium of the Cypress River fan represents a climatic interval at least as warm as the present climate, and may represent the altithermal about 5,000 years ago.

The geographic distribution of preceramic cultural materials suggests that the Campbell phase of Lake Agassiz II lasted from Folsom into early Lake Shore time (10,000 to 5,000? years ago), that the lake subsided during Lake Shore time (3,400 years ago) and was drained by Larter time (2,700 years ago). The Lake Shore culture may be partly contemporary with the altithermal. Lake Agassiz II (Campbell phase) is correlated with Lake Algonquin III on the basis of Plainview cultural materials and radiocarbon dates.

Radiocarbon dates (C497, Y165, and Y166) indicate that Lake Agassiz II attained its highest level (Campbell phase) about 11,000 years ago.

Chapter 5

PALEO-HYDROGRAPHY

INTRODUCTION

"Paleo-hydrography" is the study of the horizontal and vertical relationships of former drainage systems and lakes. The progress of glacier recession may be revealed by the locations of valleys, abandoned spillways, and glacial lake margins, and by the vertical relationships of valley terraces, spillway floors and inferred levels of former lakes.

As the last ice sheet withdrew from the Tiger Hills region it split into two lobes, one of which retreated northwestward while the other flowed southward in the Lake Agassiz basin, east of the Manitoba Escarpment. Meltwater from the northwestern ice margin flowed eastward through Pembina trench to the west margin of the glacier lobe in the Lake Agassiz basin. Simultaneously, meltwater from a sublobe, north of the Tiger Hills, of the glacier in the Lake Agassiz basin discharged southward across the Tiger Hills into Pembina trench. Hence, Pembina trench forms a key to which the recession of both ice lobes can be correlated by means of abandoned channels, relationships of channel floors to terraces in the trench, and knowledge of the nature of the terraces (whether they are cut terraces or alluvial fill terraces).

The various features are discussed as nearly as possible in chronological order. The writer attempts to show that:

1. Much of Pembina trench originated as an ice-margin feature, but part of it antedates the last glaciation.

2. Several glacial and proglacial lakes in the Souris basin discharged through Pembina trench and are represented by paired terraces.

3. The "delta" formed in the Lake Agassiz basin at the terminus of Pembina trench is probably an alluvial fan deposited between the Manitoba escarpment (Pembina Mountain) and an ice margin, and modified by wave action in glacial Lake Agassiz.

4. While Pembina trench was being excavated the glacier margin retreated northward from the Tiger Hills, ponding several lakes that coalesced to form the Brandon glacial lake. The Brandon lake discharged into Pembina trench through Dry River and then discharged eastward through the Treherne spillway into the Lake Agassiz basin.

5. Paired terraces in the Assiniboine valley represent pauses in the lowering of Lake Agassiz. The lake subsided to a level below the floor of the southern outlet (Lake Traverse, Minnesota) and apparently discharged eastward through a lower outlet and may have drained completely. Subsequently the lake was reformed and the water level again rose so that it discharged through the southern outlet. The lake was finally drained through eastern and northern outlets.

6. Crustal warping deformed the older strandlines of Lake Agassiz more than the younger strandlines. There is

evidence of isostatic adjustment of the earth's crust to the Assiniboine delta.

PEMBINA TRENCH

GENERAL CONSIDERATIONS

Description

In this discussion the term Pembina trench refers to the valley extending from Bunclody (Pl. 6) to Pembina Mountain 4 miles west of Walhalla, North Dakota (Fig. 5-5). Pembina trench winds across the Tiger Hills region from northwest to southeast (Fig. 1-1; Pl. 3). West of La Riviere it is a flat-bottomed ditch 125 to 200 feet deep and 1 to 2 miles wide, containing a few narrow terraces (Pl. 4); east of La Riviere it is locally as wide as 3 miles, from rim to rim, as deep as 450 feet, and contains broad terraces. Paired terraces cut by lateral stream erosion and formed by the surface of an alluvial fill are present, as well as many nonpaired terraces.

Upstream from Souris River gorge the floor of the trench is incised from 75 to 120 feet by Souris River (Figs. 5-1 and 5-9). There are several high-level terraces on the north side of this part of the trench, one at an altitude of about 1,470 feet being well preserved. Later in the chapter (Table 5-1) it is shown that terraces corresponding with levels of lakes in the Souris basin should occur at altitudes of about 1,490, 1,470, 1,460 and 1,435 feet.

The part of Pembina trench between Ninette and the Souris River gorge (Fig. 5-2), called Lang's Valley by Upham

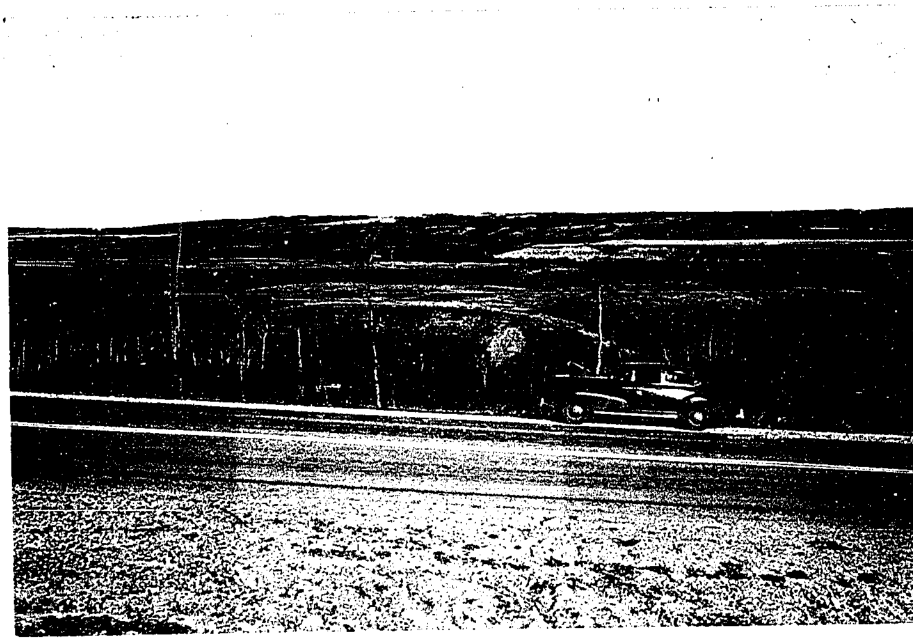


Figure 5-1. View northeast from section 20-6-19 W. Prin., showing the upstream end of Pembina trench. Souris River is out of sight below the cliffs in the middle distance; high level terraces are seen on the north side of the trench; the Tiger Hills - Darlingford moraine forms the skyline.

Figure 5-2. View northwest from NW 20-5-16 W. Prin. showing the part of Pembina trench known as "Lang's Valley".

(1890, p. 22E), has a flat floor as wide as 1.75 miles about 125 feet below the upland surface. Narrow terraces occur high on the north side of the trench. From Ninette to La Riviere the trench is flat-bottomed, steep-sided, from 100 to 200 feet deep, and has a floor about 1 mile wide. The average gradient of the present stream is about 1 foot per mile.

Downstream from La Riviere the walls are less precipitous and Pembina trench is more than 250 feet deep (Fig. 5-3). Its width at the rim ranges from 1 mile at La Riviere to 3 miles northeast of Snowflake and 4 miles near Mowbray. At the International Boundary the trench is 450 feet deep and 2 miles wide at the rim, and is generally V-shaped in cross profile. The average gradient of Pembina River between La Riviere and Walhalla is a little more than 6 feet per mile. The first 8 miles of the trench downstream from La Riviere have a cross profile transitional between the flat-floored, steep-sided trench upstream and the broad-terraced V-shaped valley downstream. The valley sides in the transitional portion are mainly colluvial - and alluvial fans that mask the terraces and preclude the measurement of former stream gradients. From township 2, range 9 to the International Boundary, terraces are well-developed and several are apparent on the map (Pl. 1) with a contour interval of 50 feet.

From section 27-1-7 W. Prin., downstream to Pembina Mountain, 5 miles west of Walhalla (Fig. 5-5) the trench is more than 400 feet deep, is 2 to 3 miles wide at the rim, and

Figure 5-3. View south from La Riviere, looking down Pembina trench. Alluvial and colluvial fans form the valley sides. The present flood plain is in the wooded area in the center of the valley.

Figure 5-4. View of the southeast end of Pembina trench, seen from a point about 5.5 miles southeast of the International Boundary crossing. The cleared areas in the middle distance are terraces, and the Pembina "delta" is in the left distance.

contains well-preserved terraces (Fig. 5-4).

Landslides and slump blocks are especially common downstream from La Riviere because the soft Vermillion River formation is exposed below the more competent Odanah shale.

Problems

Pembina trench connected glacial Lake Souris to the basin of glacial Lake Agassiz. Lake Souris existed before, and its successor, Lake Hind, existed before and, possibly, partly during the highest phases of Lake Agassiz I. The former gradients of Pembina trench were controlled by baselevels afforded by the Pembina "delta" and Lake Agassiz in the east, and by outlet sills of Lakes Souris and Hind in the west. The terraces representing these former gradients are the means of correlating the western lakes and Lake Agassiz. At least three sets of terraces are graded to altitudes at Pembina Mountain that are higher than the known levels of Lake Agassiz. Another set of terraces forms the surface of an alluvial fill that was deposited after the trench had been eroded to a baselevel at least 150 feet lower than the highest level of Lake Agassiz.

The origin of the trench is only partly established; Upham (1895, p. 269) stated that it was preglacial but recent evidence (Pl. 2) shows that much of it is ice-marginal in origin.

Discharge through Pembina trench passed through four phases as the character (glacial or non-glacial) and area of its watershed changed, as follows: (1) Meltwater from about 180 miles of ice margin between Walhalla, North Dakota, and Medora, Manitoba, passed through the trench. (2) Melt-water from an ice margin extending from Treherne, Manitoba, west at least as far as the elbow of South Saskatchewan River (longitude 105°35') discharged through the trench. This ice front was more than 400 miles long and may have been as long as 1,000 miles. (3) The trench next carried runoff (non-glacial) from a watershed of about 22,500 square miles. (4) Present discharge comprises runoff from a water-shed of 2,500 square miles. The first two discharge phases occurred during the recession of the ice sheet. The third phase began when ice recession opened the Qu'Appelle - Assiniboine River system and cut off the glacial source of the Souris - Pembina River system. The final phase (the present phase) resulted from the capture of Souris River by Assiniboine River.

The significance of the terraces in Pembina trench can be appreciated only after its source, a succession of lakes in the Souris basin, and its terminus, the Pembina "delta", have been described. These features lie outside the Tiger Hills region, but reconnaisance work in the Pembina "delta" area and recent mapping (Pl. 6) west of the Tiger Hills region make a summary treatment possible.

SOURCE: THE SOURIS BASIN LAKES

General statement

Five extinct lakes, mainly west and north of the Tiger Hills region, discharged through Pembina trench:

(1) a small lake (the Boissevain Lake) in the present Whitewater Lake basin, north of Turtle Mountain, formed the first lake source of the trench; (2) a glacial lake (the Carroll Lake) at Bunclody, partly contemporary with the Boissevain Lake, subsequently became the main source of the trench; (3) glacial Lake Souris, smaller than generally supposed, next formed the main source of the trench; (4) Lake Hind[1], a smaller successor of Lake Souris, which had little or no ice margin during most of its existence, and occupied the northern part of the Souris basin and discharged into Pembina trench; and (5) the western part of the Brandon glacial lake, which flowed southward into Pembina trench through successive spillways across the Tiger Hills, is in the Souris basin. The second, third and fourth lakes are termed the Souris basin lakes. A resume of the evidence for these lakes is given below: their history is incorporated into Chapter 6 (see also Pl. 7 B to L).

Early concepts

Previous interpretations of glacial Lake Souris (e.g. Upham, 1895, p. 267-272) were based on the premise that an ice margin forming one shore of the lake retreated northeastward. Upham stated that the lake discharged through a southern outlet (Big Coulee) in North Dakota while the ice margin retreated northeastward until a lower outlet, the

1. Named by the writer in honour of Henry Youle Hind (1823 - 1908) who explored southwestern Manitoba (Hind, 1859) and made several contributions to glacial geology (e.g. till fabric) that have been overlooked because of obscure publication.

Pembina valley, was uncovered. Glacial Lake Souris was ultimately drained as the Pembina valley deepened.

Upham based his lake boundaries on topographic evidence and described Lake Souris as much larger than it actually was according to more recent mapping by Johnston (1934) and Lemke (1951), both of whom determined the lake boundaries by lithologic evidence.

Recent mapping

The shorelines of Lake Souris (Pl. 6) are indistinct. In general a layer of poorly sorted silt as thick as 4 feet, with local pebble concentrations at the base, wedges out on ground moraine. Near Pierson the ends of several shallow outwash channels mark the former lake margin, which elsewhere is generally arbitrary and may locally be as much as 2 miles in error. The margin is at a higher altitude in the south than in the north because the lake subsided as the ice margin withdrew northwestward.

Beach ridges and small scarps in township 5 range 23 mark former levels of Lake Souris, and scarps in the Souris - Bunclody area and south of Virden may be former strandlines of Lake Hind. Other evidence of former lake levels is provided by deltas which, however, are commonly difficult to distinguish from alluvial (or outwash) fans.

Early lake deposits in the area outlined by the towns of Souris, Griswold, Kenton, Brawardine, Kemnay and Carroll were reworked by a glacier sublobe from the east, and the problem of distinguishing ground moraine with an attenuated border from the original lake deposits is difficult. Near Alexander and Kemnay the till is unequivocal, but elsewhere the sediments resemble lake deposits although the topography is that of ground moraine and washboard moraine. Some of the numerous shallow depressions may represent former thermokarst features (thaw lakes). The boundary between ground moraine and problematical lake deposits was arbitrarily drawn to fit the margin of an inferred ice lobe that deposited end moraine in township 8, range 20 and township 9, range 21; ice-contact stratified drift in townships 10 and 11, range 23; and end moraine in townships 11 and 12, range 21 (Pl. 6).

Drumlins near Lenore, streamlined ridges and grooves near Medora, and striations on boulder pavements near Dand indicate that the last ice sheet flowed southeast. Minor moraines, washboard moraines, and marginal meltwater channels west and north of Turtle Mountain show that the former ice margin trended northeast as it withdrew northwestward across the Lake Souris basin.

Other indications of northwestward ice-margin retreat are: (1) Gradients of the Dand spillway system slope northeast, and several deltas were deposited in the Carroll lake at the northeast end of the spillway channels. (2) The small glacial lake north of Turtle Mountain first discharged eastward past Boissevain into Pembina River, over sills at successive altitudes of about 1,690 and 1,670 feet, and then discharged westward past Goodlands into Lake Souris, over sills at altitudes of about 1,660 and 1,640 feet. (3) The higher altitude of the Lake Souris shoreline near Waskada and Goodlands (about 1,600 feet) as compared with its altitude near Pierson, Broomhill, and Brawardine (about 1,550 feet) and near Scarth, Virden, and Lenore (about 1,500 feet), can only be explained by northwestward retreat of an ice sheet as the lake subsided because of deepening of its outlet.

The altitudes of the lakes that discharged directly into Pembina trench, with notes on the type of evidence used, are presented in Table 5-1. When Lake Souris expanded northward and began to discharge northeastward through the Dand channel, its level stood at an altitude of about 1,550 feet; before the channel was abandoned the lake subsided to about 1,510 feet near Medora. If it is assumed that the southern outlet (Big Coulee), the floor of which has an altitude of about 1,510 feet[1] was abandoned when the Dand outlet began to function, the southward component of postglacial tilt of the Lake Souris basin amounts to at least 40 feet in about 85 miles, or roughly 0.5 feet per mile. If the altitude of the delta at Scarth is corrected for this tilt, it correlates with the Napinka phase of Lake Hind; and the toe of the scarp south of Virden may correlate with the Lauder phase. The southward tilt from the head of Pembina trench to the Melita, Napinka, and Lauder deltas is about 5 feet, well within the limits of accuracy of the data.

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1. R.W. Lemke, personal communication dated Feb. 8, 1954.

Table 5-1. Altitudes of levels of lakes in the Souris basin and nature of the evidence.

Lake	Altitude of lake level	Nature of the evidence
The Carroll lake	1,520 feet	Delta southwest of Bunclody; margin of area of waterworked till.
Lake Souris	1,490	Strandlines in township 5, range 23; Valley terraces in Pembina trench near Souris River elbow.
Lake Hind		
Melita phase	1,470	Delta northeast of Melita; valley terrace near Bunclody.
Napinka phase	1,460	Delta at Napinka; valley terrace near Bunclody; Scarp in Souris-Bunclody area.
Lauder phase	1,435	Delta northwest of Lauder; head of channel north of Bunclody.

TERMINUS: THE PEMBINA DELTA

Four fan-shaped alluvial bodies along the west side of Lake Agassiz (Fig. 6-1) were called deltas by Upham (1895); from south to north these are the Sheyenne, Elk Valley, Pembina, and Assiniboine deltas. The northeast side of each delta has a steep slope which Upham (Idem.) and Leverett (1932, p. 126) believed to be an ice-contact slope modified by wave action. The Elk Valley delta also has a short end moraine on the lakeward side of its apex (Barry and Melstad, 1928). Upham stated that the deltas contained much outwash deposited directly from the ice margin and that less than half the material in them was contributed by inflowing streams; in fact, there are no inflowing streams of appreciable size that could have contributed to the Elk Valley delta. Leverett challenged Upham's use of the term delta because these alluvial bodies apparently were deposited in reentrants between a glacier and the Manitoba Escarpment, and because they contain a high proportion of glacial sediment.

The Pembina delta (Fig. 5-5) was described by Upham (1895, p. 357-363) and the writer can add little data from two days reconnaisance in the area. The delta has the shape of a fan, one side of which extends southward along Pembina Mountain from an apex 2 to 3 miles north of Pembina River. The "apron" of the fan extends 10 to 11 miles south and southeast. In township 163, ranges 56 and 57, the lakeward side of the fan is a scarp more than 100 feet high that trends southeast, aligned with the Darlingford moraine (Fig. 5-5). The surface

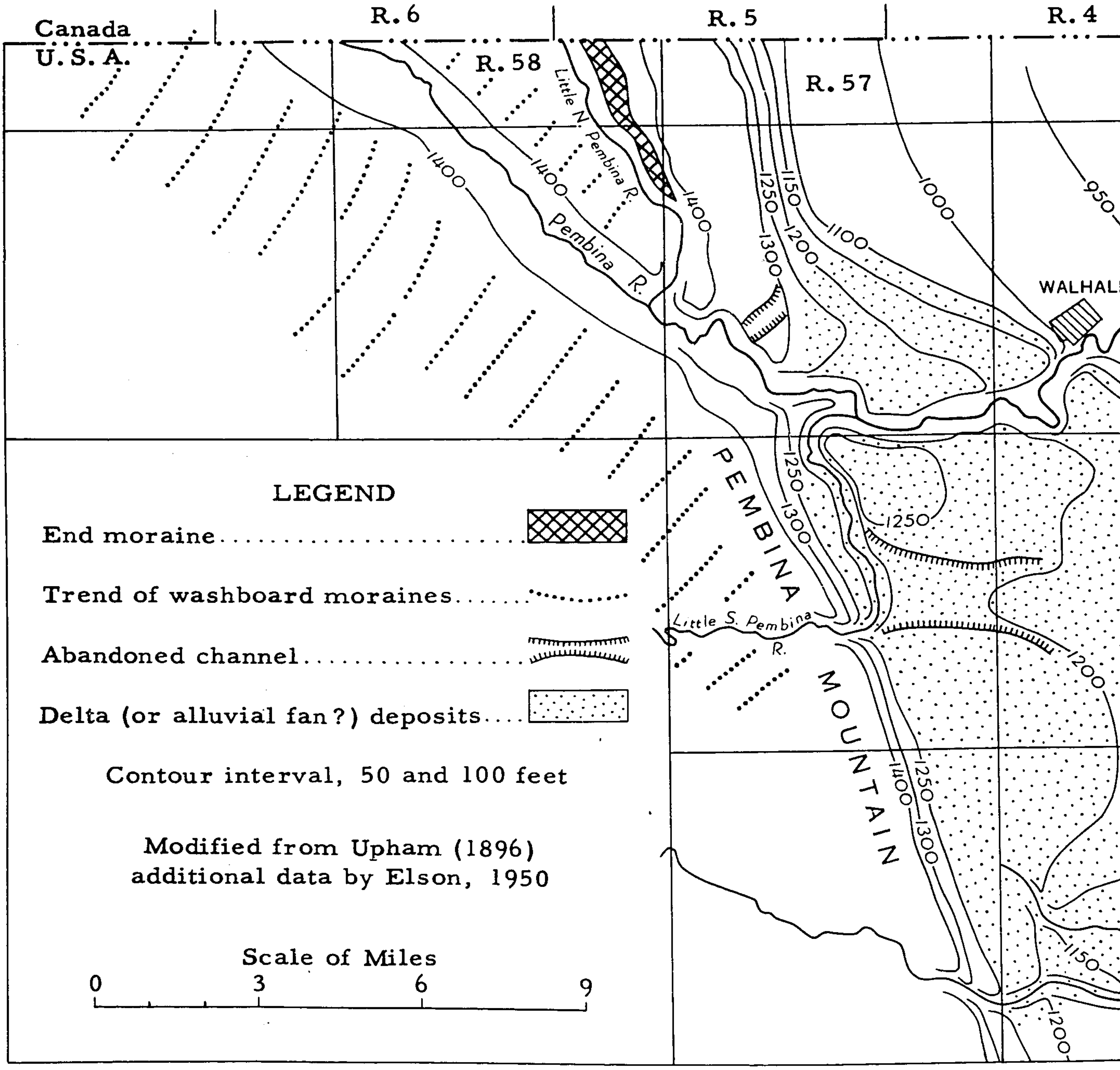


Figure 5-5
Sketch Map Lower end of the Pembina Tre
and the Pembina "delta" in Lake Agassi

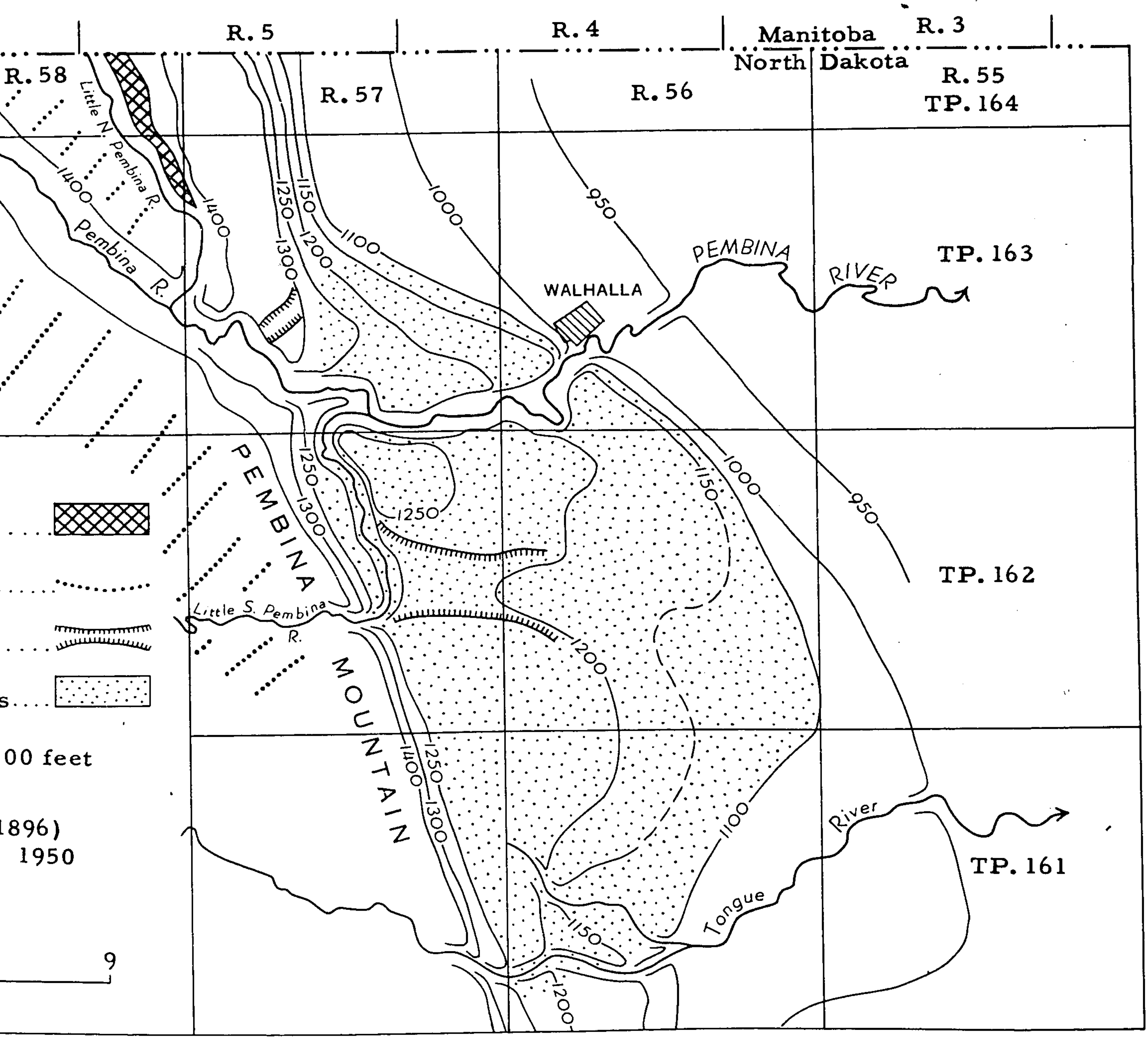


Figure 5-5
Sketch Map Lower end of the Pembina Trench
and the Pembina "delta" in Lake Agassiz

of the fan slopes fairly uniformly southeastward from an altitude of about 1,270 feet at the apex to about 1,100 feet at the southeast margin. The highest strandline of Lake Agassiz in this region is at an altitude of about 1,225 feet. A shallow abandoned channel trends eastward across the fan in township 162, ranges 56 and 57, and probably was once part of Pembina River, to which it is now connected by a north-trending portion of Little Pembina River.

The sediments of the delta are chiefly sand and fine to coarse pebble gravel, apparently more than 100 feet thick. Upham noted about equal proportions of Precambrian, Paleozoic, and Mesozoic rocks represented in the pebbles. There were two sources of sediment: (1) a stream discharging from the glacier margin 1 to 2 miles north of Pembina River, and (2) Pembina trench. The lithologic composition of sediment eroded from the trench, cut into drift and Cretaceous bedrock, would be about the same as that of the delta.

From the alignment of the steep northeast side of the Pembina delta and the Darlingford moraine - a situation analogous to the end moraine on the lake side of the Elk Valley delta - it is inferred that the Pembina delta was deposited in a reentrant between a glacier margin and the Manitoba Escarpment; in this the writer agrees with Upham and Leverett. From the generally uniform southward slopes of both the Pembina and Elk Valley deltas, the apparent absence of foreset slopes, and the apparently great thickness of the topset beds, it is inferred that both "deltas" probably are alluvial fans that were deposited in the Lake Agassiz basin before the lake level rose as high as the Norcross water plane, and were subsequently modified by wave action.

TERRACES IN PEMBINA TRENCH

Introduction

The terraces in Pembina trench are discussed below in chronological order and are grouped according to their common sources or termini. The long profile of Pembina trench (Pl. 5(b)) was measured along the axial line of the valley rather than along the sinuous, underfit stream channel; most altitudes were determined by aneroid altimeter, and several were determined by parallax measurements on air-photos. Several terraces are in the mouths of tributary valleys rather than on the wall of the trench. Time did not permit detailed study of all the terraces. Three interpretations of the data are presented (Fig. 5-6, the favoured hypothesis, and Figs. 5-7 and 5-8).

Outwash terraces

The three highest former gradients of Pembina trench are represented by terraces covered with outwash gravel; all conducted meltwater directly away from the margin of the glacier. The first (highest) spillway headed at an ice margin depositing end moraine about 8 miles northwest of La Riviere and was graded to an altitude of about 1,375 feet at Pembina Mountain. It discharged into an ice-marginal stream that flowed southward along Pembina Mountain when the Elk Valley "delta", 45 miles south, was deposited. The second spillway included the Wood Bay channel and headed at the ice margin that was depositing the Tiger Hills - Darlingford moraine system northwest of Pembina Lake; it was graded to a unilateral spillway on Pembina Mountain at an altitude of about 1,350 feet. The third spillway was the Whitemud Creek spillway (Fig. 5-6). It began as an ice-margin channel west of Killarney, flowed along the ice front as far east as Pembina Lake, and was graded to an altitude of about 1,270 feet at the apex of the Pembina "delta".

Terraces related to the Souris basin lakes

In Table 5-1 it is shown that lakes in the Souris basin had more or less static levels at altitudes of about 1,520, 1,490, 1,470, 1,460, and 1,435 feet. The outlets of the highest of these lakes are not well represented by terraces in Pembina trench because the first channels were relatively small and were destroyed during subsequent erosion of younger, larger channels. From La Riviere 10 miles upstream and 14 miles downstream, no terraces were observed below outwash terraces or above recent terraces; hence, the gradients of the outlets of the Souris basin lakes are conjectural. The picture is further complicated by a nickpoint near La Riviere, above which the resistant Odanah shale has retarded erosion, and by an alluvial fill that is indistinguishable from younger deposits in this part of the trench.

The Carroll lake (altitude 1,520 feet) cannot be correlated with terraces in Pembina trench by means of the present data.

Late Lake Souris (altitude 1,490 feet) is represented by terraces at the Souris River elbow (Fig. 5-9) and north of Ninette, and by the floor of a spillway in township 5, range 6. During this phase of the Souris basin lakes the discharge of Pembina trench reached its maximum and included meltwater from an ice margin extending westward for at least 400 miles; most terrace remnants of the smaller, earlier outlets were destroyed. The Lake Souris outlet apparently was graded to the eroding apex of the Pembina "delta" (alluvial fan).

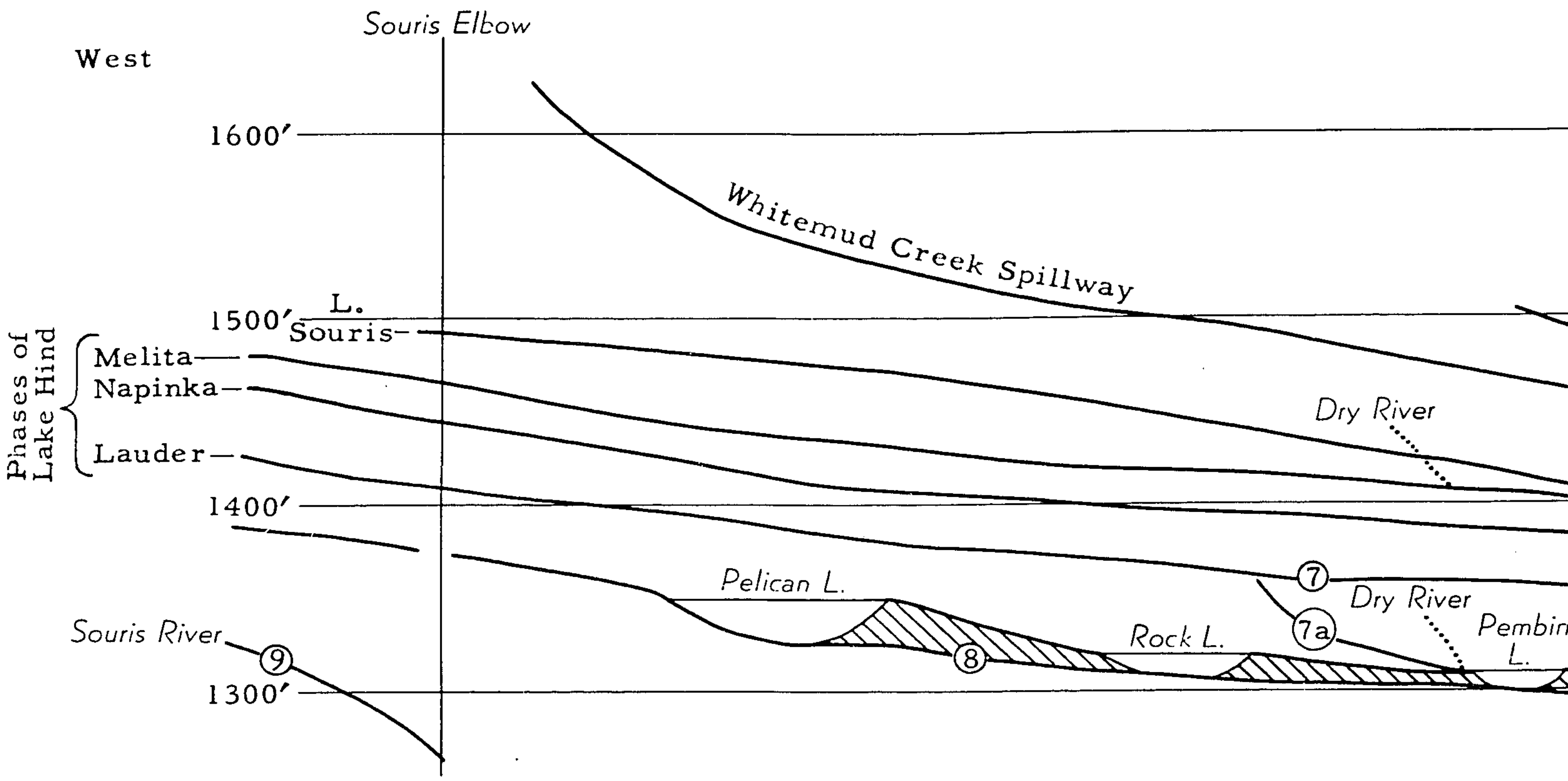
The outlet of the Melita phase (altitude 1,470 feet) of Lake Hind is represented by terraces between Bunclody and the Souris River elbow, and probably by terraces at an altitude of about 1,430 feet in a tributary valley west of Rock Lake. It seems to have been graded to an altitude of about 1,225 feet at the Pembina "delta".

The outlet of the Napinka phase of Lake Hind is the best represented of all the outlets of the Souris basin lakes. Terraces are preserved between Bunclody and the Souris River elbow, at Pelican and Rock Lakes, and at an altitude of about 1,380 feet in a small tributary valley east of Pembina Lake. A former gradient of the Dry River spillway correlates with the Napinka phase outlet, which seems to have been graded to an altitude of about 1,200 feet at the Pembina "delta".

The outlet of the last of the Souris basin lakes, the Lauder phase (altitude about 1,435 feet) of Lake Hind, is represented by a channel cut in bedrock north of the trench at Bunclody, and by several terraces at Rock Lake. The floor of this outlet downstream from La Riviere may be represented by the bedrock surface below the alluvial fill (see below). From the abandonment of a glacial spillway west of Swan Lake (Fig. 5-10) and another at Carroll (Pl. 6; Chapter 6; Pl. 7 J and K) it is inferred that the end of the Napinka phase was marked by general ice-margin retreat from the Tiger Hills - Darlingford moraine. However, this retreat did not open the Treherne outlet of the Brandon Lake (Pl. 7 L and M); the ice margin probably extended generally eastward across the Lake Agassiz basin from the vicinity of Cardinal. The ice supporting the northeast side of the Pembina "delta" near its apex was removed, and the baselevel of the Lauder phase outlet suddenly fell to an unknown altitude below 1,110 feet (the base of the alluvial fill in the trench north of Windygates; p. 131). If the gradient of the bedrock floor between La Riviere and Windygates is extrapolated downstream (Fig. 5-6, terrace sequence no. 7) the unknown baselevel may be inferred to have been lower than an altitude of 1,000 feet.

Alluvial fill terraces

The surface of an alluvial fill in Pembina trench (p. 130-132) slopes from a little above the present floor of the trench at La Riviere to an altitude of about 1,150 feet near the Pembina "delta". The coarse grain-size and large volume of the fill indicate that the discharge of the trench was much greater than at present. The gradient of the surface



Hypothesis 1. (Preferred)

Terrace levels 1 and 2 were graded to ice-marginal channels. The Pembina "delta" (alluvial fan) was deposited between an ice margin and Pembina Mountain before the inception of Lake Agassiz. The base levels of gradients 4 and 5 were the eroding fan apex. The glacier retreated a few miles after phase 6, and the present short valley across the fan formed as Pembina trench eroded to a base level at the foot of Pembina Mountain. Lake Agassiz did not exist. Above La Riviere a youthful valley (7a) eroded headward following a knickpoint in 7. The Dry River spillway was graded to 7a before being abandoned because of glacier retreat opening lower channels north of the Tiger Hills. Advance of a glacier north of Lake Superior blocked eastern drainage and formed Lake Agassiz I. The base level of Pembina trench rose and fell with the phases of Lake Agassiz I. During the rising phase, excavation of the trench continued above La Riviere, but below La Riviere alluviation took place and lasted until the Norcross phase (8). Minor terraces (not shown) correlate with lower phases of Lake Agassiz. The present gradient (9) developed after Souris River was captured by Assiniboine River and tributaries of Pembina trench deposited alluvial fans that form the present lakes.

This hypothesis explains everything, although an ad hoc reason is given for the floor level of the Dry River spillway.

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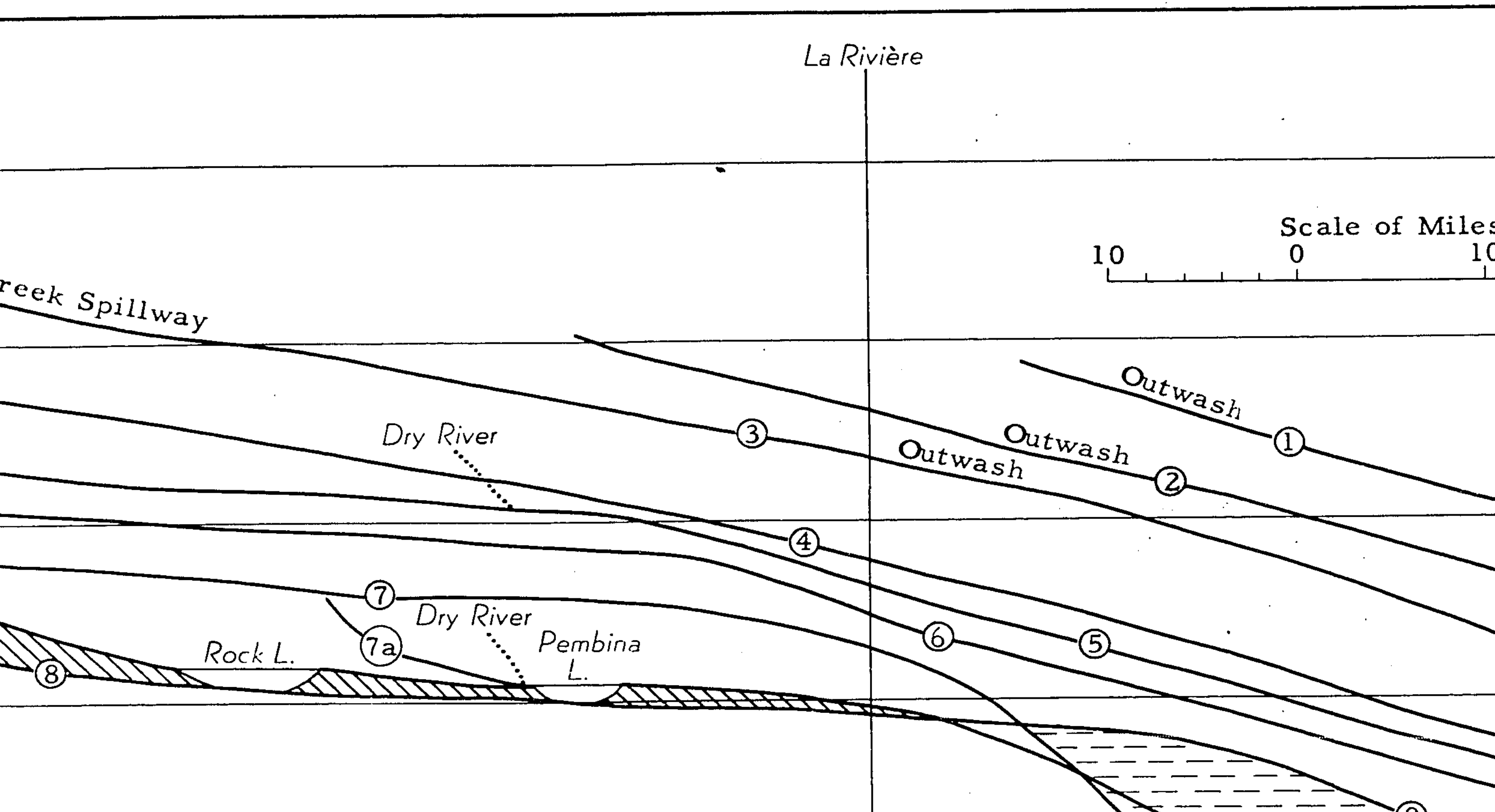

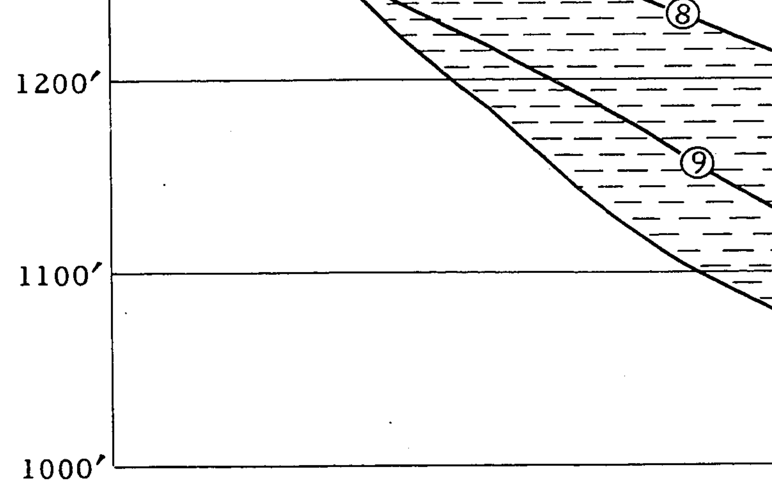

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LEGEND

Alluvium, Cretaceous shale sou

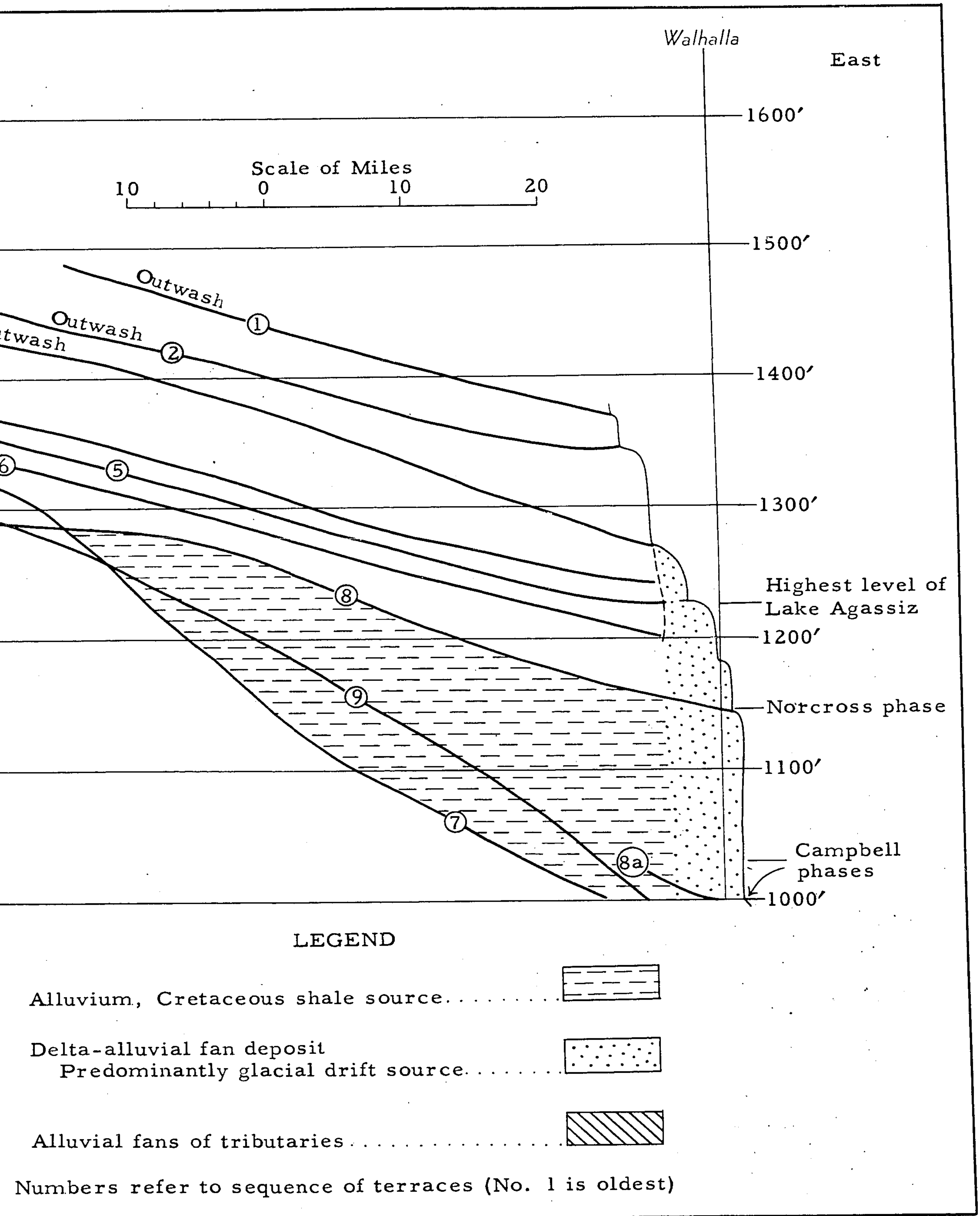
Delta-alluvial fan deposit
Predominantly glacial drift sc

Alluvial fans of tributaries . . . .

Numbers refer to sequence of ter

Figure 5-6

POSSIBLE RELATIONSHIP OF TERRACES IN THE PEMBINA TRENCH



PEMBINA TRENCH

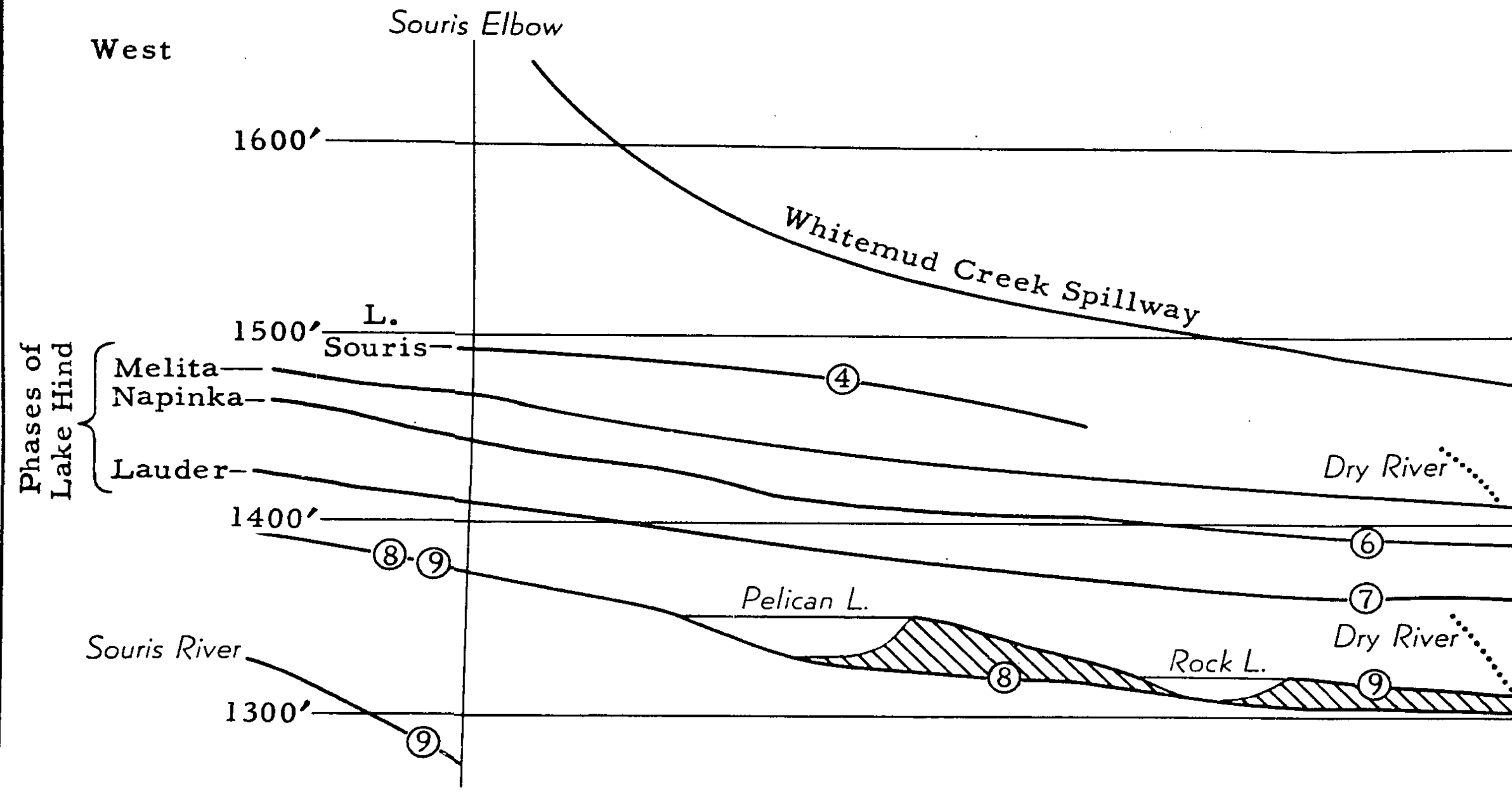
of the fill is aligned generally with the gradient of the bedrock floor of the trench above La Riviere, which indicates that the Souris basin lakes probably were extinct at the end of this episode of alluviation in the lower part of the trench. The relationship of the floor of the Dry River spillway, which hangs 15 to 20 feet above the bedrock floor of Pembina trench (Fig. 5-6), indicates that the Brandon lake existed through much, but not all, of this episode.

It is inferred that deposition of the alluvial fill began during the rise of Lake Agassiz I and continued during the retreat of the glacier from Treherne northward out of the area, through the rise of Lake Agassiz I to its highest level and its subsidence to the Norcross level (altitude about 1,150 feet). Thus, alluvium deposited during the rising phase of the lake may have been reworked during the subsiding phase. Alluviation ceased when Souris River was captured by Assiniboine River during the Tintah or Norcross phase of Lake Agassiz I (see "Capture of Souris River" later in the present chapter).

<u>Younger terraces of Lake Agassiz age</u>

Valley terraces in the Pembina "delta" near Walhalla are graded to altitudes of about 1,060, 1,050, and 1,000 feet; the lowest represent the Campbell phase of Lake Agassiz.

If the evidence of terrestrial gastropods (Chapter 4) is valid, the basal part of the younger alluvium in Pembina trench correlates with late phases of Lake Agassiz II, and it may be inferred that a broad flood plain existed near Mowbray during the Campbell phase of Lake Agassiz II and that

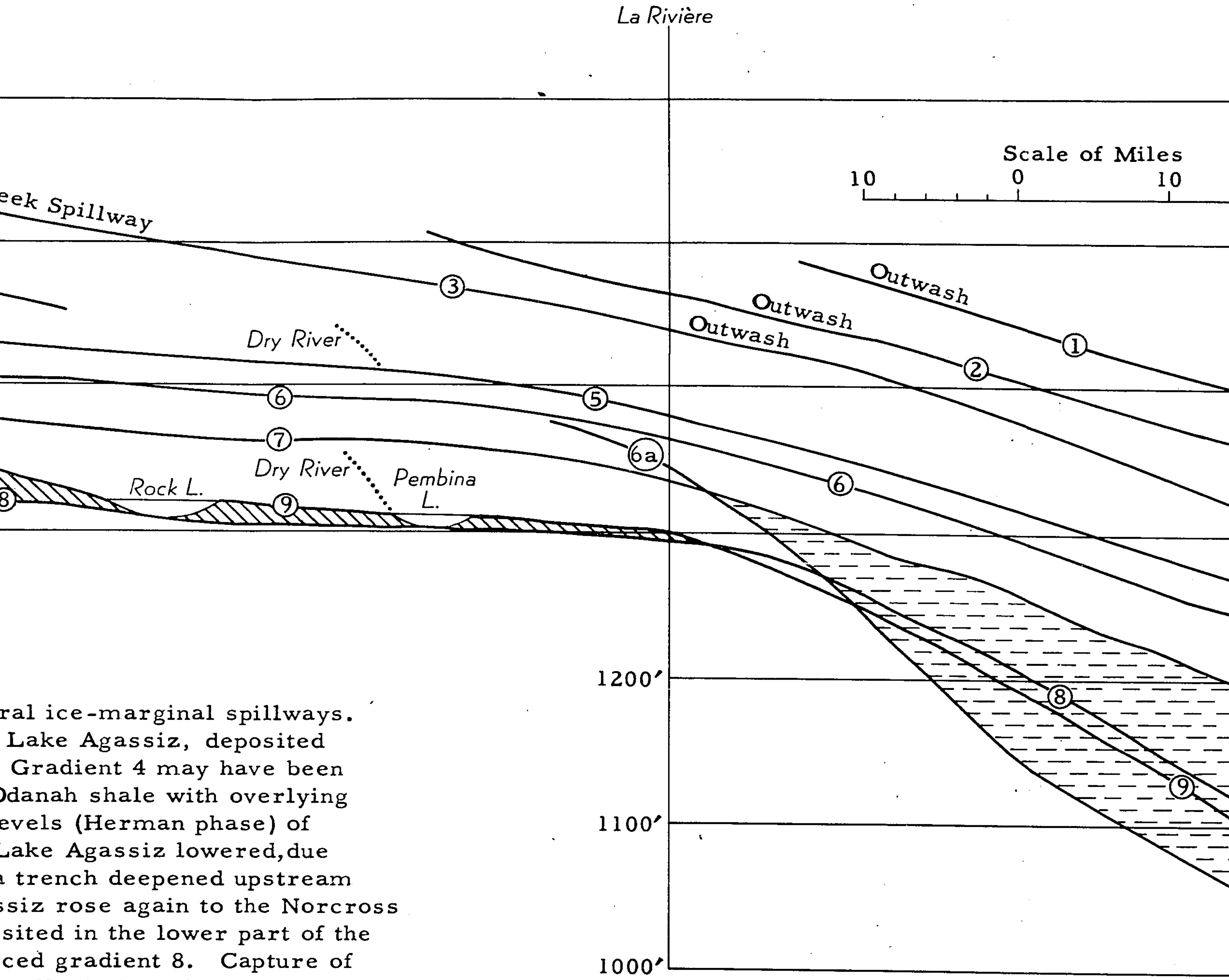


Hypothesis 2. (Not preferred)

Phases 1 and 2 were graded to unilateral ice-marginal spillways. Phase 3 was graded to the apex of a delta in Lake Agassiz, deposited between an ice lobe and Pembina Mountain. Gradient 4 may have been controlled by a knickpoint at the contact of Odanah shale with overlying drift. Phases 5 and 6 were graded to high levels (Herman phase) of Lake Agassiz. During phase 6 the level of Lake Agassiz lowered, due to opening of an eastern outlet, and Pembina trench deepened upstream beyond La Riviere (gradient 6a). Lake Agassiz rose again to the Norcross level during phase 7, and alluvium was deposited in the lower part of the trench. Subsequent drop in lake level produced gradient 8. Capture of Souris River by Assiniboine River and minor alluviation of the trench by its tributaries produced the present gradient (9).

This hypothesis requires very rapid withdrawal of the glacier after deposition of the Pembina "delta" to make possible the deposition of the Assiniboine delta. The Assiniboine delta area must have been occupied by an ice lobe to enable the Dry River spillway to be active throughout excavation of Pembina trench. The thick topset beds and the shape of the Pembina "delta" are not explained.

POSSIBLE RELATIONSHIP



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Alluvium, Cretaceous shale source .

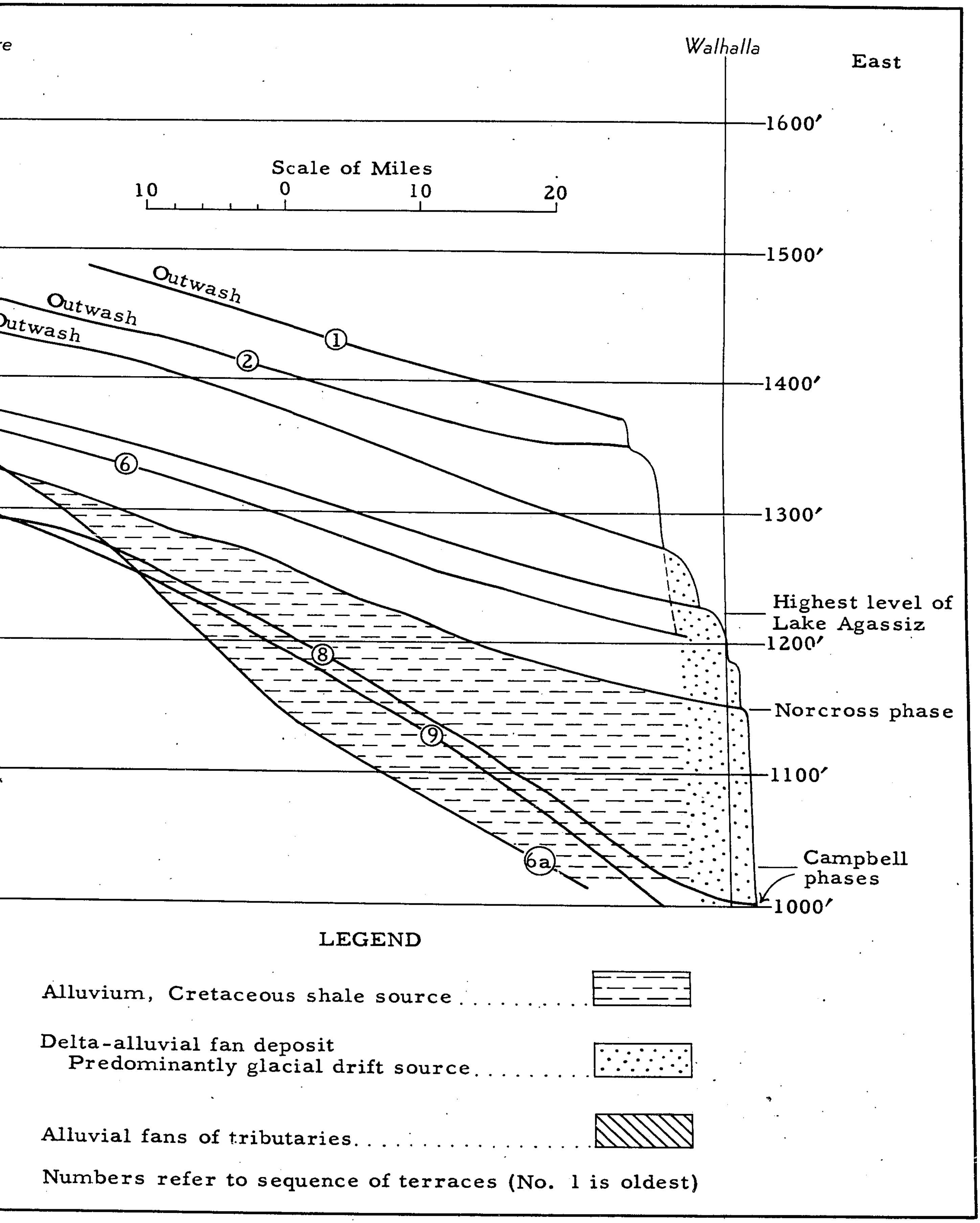
Delta-alluvial fan deposit
Predominantly glacial drift source

Alluvial fans of tributaries. . . . .

Numbers refer to sequence of terrac

Figure 5-7

POSSIBLE RELATIONSHIP OF TERRACES IN THE PEMBINA TRENCH



E PEMBINA TRENCH

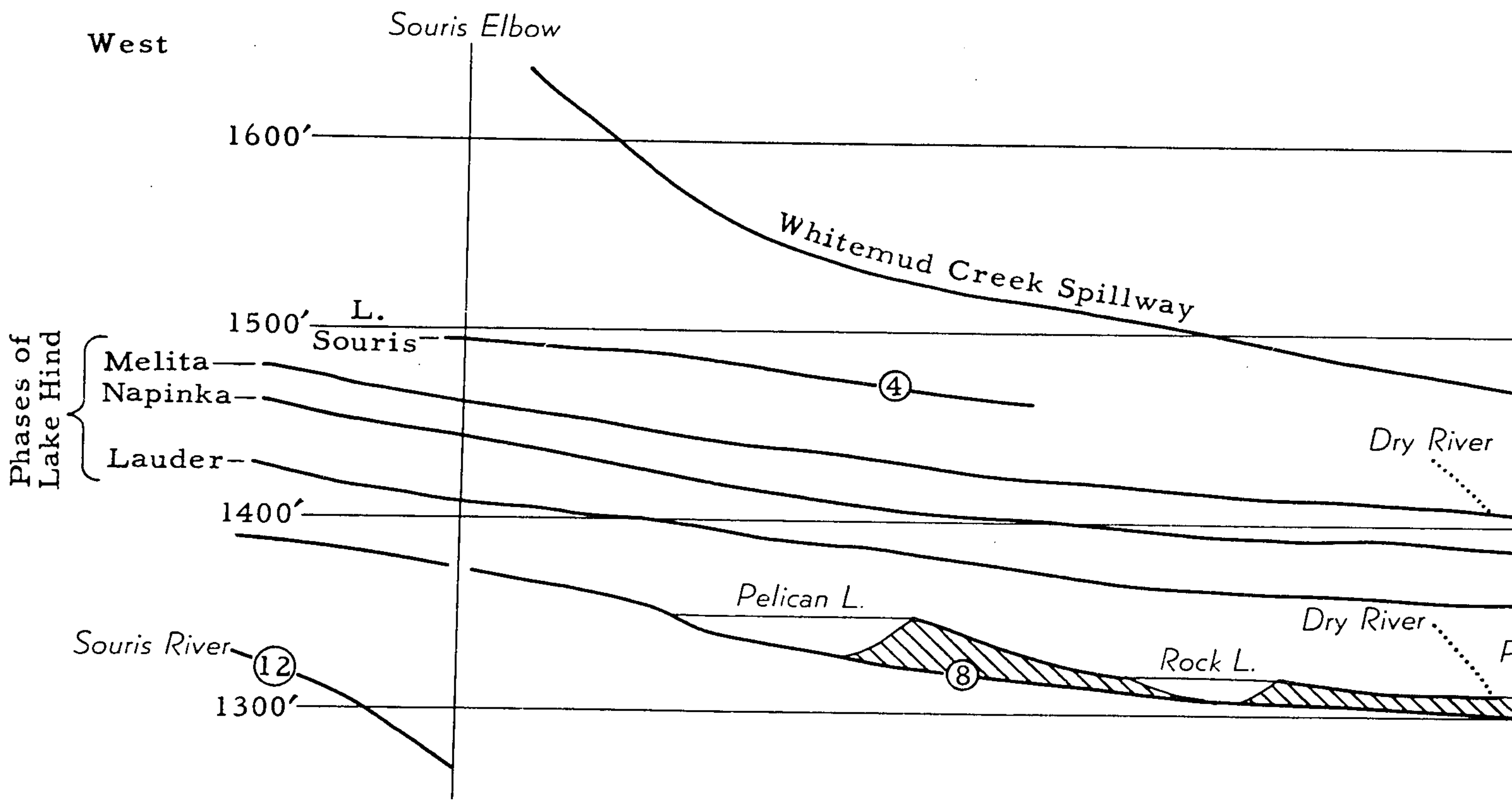
deposition on it continued until the discharge of Pembina River was reduced by climatic conditions during the altithermal.

Terraces on recent alluvium

Much of the younger alluvium in Pembina trench (p. 127-128) is in the form of alluvial fans and lake fillings. Downstream from La Riviere Pembina River is a sinuous, underfit stream that meanders across a flood plain 0.25 to 0.5 mile wide; numerous non-paired terraces are being formed. Downstream from north of Windygates the floodplain narrows, the channel straightens and the stream flows more rapidly; the gradient is about 8 feet per mile. It is inferred that Pembina River is slowly deepening the lower part of Pembina trench and alluviating the upper part.

ORIGIN OF PEMBINA TRENCH

Upham (1895, p. 269) stated that the Pembina valley was of preglacial origin from Lake Lorne to its delta, and that it was only partly filled with drift during glaciation. He showed that the volumes of the delta and the Pembina valley are about equal, and that much of the sediment in the delta is of glacial origin. The delta sediment contains about equal parts of gravel derived from Paleozoic, Precambrian, and Cretaceous rocks. Upham thought that all the pre-Cretaceous material was supplied from the glacier rather than from the erosion of drift, and inferred that the valley was excavated mainly in preglacial time. He probably underestimated both the quantity of finely comminuted rock from the Pembina valley that was spread on the floor of the Lake Agassiz basin as clay



Hypothesis 3. (Not acceptable)

Terrace levels 1 and 2 were graded to unilateral ice-marginal spillway terrace level 3 to the apex of an alluvial fan or delta. Gradient 4 may have been controlled by a knickpoint, or graded to the apex of the Pembina "delta" Levels 5, 6 and 7 were graded to high phases of Lake Agassiz during depositi of the Pembina delta. Spillway 8 was graded to a middle Herman phase and lasted through the draining of the Souris basin lakes and abandonment of the Dry River spillway. The Assiniboine delta was deposited during the last part of phase 8. A fall in the level of Lake Agassiz caused deepening of Pembina trench downstream from La Riviere (phase 9). Subsequent rise of Lake Agassiz to the Norcross level caused alluviation in the lower part of the trenc (10). Downcutting in the trench kept pace with the lowering of Lake Agassiz (gradient 11). Capture of Souris River by Assiniboine River resulted in the present gradient (12).

This hypothesis disregards the thick top-set beds of the Pembina "delta (either an alluvial fan or a delta built in a rising lake). The source of sedime for the alluvial fill seems inadequate. An extra cycle (rise and fall), for whic we have no other evidence, is introduced into the history of Lake Agassiz.

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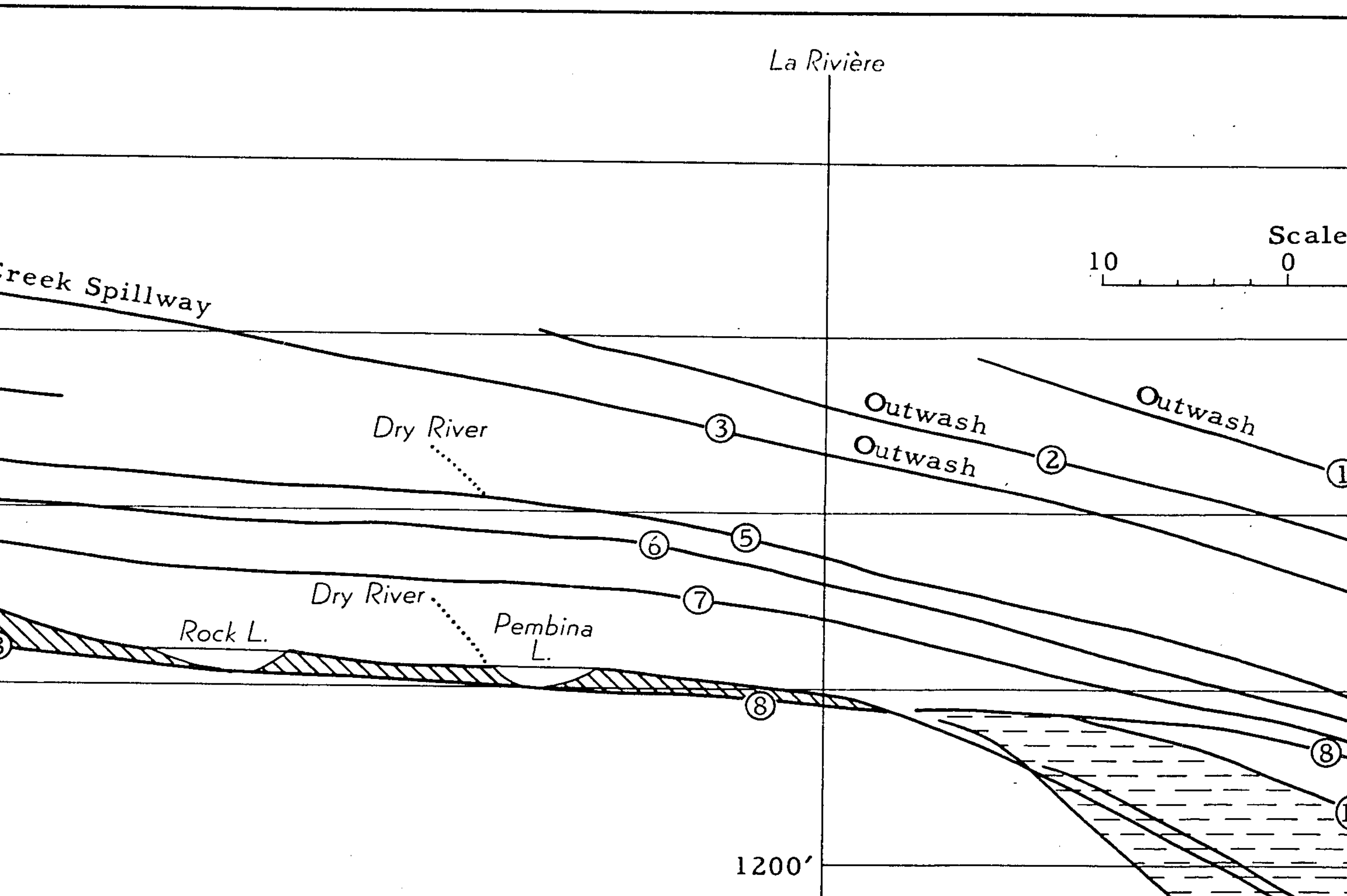

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Delta-alluvial fan deposit
Predominantly glacial dri

Alluvial fans of tributaries .

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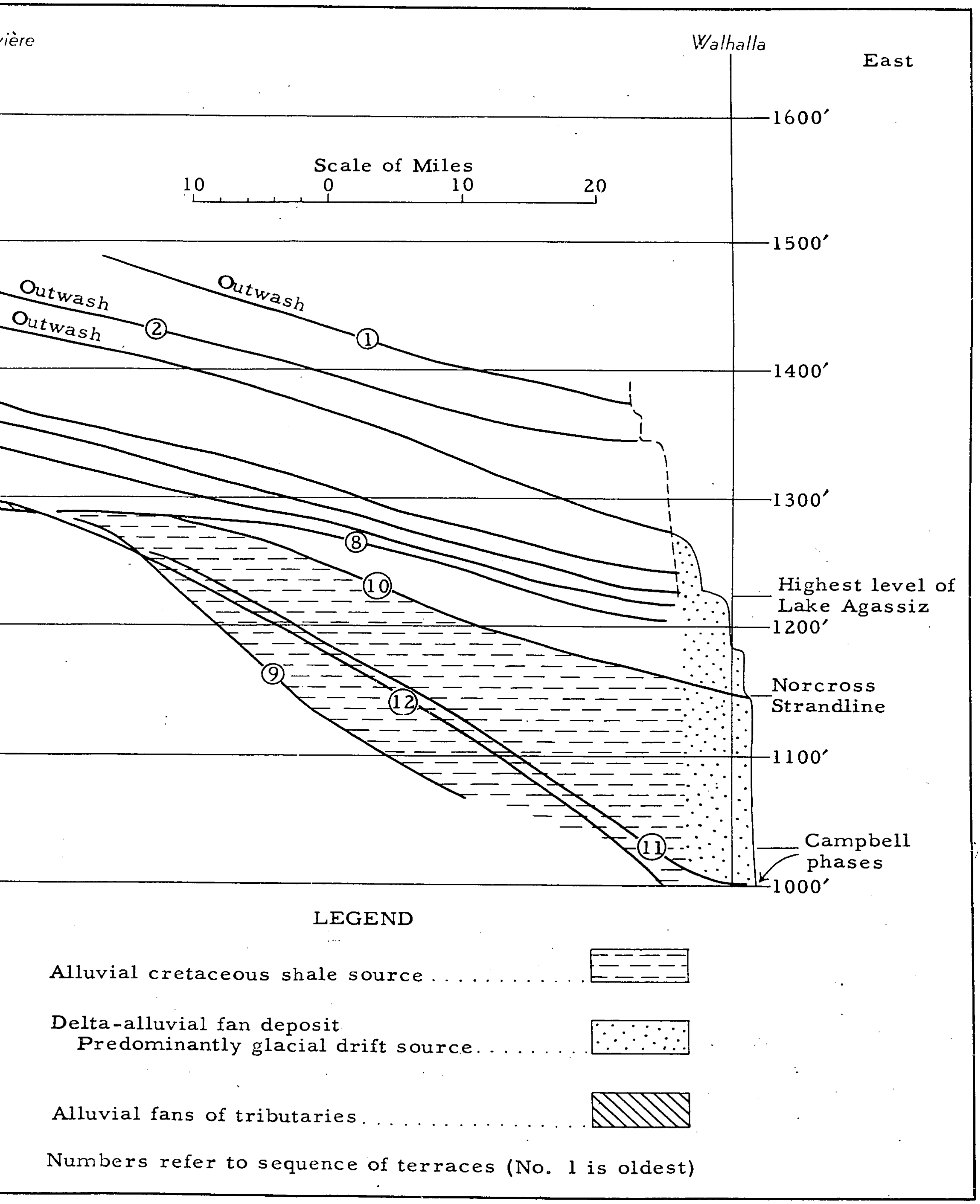
Figure 5-8

POSSIBLE RELATIONSHIP OF TERRACES IN THE PEMBINA TRENCH



IE PEMBINA TRENCH

and silt, and the thickness of drift overlying the Cretaceous rocks west of Pembina Mountain.

Bedrock-surface contours (Pl. 2) show that downstream from township 3 range 10 the trench occupies a small preglacial valley that had the form of a steep ravine. In township 4, range 10, and township 5, range 11, the trench generally follows a preglacial depression that trends north and west. Farther upstream the trench is parallel to preglacial slopes and locally passes directly across highs and lows on the bedrock surface.

The lower part of the trench antedates the last glaciation of the Tiger Hills region, but it is not necessarily pre-Pleistocene. In a tributary ravine, eroded deep into bedrock in NW 18-2-7 W. Prin., a stream cut along a broad terrace exposes 7 feet of gravelly alluvium overlying 15 feet of brown sandy till, the upper 4 feet of which is oxidized to a buff colour, underlain by 6 feet of grey clayey till. The till appears to be in situ rather than slumped. Masses of till that may have slumped to the valley bottom were observed in NW 6-2-7 W. Prin. and SE 4-2-7 W. Prin.. Till also was found overlying the bedrock floor of the trench in the course of two damsite investigations[1].

Further evidence of a valley system antedating the last ice advance is supplied by eskers trending southeast

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1. Oral communications, Messrs. D. Youngman and K. Lambe, Engineers, Prairie Farm Rehabilitation Act, Saskatoon. Unconsolidated deposits at altitudes as low as 1,105 feet, at least 50 feet below the present river level, were found in SW 5-2-7 W. Prin.

through sections 23, 24, and 25, 14 and 13, township 2 range 8. The northwestern parts of these eskers are 10 to 15 feet above neighbouring ground moraine, but they enter ravines tributary to Pembina trench in the southeast and become belts of gravel along the north sides of the ravines. Although these ravines originally may not have been as deep as they are now, they must have existed prior to formation of the eskers.

Bedrock on the south rim of Pembina trench has been deformed by ice shove in several places (p. 41; Fig. 2-4) as far upstream as Rock Lake. It is inferred that there was a depression, possibly an earlier meltwater channel, in the position of Pembina trench as far upstream as Rock Lake; this early channel may have been much smaller than the present one.

In summary, the lower portion of Pembina trench antedates the last glaciation of the area and may be preglacial. Above La Riviere the trench is of glacial origin, but may partly antedate the last glaciation. Between La Riviere and Pembina Lake the trench formed by headward erosion, following a retreating source of glacier meltwater along a pre-existing depression in the bedrock surface. From Pembina Lake to its head, at Bunclody, Pembina trench originated as an ice margin channel; from Pelican Lake to Bunclody it occupied an interlobate position, and extended headward to its retreating glacial source.

CONCLUSION

The portion of Pembina trench downstream from La Riviere was excavated before the last ice advance, and was partly filled with drift. Upstream from La Riviere the trench originated mainly as an ice-margin and interlobate spillway during recession of the last glacier.

Most of Pembina trench was excavated by discharge from the Souris basin lakes. Sediment eroded from the trench was deposited in a reentrant between a glacier in the Lake Agassiz basin and the Manitoba Escarpment, in the form of an alluvial fan ("delta") that was later modified by wave action in Lake Agassiz I.

The two highest spillways represented by terraces in the trench conducted meltwater from an ice margin in the Tiger Hills to ice-margin channels trending southward along Pembina Mountain, perhaps to the Elk Valley delta. The third spillway conducted meltwater from the Whitemud Creek system and began the deposition of the Pembina "delta".

Because of a gap 24 miles long in the terraces near La Riviere, the complicating effect of an alluvial fill, and a marked change in gradient near La Riviere, correlations of the younger terraces in Pembina trench are speculative (Figs. 5-6, 5-7, 5-8).

The spillway represented by the first set of terraces below the Whitemud Creek system carried meltwater from a small glacial lake at Bunclody (the Carroll lake); subsequently the main source of the trench was the Souris basin lakes, which include Lake Souris and its successor, Lake Hind.

Retreat of the ice sheet on the plains far to the west caused all the meltwater from an ice front more than 400 miles long to flow through Pembina trench by way of the Souris basin lakes. The Brandon glacial lake discharged into Pembina trench through the Dry River spillway. Most of the Pembina "delta" was deposited before the Dry River phase of the Brandon lake ended. After the Napinka phase of Lake Hind the ice margin withdrew from the Pembina "delta", and the baselevel of Pembina trench fell below 1,000 feet because the Lake Agassiz basin was dry or nearly so.

Following the Lauder phase of Lake Hind the level of Lake Agassiz rose, resulting in alluviation of the lower part of Pembina trench during the filling of Lake Agassiz to its highest level and the subsidence to the Norcross level (1,150 feet). Subsequently, terraces were cut in Pembina trench at altitudes of about 1,060, 1,050, and 1,000 feet during pauses in the subsidence of Lake Agassiz.

Capture of Souris River by Assiniboine River reduced the Pembina watershed from 22,500 square miles to about 2,500 square miles. Finally damming of Pembina trench by alluvial fans of small tributaries formed a series of shallow lakes.

DRAINAGE IN THE KILLARNEY PLAIN

EVOLUTION FROM MELTWATER STREAMS

The evolution of drainage on newly exposed glaciated terrain is well illustrated on the slope of Turtle Mountain and on the Killarney plain.

Ice-marginal channels that carried glacier meltwater southeastward across the slope of Turtle Mountain, located in sections 1,2, 12, 16, 17, 19, and 20, township 2, range 17, and in sections 14, 15, 22, 21, 19, and 29, township 1, range 16, were dismembered by other streams flowing downslope. The downslope streams resulted from the collecting of runoff in low areas and from the overflowing of small lakes on Turtle Mountain.

In the southern part of the Killarney plain, glacier meltwater flowed south and southeast over outwash plains 1 to 2 miles wide. Farther north, drainage systems developed when one closed depression overflowed into another until a channel formed between them; a series of depressions thus linked discharged into a well-integrated stream. When its baselevel lowered, this stream eroded headward along the incipient channels through the chain of closed depressions. Streams that originated in this way generally follow random courses except where the pattern of the original depressions is controlled by washboard moraines (Pl. 4, townships 2 and 3, range 15; and township 3, range 16), where they have a crude trellis pattern.

Delevelling, generally the result of the deepening of Pembina trench, caused several stream captures: Whitemud Creek was dismembered by Badger Creek and Pembina River (see below); and upper Pembina River also captured a glacial spillway in NW 24-3-17 W. Prin. and another smaller spillway at NE 17-3-17 W. Prin..

WHITEMUD CREEK

Whitemud Creek formed as an ice-marginal channel on the north slope of Turtle Mountain in the west, and as a stream consequent on washboard moraines in the east. It joined Pembina trench at Rock Lake and deposited an alluvial (outwash) fan before the present Pembina trench was fully integrated; it may have been one of the outlets of the Boissevain glacial lake (Pl. 6).

The Whitemud spillway was dismembered as a result of captures (1) in section 7-3-17 W. Prin. (west of Killarney) by Pembina River, (2) in section 3-3-18 W. Prin. (south of Rhodes, Pl. 1), also by Pembina River, and (3) about 11 miles upstream from Rock Lake by Badger Creek. Thus, Whitemud Creek became a tributary of Badger Creek, the upper part of its watershed became tributary to upper Pembina River, and the lower part of the Whitemud spillway became tributary to Rock Lake.

UPPER PEMBINA RIVER

The upper Pembina River is that portion of the river west of section 31-3-15 W. Prin., upstream from Pembina trench.

The northern (youngest) channel of several ice-margin channels in township 3, range 16, developed into upper Pembina River when Pembina trench deepened and rejuvenated all its tributaries. Pembina River extended upstream by the integration of ice-marginal channels and by capture of two small spillways in township 3, range 17 and of the headwaters of Whitemud Creek.

The lowest (northern) outlet of the Boissevain glacial lake, with a sill at an altitude of about 1,670 feet, is a hanging valley where it joins the Pembina valley south of Ninga. The absence of corresponding terraces in the Pembina valley suggests that the outlet was abandoned before Pembina River captured the upper Whitemud Creek watershed.

SPILLWAYS ACROSS THE TIGER HILLS

Several spillways conducted glacier meltwater southward across the Tiger Hills into Pembina trench. The length of these spillways is generally an indication of the amount of ice-margin retreat during their use. The altitudes of their floors at their mouths, and of terraces near the mouths, compared with terraces in Pembina trench, are a means of correlating ice retreat in the Tiger Hills with the phases of the Souris basin lakes. Most of the spillways are 200 to 600 feet wide and 50 to 100 feet deep; they are listed in Table 5-2 in order from west to east. The first spillway, at Carroll, discharged into the Melita and Napinka phases of Lake Hind (Pl. 7J) and headed in the Tiger Hills moraine east of Carroll. The Souris River gorge (p.5-28) and the Dry River spillway (p.5-29) receive further attention in the discussion of the Brandon glacial lake, later in this chapter.

An ice margin retreated across the Tiger Hills region during the existence of the Souris basin lakes; it is inferred that the northwestern ice, in the Souris basin, retreated more rapidly than the northern ice, north of the Tiger Hills and east of the Manitoba Escarpment. The northern ice retreated most rapidly in the widest part of the Tiger Hills, where bedrock knobs impeded flow. Thus, the ice margin withdrew from the central part of the Tiger Hills - Darlingford moraine first: retreat in the Baldur - Neelin area amounted to 8 to 12 miles before any retreat occurred at Carroll or south of Treherne.

THE BRANDON GLACIAL LAKE[1]

INTRODUCTION

The Brandon glacial lake (Pl. 7 L and M) was ponded between a shrinking sublobe of northern ice and the north side of the Tiger Hills. It was formed by the merging of three small glacial lakes (Pl. 7 K). The basin of the Brandon lake extended eastward from Alexander (Pl. 6) to Holland (Pl. 3), although not all of it was flooded at once.

EVIDENCE OF THE BRANDON LAKE

The existence of the Brandon glacial lake is inferred from the occurrence of lake sediments higher than the highest level of Lake Agassiz, and from the relationships of spillways through the Tiger Hills. Scarps, beach ridges, and well defined deltas marking former shorelines are lacking; this is probably the result of rapid lowering of the water level due to the downcutting of outlets, and limited wave

1. Upham (1890, p. 87E-88E) applied the term "the Brandon lake" to an inferred glacial lake south of Brandon; however, the history of the lake apparently was not altogether clear to him and he used the name in an informal sense only.

Table 5-2. Glacial spillways crossing the Tiger Hills; "est." = estimate based on contour map or extrapolation of terraces or spillway floor.

General location (or mouth only)	Length (miles)	Altitude of mouth (feet)	Nature of source
Carroll	6	1,555	Ice margin
Souris River gorge	0-4 5	1,490 1,380	Ice margin Glacial lake
NW 6-6-17 W. Prin.	3.5	est. 1,475	Ice margin
SE 1-6-17 W. Prin.	2.5	1,380 est. 1,500	Ice margin Glacial lake
Sec. 9-5-16 W. Prin.	4	1,420	Ice margin
Rock Lake to Baldur	est. 3 est. 5 est. 8 10.5	1,420 1,400 1,375 est. 1,330	)Ice margin) and) outwash) plain
Dry River spillway	4 12 to 14	est. 1,400 1,350	Glacial lake Glacial lake
NE 1-5-11 W. Prin.	4 to 7	1,380	Ice margin

action in a small ice-choked lake. The distribution of lake deposits is further evidence of lakes inferred from (1) a small spillway south of the Brandon Hills that discharged eastward, (2) Souris River gorge, and (3) Dry River spillway.

Brandon Hills spillway

A channel 10 to 30 feet deep, 500 to 1,000 feet wide, and about 5 miles long discharged eastward from SE 34-8-19 W. Prin. to NW 28-8-18 W. Prin.. This spillway appears as an intermittent stream (Pl. 3) and as indentations in the 1,400-foot contour (Pl. 1). The head of the channel has an altitude of about 1,420 feet, and the mouth an altitude of about 1,350 feet. A lake about 1.5 miles long and 1.0 miles wide formed the central part of the spillway. A thin deposit of gravel at the east end was too small to be mapped.

It is inferred that the spillway drained a glacial lake, with its level at an altitude of about 1,430 feet, that was ponded between an ice margin, extending westward from the Brandon Hills to about 5 miles south of Alexander, and a small end moraine north of Souris and Carroll (Pl. 6; Pl. 7 K and L). It discharged into the Brandon Lake during the Dry River spillway phase (Chapter 6) and was abandoned when glacier recession northward from the Brandon Hills caused the lakes to merge.

Souris River gorge

Souris River crosses the Tiger Hills moraine in township 6, range 18 (Pls. 1, 3, and 6) in a gorge about 300 feet deep and 0.5 to 0.75 mile wide (Fig. 5-9). The stream meanders through the gorge, the sides of which comprise slip-off slopes and slump blocks. The gorge connects the upland (altitude about 1,510 feet) south of the Tiger Hills moraine to a lake basin (altitude about 1,350 feet) north of the moraine. The fall from the floor of Pembina trench (altitude about 1,380 feet) to the lake basin is about 30 feet in 6 miles. The present gradient of Souris River through the gorge is 65 feet in 4 miles (Upham, 1890, p. 34E). The lack of stream terraces and alluvial fans of tributary gullies in the gorge suggests (1) that downcutting has been almost continuous, and (2) that discharge was never much greater than it is at present.

Upham (1895, p. 272-275) thought Souris River gorge began as the outlet of a glacial lake north of the Tiger Hills moraine and discharged southward into Pembina trench (Lang's valley). He stated that the gorge was so deeply incised that when the glacial lake was drained Souris River changed its course to flow northeastward through it. This is not possible because the north end of the floor of the gorge (the head) must have been higher than the south end when the lake drained, and both ends were higher than Souris-Pembina River.

The writer agrees that a glacial lake discharged southward through the gorge; probably the gorge headed at an ice margin when it first formed. Downcutting of the lake

Figure 5-9. View north across Pembina trench from section 4-6-18 W. Prin., showing high-level terraces and the south end of Souris River gorge through the Tiger Hills moraine.

outlet progressed until ice recession near Ashdown and Hilton (Pl. 3) caused the lake to merge with another lake, farther east, that was discharging through Dry River. The Souris gorge outlet was then abandoned. The altitude of the level of the new lake (the Brandon Lake) was between 1,375 and 1,350 feet; presumably the altitude of the sill of the newly abandoned Souris gorge spillway was about 1,400 feet. Souris River was later captured through the gorge by headward erosion of a tributary of Assiniboine River (p. 5-38 - 5-40).

Dry River spillway

Dry River spillway crosses a relatively narrow part of the Tiger Hills, in township 4, range 12, and township 5, range 13; its southeast end breaches the Tiger Hills - Darlingford moraine.

The spillway is a flat-bottomed, steep-sided valley 35 to 175 feet deep, as wide as 0.25 mile, and 12 to 14 miles long (Fig. 5-10). The southeast part contains terraces (at E in Fig. 5-10) graded to an altitude of about 1,400 feet in Pembina trench. It is inferred that the spillway represented by these terraces was the outlet of a small glacial lake southeast of Greenway, partly contemporary with either the Melita or the Napinka phase of Lake Hind.

The spillway had two heads, one about 2 miles west-northwest of St. Alphonse (at A in Fig. 5-10(a)), and another 3 to 4 miles north of Greenway. Westward-trending channel south of St. Alphonse connected the upper part of Cypress River to Dry River. The sill of the spillway head west of St.

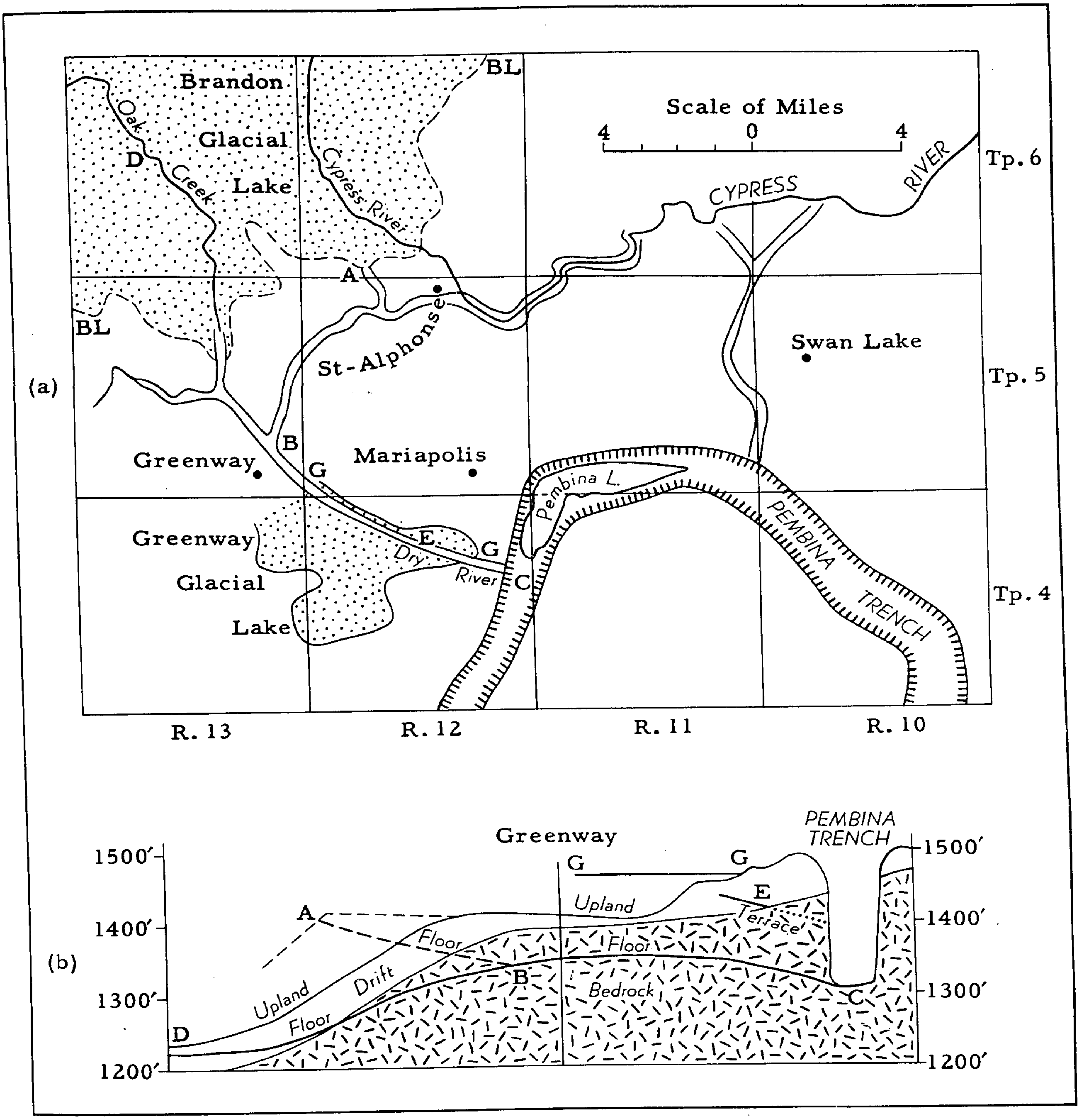


Figure 5-10.
The Dry River Spillway.

(a) Map showing spillways in the vicinity of Dry River. Letters correspond to positions in (b). BL-BL is southern limit of the Brandon glacial lake. Double lines are spillways.

(b) Profile of Dry River spillway showing floor and upland surface, and including tributary spillway A-B and paired terraces at E. G-G represents the Greenway glacial lake. Horizontal scale as in (a).

Alphonse has an altitude of about 1,410 feet, having cut down from about 1,420 feet. The gradient of Dry River spillway between Greenway and the end north slopes northward; it is inferred that at its inception the gradient sloped southward from a sill at an altitude slightly higher than 1,400 feet; subsequently the sill was eroded to an altitude of about 1,355 feet, a little higher than the divide in the spillway near Greenway.

The following history of Dry River is inferred from the above data: (1) Inception as a small spillway conducting meltwater from an ice margin southeastward across the Tiger Hills - Darlingford moraine. (2) Ice margin recession and formation of a small glacial lake southeast of Greenway; continued downcutting of the spillway except for a pause during the Melita phase or the Napinka phase of Lake Hind. (3) Draining of the Greenway glacial lake as the ice margin withdrew and the outlet lowered. (4) Further ice margin recession and opening of an ice-marginal channel that joined upper Cypress River to Dry River and caused upper Cypress River to abandon a channel trending southward past Swan Lake. (5) Ice margin recession from the Tiger Hills created two small glacial lakes, one north of Greenway and one north of St. Alphonse. The outlet of the latter lake cut its sill down to an altitude of about 1,410 feet. (6) Ice recession caused the two small lakes to merge and the St. Alphonse outlet was abandoned for the lower Greenway outlet. (7) Expansion of the glacial lake due to ice recession until it merged with the glacial lake north of Souris River gorge and became the Brandon lake. The Souris River gorge outlet was abandoned and the Brandon lake discharged through Dry River while its level subsided from an altitude of about 1,380 feet to about 1,360 feet. (8) Further rapid lowering of the lake resulted when ice recession opened the Treherne spillway and the Dry River outlet was abandoned. Upper Cypress River still discharged southeastward through Dry River. (9) Capture of upper Cypress River north of Greenway by headward growth of Oak Creek up a comparatively steep slope north of Greenway resulted in abandonment of the Dry River spillway southeast of Greenway. (10) Capture of upper Cypress River by headward erosion of lower Cypress River at St. Alphonse resulted in complete abandonment of the Dry River spillway.

Treherne spillway

The Treherne spillway (p. 23-24, Figs. 1-1, 1-12) is a flat-bottomed channel about 0.75 mile wide and 11 to 12 miles long that trends eastward and northeastward near the north side of the Tiger Hills between Landseer and Treherne, (Pls. 1 and 3). The valley floor slopes from an altitude of about 1,270 feet at the bedrock sill south of Holland to about 1,240 feet near Treherne. Glacially-streamlined bedrock ridges on the walls of the spillway indicate that it antedates the last glaciation. Before re-excavation, the sill of the spillway probably was about 3 miles east of Holland, at an altitude of about 1,350 feet.

The following history of the Treherne spillway is inferred: (1) The spillway was eroded to its present dimensions, probably as the outlet of a glacial lake, during a previous deglaciation. (2) It was partly or completely filled with drift during the last glaciation. (3) The channel was re-excavated as an eastern outlet of the Brandon lake when ice-recession northward from the Tiger Hills uncovered ground lower than an altitude of about 1,360 feet. The Treherne spillway lowered the level of the Brandon lake to an altitude of about 1,280 feet, and discharged eastward around the north end of Pembina Mountain into the Lake Agassiz basin. (4) The spillway was abandoned when the ice margin withdrew northward about 3 miles and the Brandon lake was drained (or merged with Lake Agassiz I).

CONCLUSION: HISTORY OF THE BRANDON LAKE

The Brandon glacial lake formed as a result of the merging of glacial lakes north of the Tiger Hills and west of the Brandon Hills. The first lake discharged southward through Souris River gorge into Pembina trench, and its level lowered rapidly to an altitude of about 1,400 feet, as the outlet deepened and the ice margin retreated northward. Simultaneously, a glacial lake north of Greenway expanded, due to ice margin retreat, and discharged through Dry River into Pembina trench. The sill of the Dry River outlet eroded the lake from an altitude of about 1,400 feet to about 1,380 feet before continued ice recession caused this lake to merge with the lake north of Souris River gorge. The lake formed by this merging is termed the Brandon lake (Dry River phase, Pl. 7 L); its level lowered from an altitude of about 1,380 feet to about 1,360 feet while it discharged through Dry River. During this phase of the Brandon lake a small glacial lake west of the Brandon Hills, with a level at an altitude of about 1,420 feet, discharged eastward through a channel south of the Brandon Hills into the Brandon lake; subsequent retreat of the ice margin northward from the Brandon Hills caused the western lake to drain and the Brandon lake to extend northwest to the city of Brandon. Ice recession at the east end of the Tiger Hills opened the Treherne spillway and resulted in abandonment of Dry River. The level of the Brandon lake subsided from an altitude of about 1,360 feet to about 1,280 feet while it discharged through the Treherne outlet. Further ice recession opened a lower drainage line north of the Treherne spillway and the Brandon lake was drained or merged with Lake Agassiz II.

MINOR SPILLWAYS ON PEMBINA MOUNTAIN

Several channels along the eastern slope of Pembina Mountain are described in Chapter 1 (p. 27-28). These are ice margin features comprising unilateral and in-and-out channels that discharged southward along Pembina Mountain into the ice-free part of the Lake Agassiz basin. The channels are progressively younger from south to north and form terraces with southward-sloping gradients. Their altitudes generally range from 1,300 to 1,400 feet, well above the highest strandlines of Lake Agassiz known in this area.

These spillways, formed when the ice margin in the Lake Agassiz basin receded from the Pembina delta to Cardinal, were roughly contemporary with the incipient - and Dry River phases of the Brandon lake.

ASSINIBOINE VALLEY

GENERAL DESCRIPTION

Introduction

Assiniboine River enters the west side of the Brandon map-area (Pl. 1) near Brandon, and trends southeast, east, and then northeast to the north boundary of the map-area of Portage la Prairie. The axial line of the valley is about 100 miles long, and the meandering channel of the river is about 180 miles long. The river falls about 400 feet in this distance. All distances in the following discussion are measured along the axis of the valley.

The first 5 miles of the valley east of longitude 100° are a flat-bottomed cut, about 1 miles wide and 125 feet deep, through glacial drift. The next 71 miles cross the upper Assiniboine delta (Fig. 1-1), beginning as a relatively straight channel a few feet below the upland surface and enlarging into a valley 250 feet deep, containing slip-off slopes, paired - and non-paired terraces north of Treherne (Fig. 5-11). In the next 18 miles, east from the Campbell scarp, the valley crosses the lower Assiniboine delta and contains no prominent paired terraces. In this portion the depth decreases from about 150 feet, north of Rathwell, to about 20 feet, west of Portage la Prairie. The remaining 13 miles cross a plain (alluvial fan) that is only a few feet above normal river level and is subject to occasional (50-year) floods.

Figure 5-11. View south from SE 25-9-10W. Prin., across the Assiniboine valley showing the extensive fill terrace of the Campbell phase of Lake Agassiz II in the middle distance. The Tiger Hills are seen in the far distance on the right side of the photograph. The terrace in the foreground is correlated with the Tintah phase of Lake Agassiz I.

Long profiles of Assiniboine River, its terraces, and the adjacent upland (Pl. 5(a)) are shown upstream beyond Virden; an interpretation of the valley terraces in the Assiniboine delta is also presented (Fig. 5-12).

Two sets of paired terraces represent former valley floors cut by lateral erosion at altitudes higher than the extensive paired terraces on alluvial fill deposited in Lake Agassiz II (p. 132-134). Paired terraces probably occur at altitudes lower than the surface of the alluvial fill but cannot be distinguished from the abundant non-paired terraces without detailed study.

Cut terraces

The highest significant terraces cut by lateral stream erosion in the delta sector of the Assiniboine valley have a gradient that slopes eastward from an altitude of about 1,150 feet near Stockton to about 1,135 feet at the Ladysmith ferry (bridge); their gradient in the lower 30 miles is about 0.3 feet per mile. The baselevel of this former valley floor probably was the Tintah phase of Lake Agassiz I, but may have been one of the lower Norcross phases: unfortunately, the higher strandlines of Lake Agassiz are indistinct near the mouth of Assiniboine River. The terraces of the Tintah phase are as wide as 0.5 mile; high-level channels south of the main valley, 2 to 3 miles east of Treesbank, and broad, indistinct channels in the north part of township 8, range 12, are also parts of the Tintah phase valley. Sand dunes are common on these terraces and in the abandoned channels (Pl. 3: Sections 31, 32 and 33-7-14 W. Prin.; sections 4, 14, 26, and 35-8-14 W. Prin.; sections 27, 28, and 29-8-13 W. Prin., and the north part of township 8, range 12) whereas they are rare on lower terraces. It is inferred that the valley floor represented by these terraces and abandoned channels was formed during an interval of stability of Lake Agassiz I, and that the climate probably was cool and dry so that windblown sand was deposited when the terrace surfaces were abandoned by Assiniboine River.

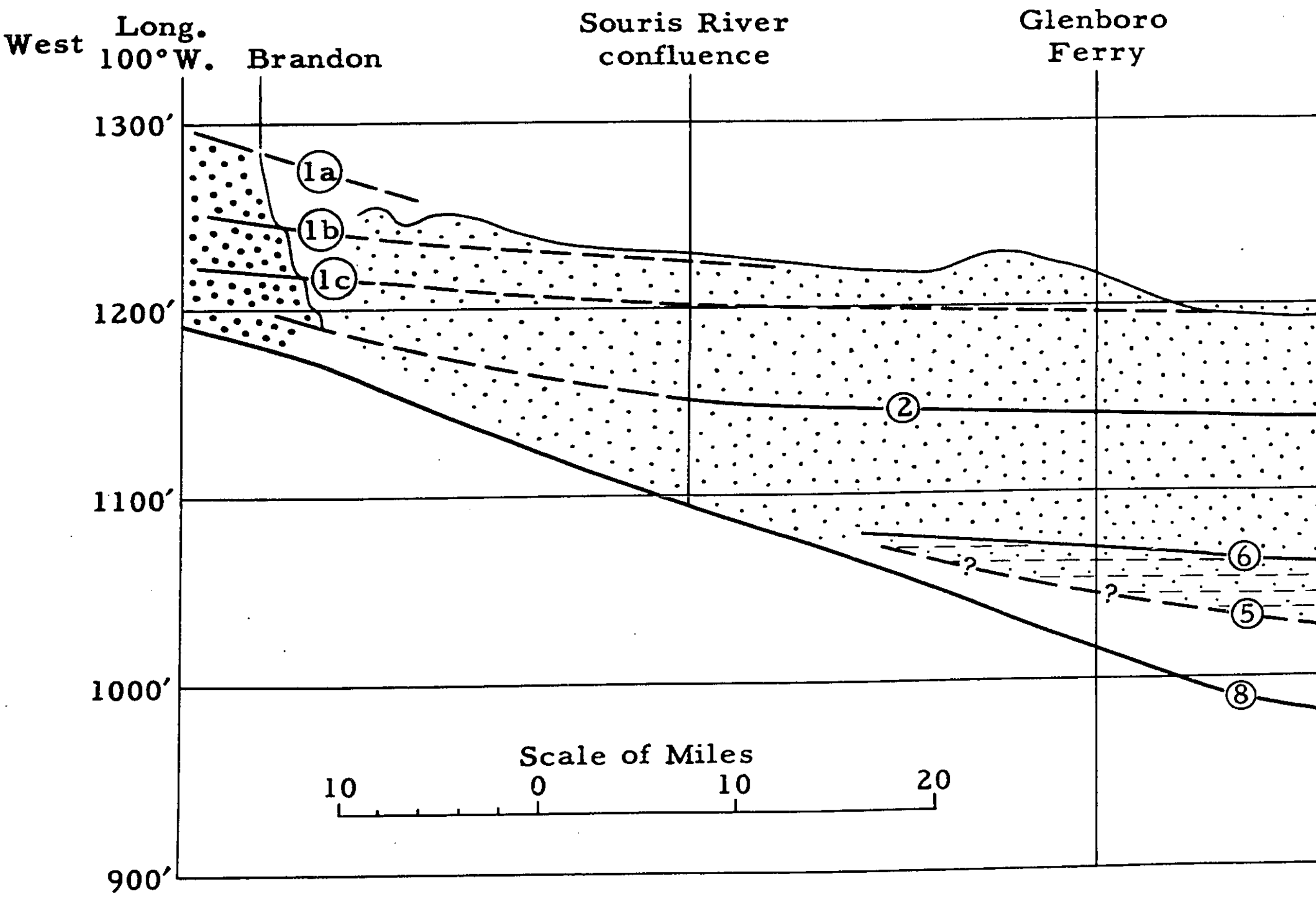
Very narrow paired terraces occur at Holland Bridge and Lavenham Ferry (Pl. 5(a)). and were graded to a level of Lake Agassiz slightly lower than 1,100 feet. No corresponding strandline was observed on the Assiniboine delta near the valley; probably a lower Tintah phase is represented by these terraces (Johnston, 1946, Fig. 2).

Narrow cut terraces also occur at altitudes of about 1,060 to 1,065 feet, just above the valley fill, downstream from the Rossendale ferry. These are believed to represent lake levels at the time of deposition of the clayey alluvium in Lake Agassiz II (Campbell phase).

Cut terraces below the level of the alluvial fill terraces were not studied; paired terraces may be present, but non-paired terraces are abundant, and the scale of the mapping limited terrace correlations to obvious features.

Valley fill terraces

Extensive valley fill terraces (Fig. 5-11), formed by alluviation of the Assiniboine valley during the rising phase

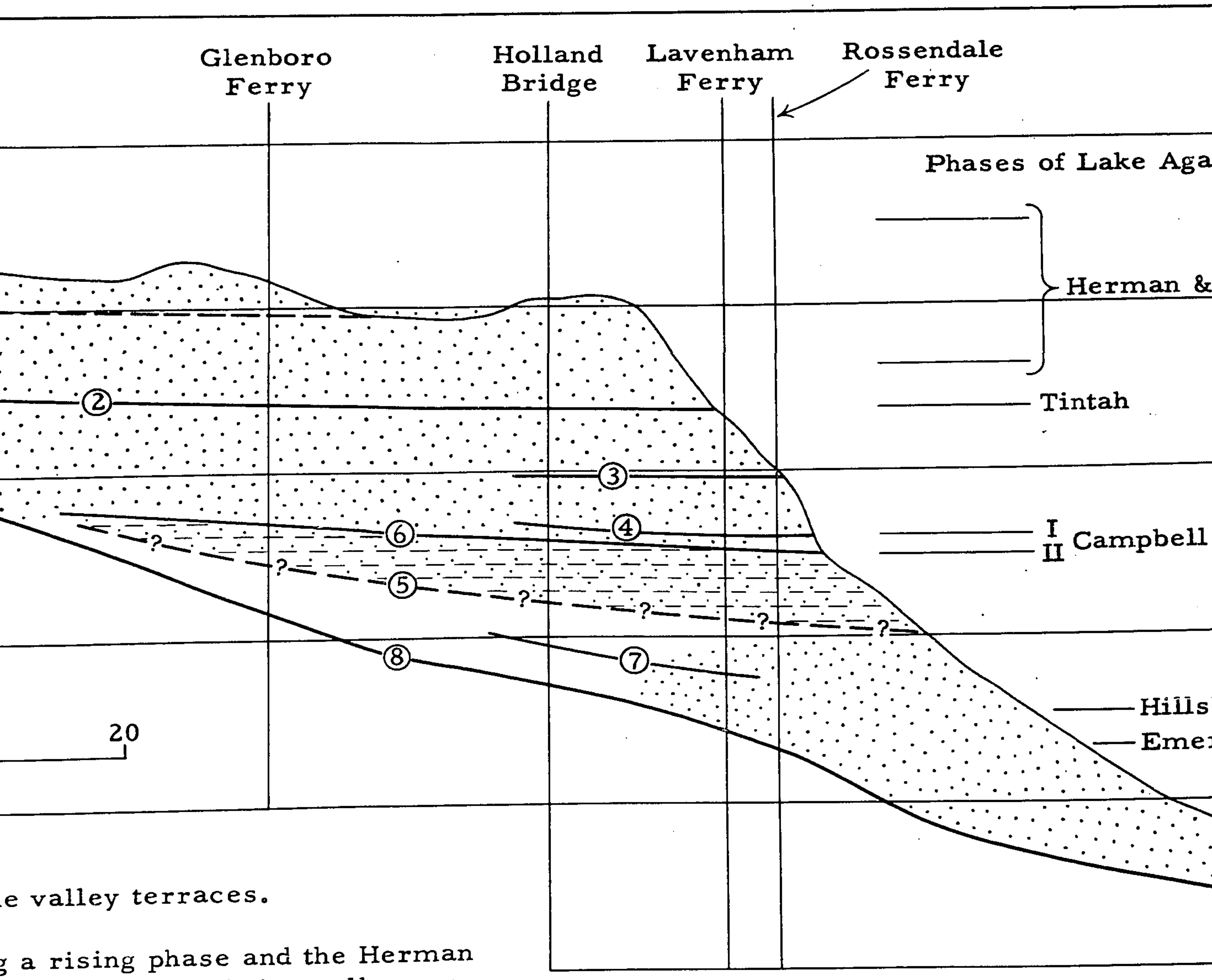


Interpretation of the Assiniboine valley terraces.

The Assiniboine delta was built during a rising phase and the Herma phases (falling) of Lake Agassiz. Excavation of the Assiniboine valley pro gressed with the lowering of lake level, and paired terraces (2, 3 and 4) resulted from pauses during lowering. After phase 5 (position not known, probably much lower than indicated), Lake Agassiz rose to the Campbell level and alluvium was deposited as lake sediment in the drowned Assinibo valley (phase 6). Subsequently, the lake level dropped intermittently; the resulting terraces are not shown except (7) which may correlate with the Hillsboro or Emerado strandlines. Finally Lake Agassiz was drained and the present gradient (8) established.

Figure

INTERPRETATION OF RIVER TERRA



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LEGEND

Till (West of Brandon) . . . .

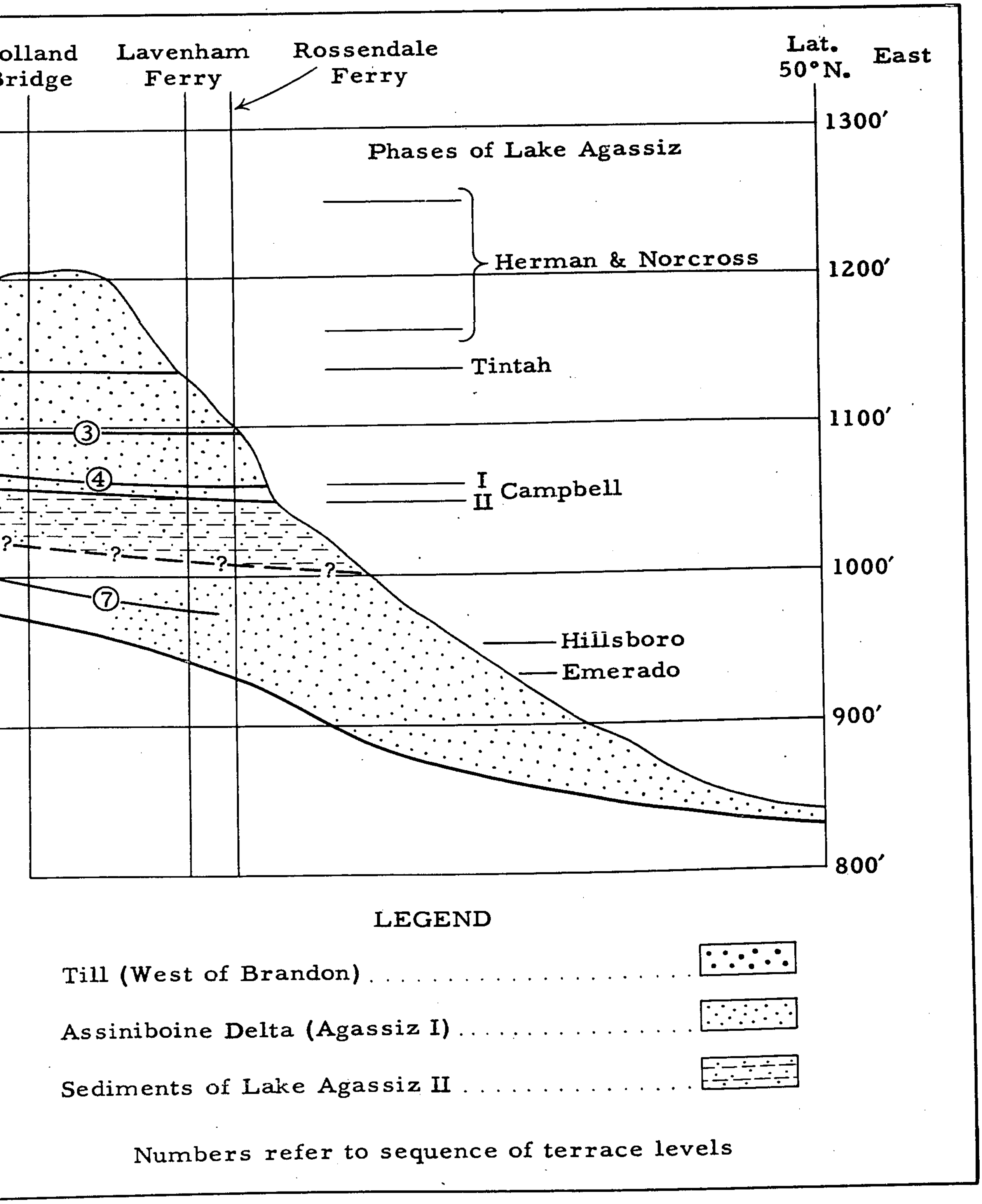
Assiniboine Delta (Agassiz I) . . . .

Sediments of Lake Agassiz II . . . .

Numbers refer to sequence of terrac

Figure 5-12

RETATION OF RIVER TERRACES OF THE ASSINIBOINE VALLEY



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OF THE ASSINIBOINE VALLEY

of Lake Agassiz II, were discussed in Chapter 3 (p. 132 - 134). The gradient of these terraces is about 0.6 feet per mile in the lower part of the valley, and they had a baselevel at an altitude of about 1,050 feet. At present, the valley fill terrace cannot be distinguished from non-paired terraces west of Stockton without detailed mapping.

Former gradients of Assiniboine River west of the delta

Detailed discussion of former channels of Assiniboine River west of the delta is beyond the scope of this dissertation, but the following general remarks contribute to an understanding of the problems of the delta.

A former channel of early Assiniboine River passes through Alexander (Pl. 6); east of Alexander it is consequent on the western part of the basin of the Brandon lake. Former channels of Minnedosa and Assiniboine Rivers, either ice-marginal or, probably, consequent on the floor of the regressing Brandon lake, also occur at Brandon and terminate in large bodies of gravel just east of the city.

The present Assiniboine valley west from Brandon is 1.0 to 1.5 miles wide, 125 to 200 feet deep and contains narrow terraces as wide as 300 feet. Most of the terraces have altitudes at Brandon that are near or lower than the highest known level of Lake Agassiz (1,235 feet, represented by scarps and bars northeast of Roundthwaite; see Pl. 5(c)). The best preserved terraces have an altitude of about 1,245 feet near Brandon and probably correlate with the strandline features near Roundthwaite. Other terraces near Brandon occur at altitudes of 1,260, 1,220, 1,205, and 1,190 feet. Terraces north of Oak Lake have an altitude of about 1,360 feet, and represent a very early phase of Assiniboine River.

Terraces at Brandon are correlated with gradients of the surface of the Assiniboine delta (Fig. 5-12). Gradient (1a) represents the apex of an early alluvial fan or of the early delta. Gradients (1b) and (1c) represent floors of the valley as the delta was deposited. Gradient (1c) correlates with an abandoned channel that trends east-northeast from Brandon to Douglas Station and then southeast across the delta.

CAPTURE OF SOURIS RIVER

The Souris valley from Pembina Trench to Assiniboine River

Between the north end of the gorge through the Tiger Hills and Assiniboine River, Souris River flows in a sinuous, steep-walled valley that ranges from 200 feet deep, near the Tiger Hills, to about 75 feet deep near Treesbank. Souris River falls from about 1,265 feet at the elbow in Pembina trench to about 1,100 feet at Assiniboine River. Ingrown meanders (Thornbury, 1954, p. 145) are common in township 7, range 17, and three of them (one in section 18-7-17 W. Prin., and two between Wawanesa and Treesbank) are abandoned. The meander scars downstream from Wawanesa have altitudes between 1,150 and 1,175 feet and the scars about 4 miles upstream from Wawanesa have altitudes of about 1,200 feet; all are about 25 feet above present river level. The tops of the meander cores have the same altitudes as the adjacent uplands on both sides of the valley. Slip-off slopes occur on the meander cores and on spurs in the valley. A well-preserved terrace with an altitude of about 1,180 feet, on the south side of the valley at Treesbank, represents a pause in valley deepening, and probably correlates with the Tintah phase terraces of Lake Agassiz in the Assiniboine valley.

The capture

Upham (1890, p. 34E-35E; 1895, p. 271-272) stated that Souris gorge originally was the outlet of a glacial lake discharging southward across the Tiger Hills moraine, and that Souris River turned north through the gorge when ice recession caused the lake to be drained.

If Souris River had turned northward suddenly from the floor of Pembina trench (altitude 1,380 feet), it would have deposited an alluvial fan near the north end of the gorge, 4 to 6 miles southwest of Wawanesa; however, no alluvial fan or delta was observed.

It is inferred that the Brandon lake was extinct when Souris River was captured by headward erosion of a tributary of Assiniboine River. The meander scars of Souris River have about the same radius as the present meanders, hence, the discharge of Souris River was about the same at the time of the capture as it is now (Dury, 1954). The capture must have occurred after glacier drainage in Saskatchewan began to discharge through the Qu'Appelle - Assiniboine River system. The meander cores have about the same altitudes as the adjacent uplands; it is believed that the meanders were established very early in the development of the valley, shortly after deposition of the adjacent part of the Assiniboine delta, and before Assiniboine River had incised the delta very deeply. The former gradient of Souris River, represented by the terrace a few feet below the upland surface south of Treesbank, correlates with terraces in the Assiniboine valley that represent the Tintah phase of Lake Agassiz I. The capture of Souris River occurred shortly before the Tintah phase of Lake Agassiz I.

HISTORY OF ASSINIBOINE RIVER IN THE DELTA AREA

Establishment of the present course

During the deposition of the Assiniboine delta in Lake Agassiz I, the course of Assiniboine River shifted at random. After the delta was deposited, a comparatively small river, comprising Little Souris River and a stream in the present course of Assiniboine River below the mouth of Little Souris River, discharged runoff from the land south of the delta into Lake Agassiz I. The main tributaries of this stream (former Little Souris River) included a small stream eroding headward into the Souris gorge, Oak Creek, and Cypress River.

After the delta was completely deposited, Assiniboine River flowed eastward from Brandon to Douglas Station (Pl. 1), from Douglas Station southeastward to the northeast corner of township 8, range 14, and from there eastward in its present course (Pl. 7 0) to the margin of Lake Agassiz I, which extended northward from Treherne. The additional discharge contributed by Assiniboine River to former Little Souris River, together with a lowering of baselevel (Lake Agassiz), rejuvenated the upper part of former Little Souris River. The tributary flowing northeast past Wawanesa from the Souris gorge eroded headward through the gorge and captured Souris River. The additional discharge of Souris River and continued lowering of Lake Agassiz I rejuvenated the Little Souris River system again, and another headward-eroding tributary extended northwestward and captured Assiniboine River just east of Brandon. Thus, the present course of Assiniboine River was established before the Tintah phase of Lake Agassiz I.

Later History of the Assiniboine valley

After its present course was established, Assiniboine River eroded, alluviated and eroded its valley in response to fluctuations in the level of Lake Agassiz. Pauses in the subsidence of Lake Agassiz I are represented by paired terraces in Assiniboine valley graded to baselevels of about 1,135, 1,095, and 1,065 feet, representing the Tintah, lower Tintah, and Campbell phases of Lake Agassiz I, respectively. Evidence of pauses in the subsidence of Lake Agassiz I lower than the Campbell phase is concealed under an alluvial fill. The level of Lake Agassiz I is known to have fallen below an altitude of about 990 feet (p. 134), is inferred to have fallen below 870 to 895 feet (p. 123), and it seems probable that the lake was drained.

The level of Lake Agassiz II rose to an altitude of about 1,060 feet, and an alluvial fill (p. 132-134) that extended west of Glenboro was deposited in the flooded Assiniboine valley. Subsequent lowering of the lake caused Assiniboine

River to erode through the alluvial fill; non-paired terraces were cut at this time. Pauses in the subsidence of the lake may be represented by paired terraces not observed by the writer.

STRANDLINES OF GLACIAL LAKE AGASSIZ

PREVIOUS WORK

The beach ridges and wave-cut terraces of Lake Agassiz were noted by the earliest explorers in the west (Keating, 1825; Owen, 1852; Hind, 1859; Palliser, 1863; and Dawson, 1875). The first data on the strandlines were published by Upham (1890, p. 59E-79E, 92E; 1895, p. 26-27; 474-522) who used additional data collected by Tyrrell and discovered the present southward slope of the former water planes. Leverett (1932, p. 119-140) revised Upham's work and added more data collected by himself, Sardeson, Todd, and Johnston. Many of the data are from traverses spaced 25 miles apart, creating openings for errors in interpolations, especially where the beach ridges are very numerous or discontinuous.

W. A. Johnston (1946) compiled new data from traverses 10 to 20 miles apart in Manitoba and all previous data, and drew isobases on the former water planes. He revised the interpretation of the present slopes of the former water planes, introduced seven hinge lines, and adduced a history of crustal warping due to glacial loading and unloading.

C. C. Nikiforoff (1947) considered crustal warping to have been more or less coincidental with glaciation, but not the result of it. He used a geometric device to explain the apparent slope of the water planes, and thought Lake Agassiz formed when several smaller lakes separated by masses of stagnant ice coalesced.

Criticism

Although Upham (1896, pp. 26-27, Figs. 6 and 7) presented his interpretation of the situation of beach ridges (bars) and wave-cut scarps with respect to water level, neither he nor Johnston stated what altitude was measured. Commonly, the altitudes of the crests of beach ridges and of the toes of scarps are measured, but both of these are higher than the water plane they represent. In several places along the Manitoba Escarpment, the toes of scarps are controlled by resistant strata. Bars are mainly the products of storms; their size depends on the supply of debris, slope of the shore, size of waves, and duration of storms. The crests of bars may be as much as 10 feet higher than the water plane, though they are generally 2 to 4 feet higher. Zeuner (1945, p. 230) described a storm bar called Chesil Bank, near Portland, England, as "170-200 yards wide and in its highest part up to 42 ft.... above high-water mark." Also, the water supply to a glacial lake fluctuates from nil at the end of winter to a maximum in early autumn; these fluctuations may cause a variation of 5 to 10 feet in the altitudes of crests of bars.

G. M. Stanley (1936) thought that some abandoned bars (of Lake Algonquin) were subaqueous. Experimental work by King and Williams (1949, p. 81) showed that offshore ("break point") bars are usually destroyed when a lake subsides; hence, subaqueous bars are not likely to be misinterpreted as strandlines.

King and Williams also built swash bars (ordinary beach ridges) in a laboratory; these form above water level and are not destroyed when the level is lowered. The position of the standing water level is generally represented by the base of the onshore (lagoon) side of the beach ridge. In a laboratory study by Watts (1954), bars with crests from 0.4 to 0.9 feet above standing water level formed on an initial slope of 1 in 20 (about 265 feet per mile). The base of the landward side of the ridge ranged from standing water level to 0.35 feet higher, and was generally about 0.25 feet higher. In many experiments a terrace was cut on the lake side of the bar at about 0.8 feet below standing water level. Evidently the zone most consistent with the water plane is the base of the landward side of a swash bar; the sub-aqueous terrace is the next most reliable indicator of the water plane; and the crest of the bar least reliable. Because the crests of bars are generally the basis of data established in the literature, it is inadvisable to change to a new system in the study of Lake Agassiz, to which several workers have contributed; but it should be noted that the water planes were at least 2 to 5 feet lower than the data indicate. This error is small and need not alter general conclusions concerning crustal warping.

Serious errors result from interpolating strandlines through wooded areas, across such gaps as the Assiniboine valley, and where the cutting of a scarp destroyed older terraces and beach ridges. Continuous tracing of beach ridges by air photos is essential. For instance, Johnston (1946, Figs. 3 and 5) had to interpolate between traverses, and confused strandlines that occur close together at Elm Creek (cf. Upham, 1896, Pl. 36). He correlated a strandline (altitude 835 to 845 feet) that is a persistent scarp with a bar at the top and extends from Elm Creek to Portage la Prairie, with a strandline having an altitude of 855 to 860 feet on the north side of the Assiniboine River (cf. Pl. 5(c)). To explain the sudden increase of slope Johnston (1946, Fig. 2) placed hinge line No. 5 at Elm Creek. New data show that the Emerado, Gladstone, Burnside and Ossowa strandlines have about the same slope north of hinge line No. 5 as they do south of it (Fig. 5-14). According to Johnston, the Campbell strandline is unaffected by this hinge line, even though it is axiomatic that the older strandlines must undergo the deformation of the younger ones. Furthermore, the Burnside strandline appears to be the crest of a bar and the Ossowa strandline the toe of a scarp that together may represent a single water plane.

STRANDLINES OF THE TIGER HILLS REGION

The strandlines in the Brandon map-area (Pls. 1 and 5 (c)) are from 30 to 80 miles long in contrast to the hundreds of miles studied by Johnston and Upham. Those measured and traced by the writer (Pl. 5 (c)) can be compared with Johnston's data (Fig. 5-13). Plate 5 (c) shows strandline altitudes projected horizontally onto a vertical plane extending from the southeast corner of the map-area (latitude 49° N, longitude 98° W) northwest through Lavenham. Johnston (1946, fig. 1)

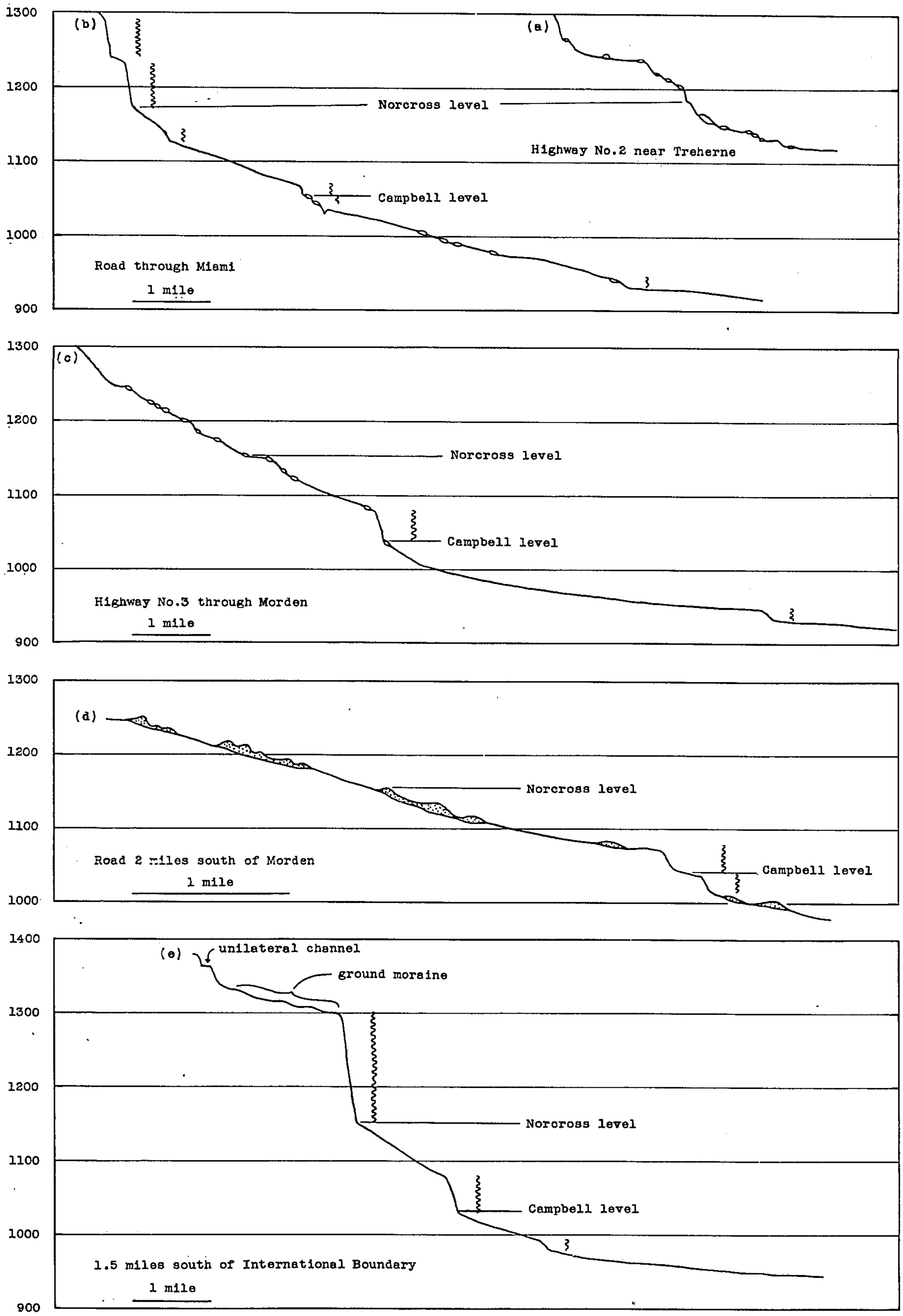


Figure 5-13

Shore profiles of glacial Lake Agassiz.
⌓ indicates bar.

showed that the strike of the former water planes trends about 60° to the west of this line: hence, the slopes of the strandlines in Plate 5 are less than the slopes of the former water planes. Points west of the plane of the profile appear low on the diagram while those to the east of the plane appear high. This partly explains the discrepancy (Fig. 5-13) between the writer's diagram and Johnston's illustrations.

The strandlines were named by Upham (1895). Their altitudes range from 835 feet (Ossowa strandline) at NE 24-8-5 W. Prin., to 1,265 feet (Herman strandline) near Treherne. Locally abundant bars and scarps (e.g. near Morden) cause confusion, hence, only the best-developed strandlines are shown (Pl. 5 (c)). These are the Norcross, Campbell, Emerado, Gladstone and Burnside strandlines, in descending order. The last two may actually be the Burnside and Ossowa strandlines, as discussed below.

Profiles across the strandlines are presented in Figure 5-13. Profile (e) shows mainly wave-cut scarps and terraces, whereas profile (d), on a larger horizontal scale, shows mainly beach ridges. The variation in data derived from beach ridges may be seen by comparing profiles (d) and (c) which are only 2 miles apart (see also Pl. 5 (c)).

<u>Description of the Strandlines</u>

The strandlines are discussed in order of their altitudes, beginning with the highest, and oldest:

1. <u>Herman</u>: The Herman strandlines are between altitudes of about 1,160 and 1,260 feet (Johnston's data) near

Morden and form a series of bars (Fig. 5-13)(c) and (d)). The surfaces of the Pembina and Assiniboine deltas are at Herman levels; because of crustal warping, the surface of the Assiniboine delta (1,250 feet) is highest. Several scarps suggest longer stands at certain Herman levels, viz. at Miami (1,235 feet), Roseisle (1,265 feet), Rathwell (1,240 and 1,260 feet) and Treherne (1,220, 1,250 and 1,265 feet). At Roseisle the 1,265-foot terrace is cut on ice-contact stratified drift in section 25-6-8 W. Prin., and there are several kettles in the terrace, as deep as 30 feet. Hence, buried blocks of glacier ice were present when the highest Herman strandlines formed.

2. Norcross: The Norcross strandlines at Morden are a series of bars ranging from 1,130 to 1,155 feet (Johnston, 1946). A well-developed scarp (Pl. 5 (c)) also belongs to the upper Norcross phase (altitude about 1,160 feet at Morden). The toe of this scarp rises from about 1,150 feet near Walhalla to 1,185 feet near Treherne. From Treherne north, the strandline appears to be nearly horizontal; it crosses No. 1 highway (Pl. 1) at 1,185 feet. Thus, the slope of the strandline decreases from 1.2 feet per mile south of Treherne to nearly horizontal north of Treherne. The lower Norcross strandlines are bars near Morden, a scarp at Roseisle (toe at about 1,150 feet) and bars near Treherne.

3. Tintah: Johnston placed the Tintah phase of Lake Agassiz between altitudes of 1,080 and 1,110 feet at Morden; Upham stated that a boulder-strewn terrace, near Morden, between

altitudes of 1,070 and 1,125 feet represents the Tintah phase. A well-developed bar on the terrace at an altitude of about 1,085 feet may represent the main Tintah strandline. It comprises scarps and bars northeast of Thornhill, south of Rathwell, and near Treherne, and terraces in the Assiniboine valley. The upper Tintah strandlines are poorly represented.

4. Campbell: The Campbell strandline is the most prominent, and has an altitude of about 1,245 feet at Morden. It generally comprises a scarp, as high as 70 feet, with a massive beach bar at the base, and in several places a second bar about 10 feet lower than the first bar. (Fig. 1-2). This strandline slopes southward from Roseisle at about 1.4 feet per mile. North of Roseisle to Highway No. 1 the slope is about 0.4 feet per mile. From Assiniboine River to Rathwell the position and altitude of the Campbell strandline are uncertain, and it may slope slightly north rather than of south. The two Campbell beach bars are more widely separated, vertically and horizontally, north of Highway No. 1 (main line of the Canadian Pacific Railway) than in the Tiger Hills region (see Upham, 1890, p. 70E; Johnston, 1946, p. 3). The upper strandline represents a relatively long phase of Lake Agassiz I, when it discharged southward over a bedrock sill near Lake Traverse, Minnesota. The lower bar represents Lake Agassiz II, formed when a glacier readvance blocked the eastern outlet of the Lake Agassiz basin. Hence, the two Campbell bars are relatively widely separated in time. They may represent two Wisconsin substages, the upper one Cary (Mankato?) and the

lower one Valders, or alternatively, Valders and Cochrane.

5. McCauleyville: The McCauleyville strandlines are from 30 to 50 feet lower than the upper Campbell strandline and are best developed in the south of the Brandon map-area. The McCauleyville waterplanes are represented near Morden by bars at altitudes of about 1,000 and 1,010 feet and by a scarp with its toe at about 1,025 feet; near Walhalla and the International Boundary by scarps 15 feet high; by a gentle scarp on Highway No. 2; and by a steepening of slope on Highway No. 1. The slope of these strandlines is parallel to that of the Campbell strandline. Upham stated that the McCauleyville was the lowest phase of Lake Agassiz to discharge southward, but Leverett (1932, p. 139) thought that southward flow was improbable.

6. Blanchard: The Blanchard strandline is a discontinuous bar a mile east of Morden and Miami, the crest of which has an altitude of about 980 feet at Miami. This bar has been breached by many streams from the Pembina Mountains, and locally is buried under alluvium.

7. Hillsboro and Emerado: Like Johnston (1946, p. 3) the writer had difficulty in deciding which of the lower (below 1,000 feet) strandlines were named by Upham. Several bars are at the tops of a low scarp(s) and the position(s) of the water plane or water planes is (are) uncertain. The Hillsboro strandline is probably the bar and scarp that extend northwest from 4 miles east of Morden to 1.5 miles west of Rosebank. Near Rosebank the crest of the bar has an altitude

of about 945 feet, and the toe of the scarp an altitude of 930 feet. The bar seems to be Upham's Hillsboro strandline, and the toe of the scarp fits his Emerado strandline. Farther north, a scarp 10 feet high south of Portage la Prairie fits the Emerado strandline and a similar scarp on Highway No. 1 fits the Hillsboro strandline. If the correlations are correct these strandlines slope southward at less than 0.5 feet per mile (Fig. 5-14).

8. Ojata and Gladstone: The Ojata strandline is very poorly developed in the Brandon map-area; Upham (1890, p. 74E) had difficulty following this strandline into Canada. A scarp south of Portage la Prairie, with its toe at an altitude of about 900 feet, may belong to the Ojata phase. The Gladstone strandline is a scarp 10 feet high with a bar along its crest locally, and is best developed about 1 mile west of Burnside where the toe of the scarp has an altitude of about 875 feet. The writer's measurements of this strandline indicate that it is nearly horizontal, but Johnston (1946, fig. 2) showed that the water plane sloped southward at about 1.5 feet per mile north of Elm Creek.

9. Burnside and Ossowa: These strandlines have a relationship to each other similar to that of the Hillsboro-Emerado strandlines. Most of the Burnside strandline is a bar at the top of a scarp 10 feet high; the crest of the bar has an altitude of about 845 feet near Elm Creek. The bar and scarp pass through Arona, about 3.5 miles east of Burnside, where the crest of the bar is at about 860 feet. This strandline slopes

southward at about 0.5 feet per mile. The toe of the scarp, at about 835 feet at Elm Creek, appears to be the Ossowa strandline of Johnston (1946, fig. 2). The hinge line that Johnston placed at Elm Creek is probably the result of an error in interpolating the strandlines across Assiniboine River: he connected the Burnside bar at Elm Creek to the Gladstone strandline at Burnside. The slopes of all the lower strandlines north of Elm Creek (Fig. 5-13) apparently are less than those shown by Johnston.

Probably some strandlines comprising scarps with bars at the top have been interpreted as two strandlines instead of as a single one, as shown by G. M. Watts (1954).

Conclusion

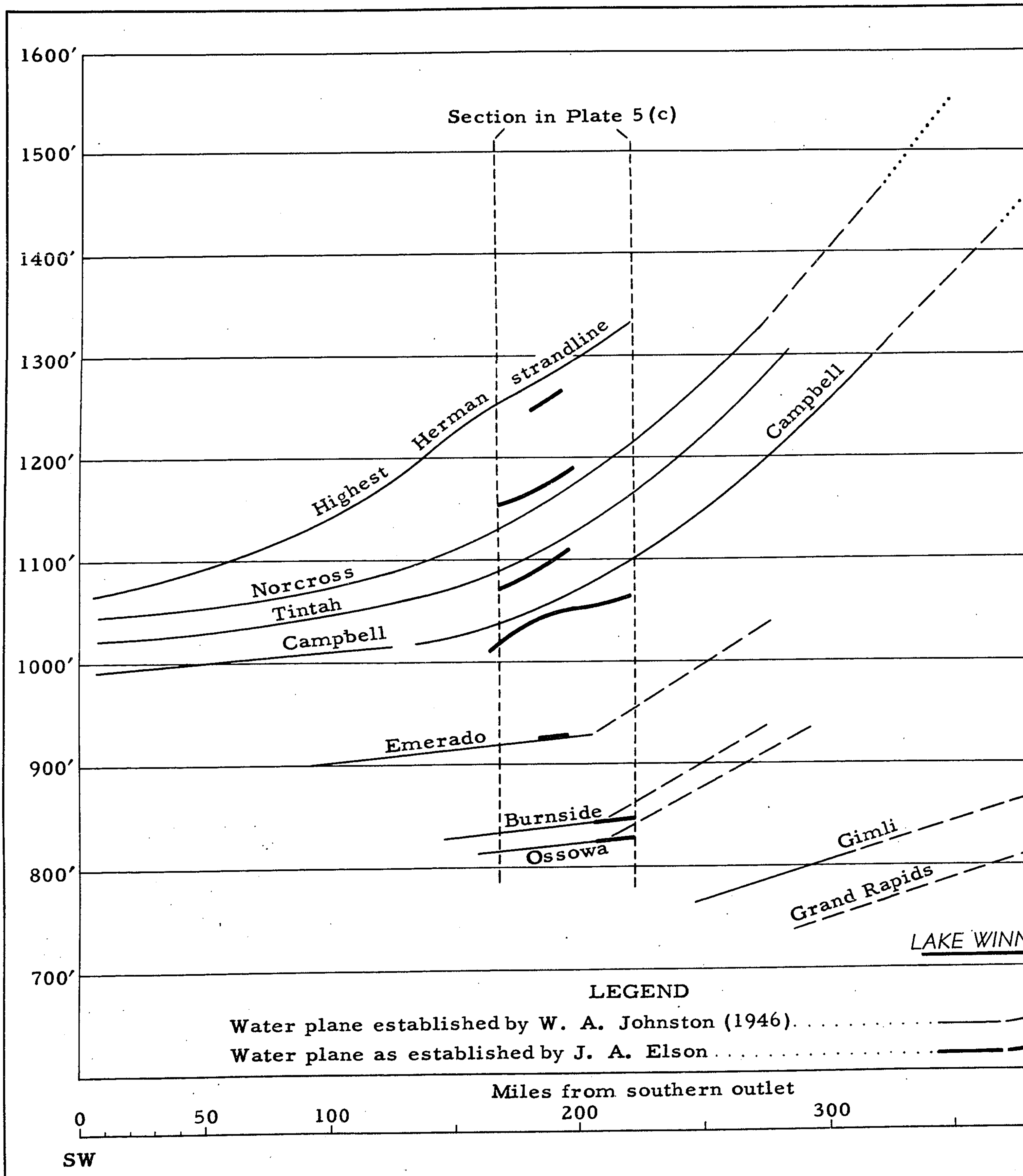
Upham grouped the strandlines of the Lake Agassiz basin to fit into nine main phases of the lake's history. During the highest four phases the lake flowed southward through the Lake Traverse, Minnesota, outlet (River Warren). The highest (Herman) phase of the lake is represented by scarps, bars and the surfaces of the Assiniboine and Pembina deltas. After the highest Herman phase, the lake level dropped rapidly about 100 feet to the upper Norcross level. This phase lasted for a considerable period, then the lake level continued to fall, with a pause during which the Tintah strandline formed about 70 feet below the upper (main) Norcross strandline. Subsidence of the lake continued to the Campbell level, whereupon further deepening of the Lake Traverse outlet was retarded by bedrock. Ice retreat opened an eastern outlet and Lake

Agassiz drained. A readvance of the ice margin that blocked the eastern outlet and the Lake again filled to the Campbell level. As a result, the Campbell strandline is a scarp with two bars at the toe. It slopes from about 1,030 feet at the International Boundary to about 1,070 at latitude 50°.

The upper Lake Agassiz strandlines (not to be confused with the water planes, which slope more steeply in a different direction) slope southward at from 1.3 to 1.5 feet per mile, except where they cross the Assiniboine delta and slope southward less than 0.5 feet per mile.

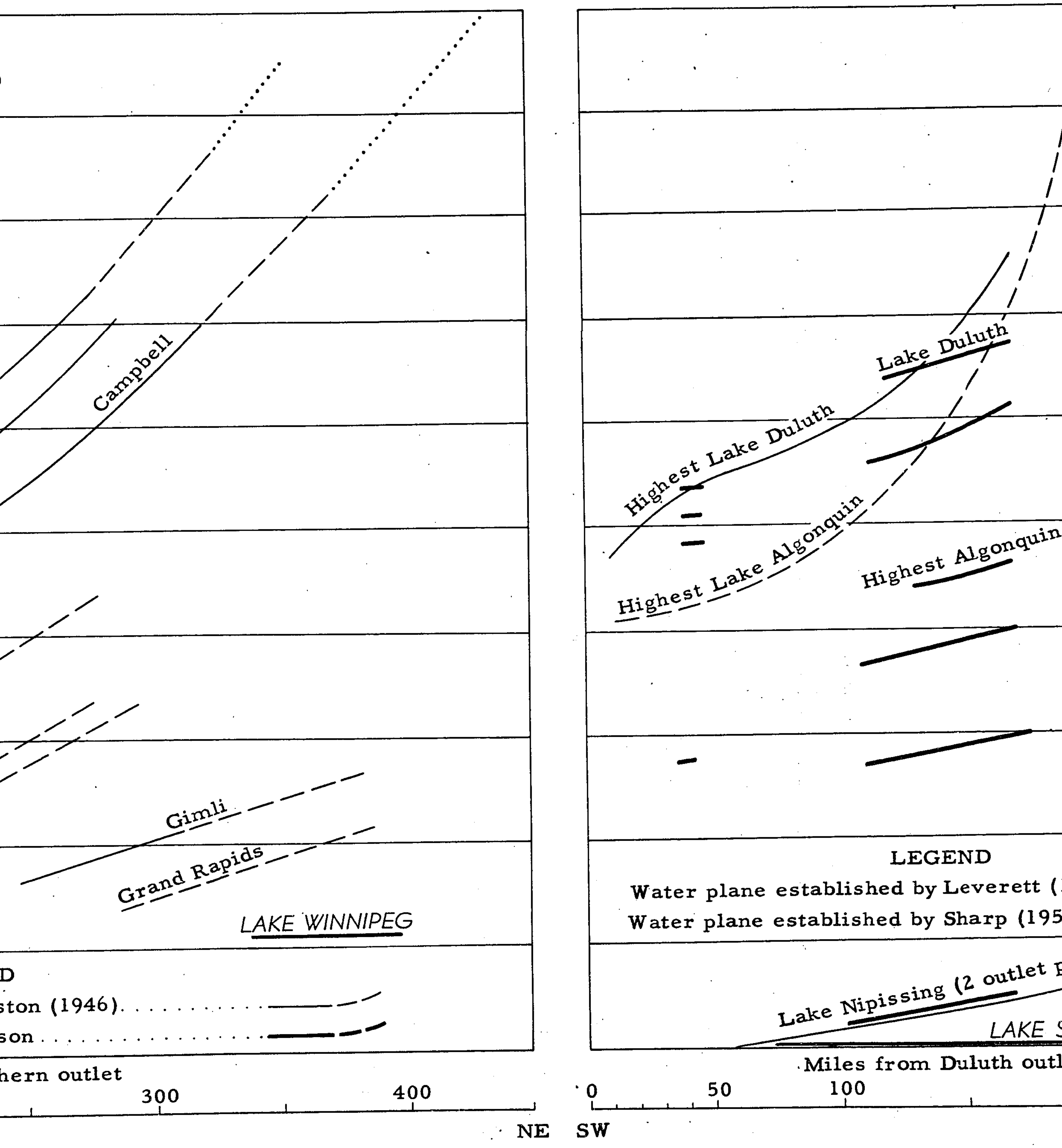
The lower strandlines, below the Campbell level, are difficult to trace, especially north of Miami where they have been obscured by windblown sand. They include the McCauleyville, Blanchard, Hillsboro and Emerado, Ojata and Gladstone, Burnside and Ossowa strandlines. The last 3 pairs generally comprise bars (given the first name of the pair) at the top of scarps (the toes of which are given the second name) and may represent only one water plane per scarp and bar. These have been shown incorrectly as sloping south at 1.5 feet per mile, north of a hinge line at Elm Creek, by W. A. Johnston. Their actual slope is about 0.5 feet per mile, much less than the slope of the Campbell and higher strandlines.

Detailed mapping of the shore features north of latitude 50° will probably show that the lower Campbell bar is part of the lower (younger) strandline series and splits from the upper Campbell strandline to conform to the slope of the lower water planes. This would be in accord with less crustal



(a) Present position of selected former water planes in the Lake Agassiz b

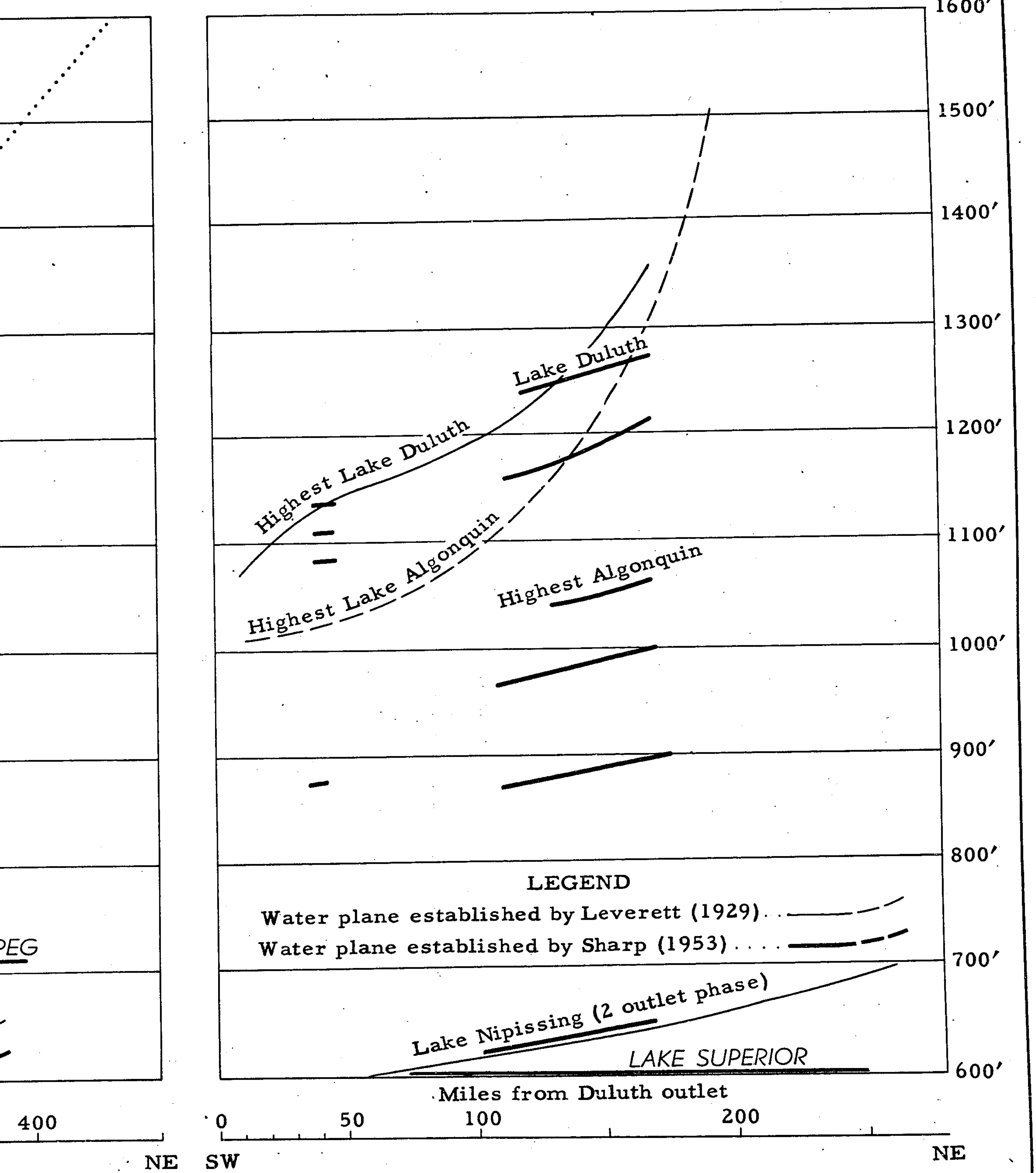
Figure



r planes in the Lake Agassiz basin

(b) Present position of selected former water pla

Figure 5-14



sin (b) Present position of selected former water planes Lake Superior Basin

5-14

uplift due to the greater distance from the glacier that recreated Lake Agassiz after the post-upper Campbell phase of drainage and subaerial erosion. The ice-sheet responsible for Lake Agassiz II differed from its predecessor in that the center of outflow (and area of maximum crustal depression) was much farther removed from the lake basin, and had shifted eastward.

POSSIBLE ISOSTATIC ADJUSTMENT OF THE ASSINIBOINE DELTA

Isostatic adjustment is commonly thought of in terms of features much larger than the Assiniboine delta. The phenomena discussed below may be the result of local crustal weakness rather than isostatic adjustment.

The southward slope of the older shores of Lake Agassiz, represented by the higher Norcross and Campbell strandlines, decreases from 1.5 feet per mile to less than 0.5 feet per mile where the strandlines cross the Assiniboine delta. North of the delta strandline slopes are steeper (Johnston, 1946, fig. 2). The changes in slope are too great to be accounted for entirely by inaccurate altimetry or geometric distortion of data during construction of the profile (Pl. 5 (c)).

Over most of the area west of the Manitoba Escarpment, the unconsolidated deposits are less than 40 feet thick, but the Assiniboine delta (Fig. 3-22) consists of as much as, and locally more than, 300 feet of sediment. As noted above strandlines on this thick wedge of sediment slope less than they do elsewhere.

Prior to formation of the higher strandlines of Lake

Agassiz, the valley now occupied by the Assiniboine delta was filled by glacier ice, which ascended the Manitoba Escarpment so that the margin of the glacier reached an altitude of 1,600 feet. The delta area was ice-covered to a depth of at least 700 or 800 feet for a long time, and the earth's crust probably attained isostatic balance.

When the highest Lake Agassiz strandline formed, the earth's crust under the Assiniboine delta had been relieved of its load of glacier ice. This load amounted to at least 800 (feet of ice) multiplied by a specific gravity of 0.9, the weight of 720 feet of water. When the ice sheet withdrew and before much isostatic adjustment could take place, about 300 feet of deltaic sediment was deposited, with a specific gravity of approximately 2.35. This sediment had the weight of about 705 feet of water, and compensated for the former ice sheet. Thus, this part of the earth's crust retained it load and there was little crustal adjustment there compared to adjacent areas. Hence, the delta did not undergo much differential uplift, and the strandlines on it are more nearly horizontal than those nearby.

If the adjustment of the delta is incomplete, or if there is an unadjusted difference in the constitution of the earth's crust due to the delta, a gravity anomaly should be present. Geophysicists, whom he is not at liberty to name, informed the writer that an anomaly does occur where expected, but they were not free to disclose its nature.

The crest of the Darlingford anticline (p. 40) coincides roughly with the zone of change in slope of the Lake Agassiz strandlines. Perhaps this anticline represents crustal warping associated with isostatic adjustment.

The area involved in this possible demonstration of isostatic adjustment is about 1,200 square miles. The thickness of the delta may average about 250 feet. Geologists generally agree that adjustment of so small a unit is improbable, and the relationships seem too close to be true. The distortion of the strandlines across the delta may result from movement in a zone of crustal weakness of long duration that has been responsible for the position of the Assiniboine valley through Cenozoic time.

MINOR NON-GLACIAL DRAINAGE FEATURES

ASSINIBOINE DELTA AREA

Channels of the depositional phase

Parts of channels used by Assiniboine River during deposition of the delta appear as abandoned segments and as isolated scarps (Pls. 1 and 3). Many of these features have been obscured by windblown sand; in several places only one side of a channel remains, resembling a strandline scarp.

The largest former channel trends northeast from Chater (Pl. 1) to Douglas Station, then southeast to the present Assiniboine valley, and is about 29 miles long. The eastern part is occupied by a marsh, as wide as 3 miles, drained by Epinette Creek; most of the channel is about 1 mile wide. The altitude of the floor increases from about 1,215 feet at Chater to 1,220 feet at Douglas Station and then decreases to about 1,200 feet 2 miles southeast of Onah. The reversal of gradient between Douglas Station and Chater is partly the effect of erosion and partly the result of differential uplift of the delta.

An inconspicuous former channel of Assiniboine River trends east through township 8, ranges 11, 10, and 9 (Pls. 1 and 3) and connects a tributary of Cypress River to Boyne (Morris) River. This channel antedates the Tintah phase of Lake Agassiz I.

Scarps of abandoned channels occur south and west of Stockton in township 7, ranges 15 and 16; in sections 7 and 8 8-13 W. Prin.; and in township 8, ranges 11 and 12.

Valleys of the Lake Agassiz (Campbell phase) shore

Several steep-sided, flat-floored ravines on the Assiniboine delta north of Assiniboine River terminate at the Campbell scarp (Pl. 1, 1,050-foot contour; Pl. 7 P and Q). These ravines are 100 feet to 0.5 mile wide at the bottom, 20 to 150 feet deep, and only the largest of them contain streams. The floors are generally marsh and locally alluvium is covered by as much as 5 feet of *Carex* peat. The gradient of the floor of the largest ravine (Pine Creek), 2 miles west of Firdale and Melbourne, ranges from 7 to 30 feet per mile, with an average of about 15 feet per mile. The floors of all the ravines are graded to the Campbell phase of Lake Agassiz II. A gravel beach ridge extends across the mouth of a ravine 2 miles west of Austin (NW 24-11-12 W. Prin.). Alluvium in a ravine south of Rossendale (SW 35-9-9 W. Prin.) contained a molluscan fauna indicating deposition in a lacustrine environment (Chapter 4).

It is inferred that these ravines were eroded during and after the Campbell phase of Lake Agassiz I, and were flooded and alluviated during the Campbell phase of Lake Agassiz II.

VALLEYS ON PEMBINA MOUNTAIN

Gullies on the east slope of Pembina Mountain are shown by contours and intermittent streams (Pl. 1) and by hachures and belts of "older alluvium" (Pl. 3). They were not studied in detail because of extensive forest cover.

These short valleys range in depth from about 30 feet, south of Morden, to more than 200 feet near Leary's, where the slope of Pembina Mountain is steepest. The valleys generally have U-shaped cross profiles near the Manitoba Escarpment (the 1,200-foot contour) and are flat-bottomed farther upstream. From the zones of transition from flat floors to U-profiles, gullies in the valley-floors extend downstream to the Campbell scarp (1,050-foot contour) so that the U-shaped parts of the valleys have a two-cycle (valley-in-valley) form. Downstream from the Campbell strandline, the streams occupy shallow channels across alluvial fans. The U-shaped portions of the valleys and the flat-floored upstream portions apparently are graded to the Campbell phase of Lake Agassiz. The outer margins of the terraces in the two-cycle valleys grade into "pediment slopes" (Frye and Leonard, 1954, p. 246, fig. 2) which suggests that the cutting power, hence the discharge, of the streams was reduced as the valleys deepened.

Several valleys north of Thornhill contain high-level paired terraces 10 to 30 feet below the upland surface, representing initial glacial spillway phases of the valleys; several of these connect with known spillways (e.g. 4 miles north-northwest of Thornhill). A few terraces represent valley floors graded to various levels of Lake Agassiz I: terraces on the south branch of Tobacco Creek 3 miles west of Miami are graded to an altitude of 1,220 to 1,240 feet.

Several of the U-shaped valleys have meanders incised so deeply that the meander cores were destroyed; theatre-forms are common. Similar features occur in the upper Pembina valley in range 16, and in the Whitemud valley from Holmfield to Badger Creek. G.H. Dury (1954) showed that the size of the loop of a meandering valley is closely related to stream discharge, and that streams that formed large loops had much greater discharge than present streams. Underfit streams meandering in the bottoms of meandering valleys in the Tiger Hills region support Dury's theory: a moderately rapid decrease of discharge would account for the U-profile of the first-cycle valley form. It is inferred that a reduction of discharge, hence precipitation, is indicated by the meandering valleys on Pembina Mountain. The inferred reduced discharge of Whitemud Creek and upper Pembina River is attributed to extinction of the Boissevain glacial lake, and to stream piracy, as well as to climatic changes.

STEEL'S LAKE

Steel's Lake, about 1 mile long, west to east, and 0.5 to 0.75 mile wide, is in section 3-4-13 W. Prin., a mile northwest of Glenora. Two small ponds to the east were once part of the lake, which is 40 to 80 feet below the surrounding upland, and has no tributary streams or outlets. The lake depression is a large kettle in end moraine composed mainly of non-compact silty till.

When the lake was visited, in June, 1950, its margin was 150 to 200 feet from, and 12 to 15 feet lower than the base of a wave-cut scarp, 8 to 20 feet high. A small, well-developed beach ridge is about 8 to 10 feet lower than the toe of the scarp and about 70 feet from the 1950 margin of the lake. The lake is estimated to be about 20 feet deep, and was about 40 feet deep when the scarp was cut.

According to A. E. Macklin of Glenora (oral communication), the lake level has been falling since 1885, with minor fluctuations in abnormally wet and dry years, and a low island appeared in the center in approximately 1940. The water level has not stood at the toe of the scarp within the memory of local residents. In the dry period in the early 1930's the water level was lower than at present and tree stumps, thought to be oak, were exposed near the shore.

Steel's Lake is believed to have resulted from the melting of a stagnant ice block after the last glacier withdrew from the area. The lake stood about 15 feet above its present level for a long interval, and cut strandline scarps

8 to 20 feet high. Subsequently, during a dry interval (the altithermal?), the lake partly or completely evaporated and an oak forest occupied part or all of the basin. More recently, a moist climate caused the lake level to rise and the oak forest was killed; since then the lake has continued to subside, with minor fluctuations. There are no outlets, hence, the lake level is controlled by precipitation and evaporation. At present the history of Steel's Lake cannot be correlated closely with other events in the Tiger Hills region.

GENERAL CONCLUSION

Study of present and former drainage systems and lakes in southwestern Manitoba reveals that glacial and proglacial lakes formed in three main basins as the last ice sheet retreated. In chronological order, these were the Souris basin lakes, west of the Tiger Hills region, the Brandon lake, north of the Tiger Hills, and Lake Agassiz, north of the Tiger Hills and, mainly, east of Pembina Mountain. The phases of the Souris basin lakes (glacial Lake Souris and proglacial Lake Hind) are correlated with the phases of the Brandon lake by means of terraces in Pembina trench and spillways across the Tiger Hills. Lake Agassiz existed after the other lakes.

The sequence of lakes and watercourses south of the Tiger Hills - Darlingford moraine system and west of longitude 100° indicates that a lobe of the last ice sheet withdrew northwestward ("northwestern ice"). While the northwestern ice withdrew, a south-flowing ice lobe in the Lake Agassiz basin ("northern ice") remained quiescent and then advanced slightly before its final retreat. A sublobe of the northern ice extended westward up the Assiniboine valley as far as Griswold.

Phases in the retreat of the northwestern ice are recorded by terraces in Pembina trench, by lake outlets, and by outwash channels west of the Lake Souris basin. The Pembina "delta" is probably not a delta but an alluvial fan that was deposited in a reentrant between the northern ice lobe and Pembina Mountain, and was subsequently modified by wave action in Lake Agassiz.

The Assiniboine delta probably was deposited in a rising phase of Lake Agassiz; the northeast part of it may have been deposited against a glacier margin.

Terraces in the Assiniboine valley indicate that the level of Lake Agassiz I was stable during the Tintah and Campbell phases. Later the lake subsided and may have been drained; streams across the Assiniboine delta deepened their valleys, which were alluviated when Lake Agassiz II formed and rose to the Campbell strandline. Final drainage of Lake Agassiz II resulted in the cutting of non-paired terraces by Assiniboine River.

Entrenched meanders in several valleys containing underfit streams, in the south part of the Tiger Hills region, indicate that discharge has been reduced since the valleys formed; it is inferred that the climate was once more humid than at present. The history of Steel's Lake indicates that a climate cooler and moister than the present one was followed by a climate warmer and, possibly, drier than the present one.

The southward slope of Lake Agassiz I strandlines (1.3 feet per mile) is much greater than the slope of Lake Agassiz II strandlines (0.5 foot per mile). This is believed to be due to an ice sheet having been closer to this part of the lake basin during Lake Agassiz I than it was during Lake Agassiz II. A hinge line at Elm Creek, inferred by W.A. Johnston, probably is the result of an error in interpolating strandlines across Assiniboine River. The lower strandlines of Lake Agassiz II probably slope less than was indicated by Johnston.

Chapter 6

PLEISTOCENE HISTORY OF THE TIGER HILLS REGION

INTRODUCTION

Plate 7 is a graphic presentation of various phases in the Pleistocene history of the Tiger Hills region and adjacent areas; place names appear on the index map (in the space next the legend), and are abbreviated to their first letters on succeeding maps. All maps in this plate are the same scale; the relative positions of Plates 1, 2, 3, 4, and 6 are shown for reference. The outline of the Tiger Hills region (Pl. 3), the International Boundary, Turtle Mountain, Pembina Mountain(s), and six important towns form a frame of reference on all maps. For simplicity, glacial features and drainage lines are omitted from subsequent maps after their historical significance is established. The time intervals between the phases described in the text and shown on Plate 7 are not necessarily equal. The letters designating the phases shown in Plate 7 correspond to those in the text.

PRE-PLEISTOCENE HISTORY

Epeirogenic uplift followed Cretaceous marine submergence during which shales, including the Riding Mountain formation, were deposited. The non-marine Boissevain sandstone was laid down on a newly-emerged lowland. A subsequent minor marine submergence in North Dakota resulted in deposition of the Cannonball formation which may form part of the west end of Turtle Mountain. Epeirogenic uplift renewed non-marine deposition, and the Paleocene (?) Turtle Mountain formation (p. 39) covered the Cannonball formation and the Boissevain sandstone. The Turtle Mountain formation and its western correlatives (Fort Union formation, Ravenscrag formation) formed a broad plain sloping eastward from the Cordillera. There are no data on the maximum eastward extent of the Paleocene deposits, and there is scant sedimentary record of events in southwestern Manitoba from Paleocene to Pleistocene times.

Mountain-building in the Cordillera was accompanied by epeirogenic uplift of the plains in late Pliocene and early Pleistocene times. Rivers on the plains were rejuvenated, and a large river system, here termed "ancestral Assiniboine River", occupied the general position of the present Assiniboine River across the Manitoba Escarpment. The watershed of ancestral Assiniboine River probably included areas drained by the former Knife, Missouri, Qu'Appelle, and South Saskatchewan Rivers.

The central and western parts of the Tiger Hills region drained northward into ancestral Assiniboine River (Pl. 7A; Pl. 2) in preglacial times, and the southwest and southeastern parts drained southward and southeastward into North Dakota. Relief in southwestern Manitoba was then about 1,600 feet, in contrast to about 1,000 feet at present. The landscape was characterized by broad, gently-sloping plains and mesa-like uplands, bounded by steep slopes (rather than cliffs). Streams on the lowlands were mature, whereas those on the uplands were in the youthful part of the fluvial cycle.

GLACIAL HISTORY

EARLY PLEISTOCENE EPOCH

A deposit of sand and gravel 1 mile east of the town of Souris (Pl. 7A) contains a pebble assemblage similar to the late-Precambrian Belt Series of Montana[1]. Granitic pebbles are rare, and may be from the Canadian shield; if so, the gravel comprises reworked deposits of previous glaciation. Crossbedding indicates that the sand and gravel were deposited from the west; apparently the deposit is on a preglacial interfleuve. The gravel resembles the so-called Flaxville gravel except for the granite pebbles. Because of the uncertain relationship to the enclosing Wisconsin drift, the presence of the granite pebbles, and the similarity to low-lying gravels of Pleistocene age near Great Falls, Montana (Lemke, Esrskine, and Maughn, 1954) and near Fort Qu'Appelle, Saskatchewan, the gravel at Souris is tentatively considered to be early Pleistocene. It may represent the course of former Knife River or former Missouri River after the Kansan or Nebraskan glaciation.

WISCONSIN AGE

First recorded glaciation

Evidence of the last glaciation of southwestern Manitoba consists of an unweathered till sheet, having a striated boulder pavement on its upper surface, overlain by a second till sheet. The deposits below the striated boulder pavement may represent a middle-Wisconsin substage (Tazewell?).

1. R.W. Lemke, U.S. Geological Survey, oral communication.

Interval of non-deposition

The striated boulder pavement below the uppermost till sheet in southwestern Manitoba probably represents a major change in glacial regimen that may have involved a margin retreat of substage magnitude (p. 97) near Des Moines, Iowa, about 500 miles south of the Tiger Hills region. It may correlate with the Tazewell-Cary interval (Ruhe, 1952), or with a glacier fluctuation in Cary time, or with the Cary-Mankato interval (Ruhe, 1954, p. 792).

Cones of Black Suruce (*Picea Mariana*), found beneath 90 feet of drift on Turtle Mountain, indicate that the climate during one interval of deglaciation was colder and moister than it is at present: the interval represented may be the Iowan-Tazewell (Peorian) interval (p. 182-183).

Final deglaciation

The last ice sheet that covered southern Manitoba extended southward as far as the Altamont moraine in Minnesota and North Dakota. During deglaciation the ice generally flowed southeastward, and the concentric arrangement of washboard moraines and minor moraines show that an ice front withdrew northwestward across southwestern Manitoba: southeast-flowing ice is termed "northwestern ice". A sublobe of a more vigorous ice tongue (hereafter termed "northern ice") that flowed southward in the Lake Agassiz basin extended westward and southward into the Tiger Hills as the northwestern ice withdrew; apparently the direction of flow shifted during deglaciation, but the ground was not uncovered as it occurred. It resulted from an eastward shift, from northern Alberta and Saskatchewan into northern Manitoba, of centers of outflow in the Laurentide ice sheet.

The first phase of the deglaciation of southwestern Manitoba is illustrated in Palte 7B. Table 6-1 is a chart showing the sequence and mutual relations of various lakes and associated features formed during deglaciation.

A. Preglacial drainage: The preglacial history of southwestern Manitoba and the early glaciations were discussed above.

B(1). Turtle Mountain phase: As the ice sheet thinned during deglaciation, the part covering Turtle Mountain stagnated, whereas thicker ice in sublobes west and east of the mountain flowed southeastward. The eastern sublobe deposited a lateral moraine that trends southward from the east end of the mountain (Upham, 1895, pl. 21; confirmed by R.W. Lemke, oral communication). Further east, on Pembina Mountain, the ice margin retreated northwestward and washboard moraines were deposited. The western margin of the northern ice (in the Lake Agassiz basin) was along the east side of Pembina Mountain. The northern ice and the northwestern ice merged north of Morden.

B(2). Cardinal moraine phase: The northwestern ice no longer covered Turtle Mountain, but terminated on the north and west slopes, where small end moraines were deposited. Southwest of Turtle Mountain, glacial Lake Souris was ponded between high ground and the shrinking glacier. Washboard moraines were deposited near Cartwright; farther east the ice front was stationary and a discontinuous end moraine that extends about 25 miles southwest of Cardinal was deposited. The northern ice and northwestern ice formed a continuous sheet north of Cardinal; south of Cardinal the northern ice terminated against Pembina Mountain.

The Wood Bay channel formed the upper part of a glacial spillway system that conducted meltwater southeastward through Pembina trench and probably extended southward along the Manitoba Escarpment to the Elk Valley "delta" (Fig. 6-1).

C. Whitemud spillway phase: The glacier sublobe in the Lake Souris basin northwest of Turtle Mountain continued to shrink and Lake Souris continued to expand northward south of the International Boundary. The ice margin northwest and north of Turtle Mountain was stationary. The margin east of Killarney retreated and deposited washboard moraines. The ice front northeast from Neelin to township 7, range 10 was stationary and deposited end moraine, mainly composed of ice-contact stratified drift. The margin of the northern ice rested against Pembina Mountain. Outwash was deposited south of the ice front between Rock Lake and the northeast corner of township 6, range 10. Meltwater from an ice margin extending from Turtle Mountain to Cardinal collected in the Whitemud spillway (then the upper part of Pembina trench) and in Cypress River, which then flowed southward west of Swan Lake into Pembina trench. The Wood Bay channel was abandoned for a lower route 2 miles east. A valley train was deposited in

Figure 6-1

SURFICIAL GEOLOGY OF THE LAKE AGASSIZ BASIN
(after Flint et al, 1945; Leverett, 1932; Hansen, 1952)

LEGEND

Lake Agassiz (maximum extent according to Flint et al, 1945) . . . .

Strandlines

Campbell: known, inferred . . . .

Norcross: inferred (possible eastern outlet only) . . . .

Altitude in feet 1500

Outlets, known, inferred . . . .

End moraine . . . .

Boulder belt . . . .

Mankato-Cary boundary; Valders-Cary boundary . . . . M / C

Grey drift-red drift boundary . . . . g / r

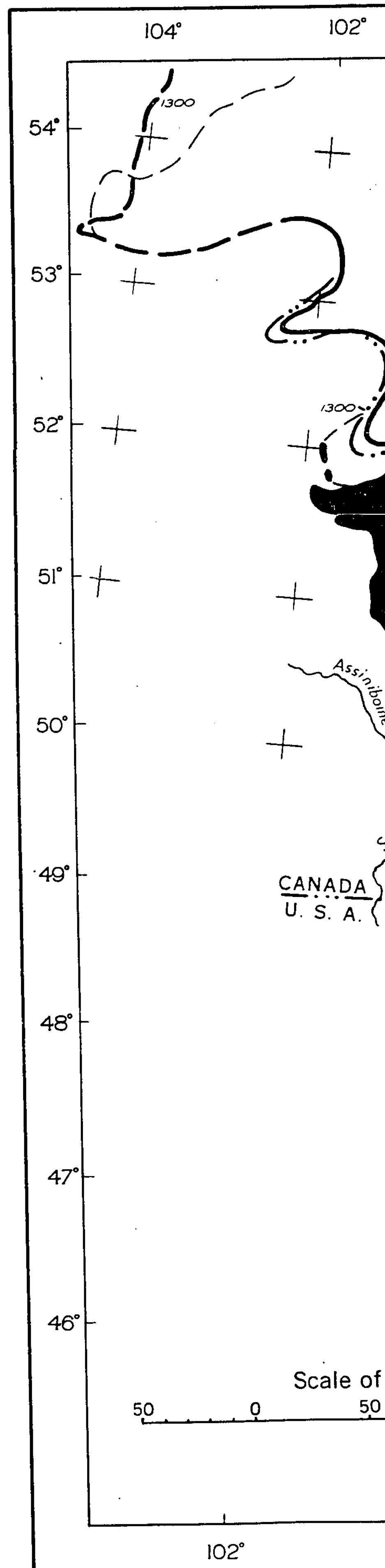
Delta

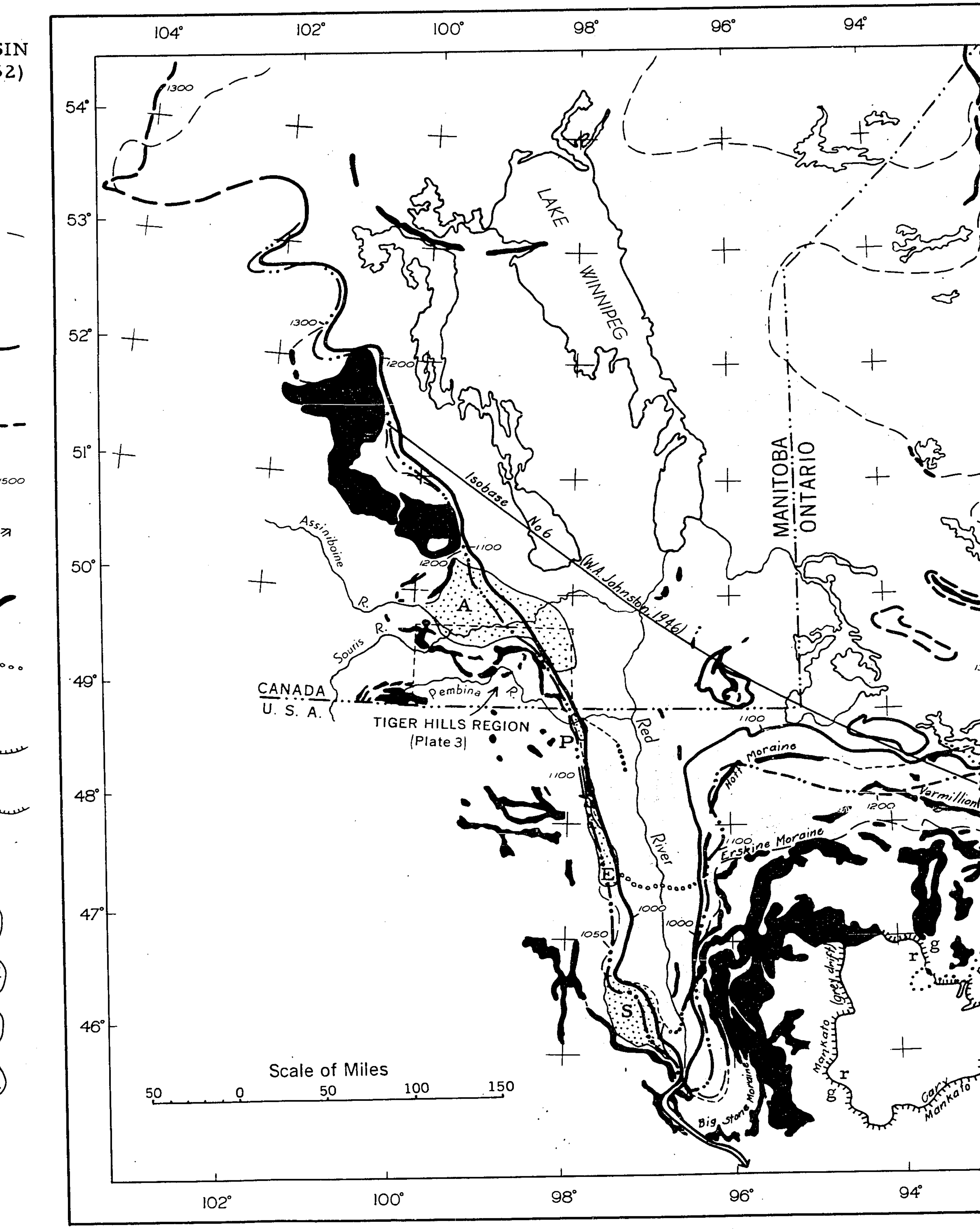
Assiniboine . . . . A

Pembina . . . . P

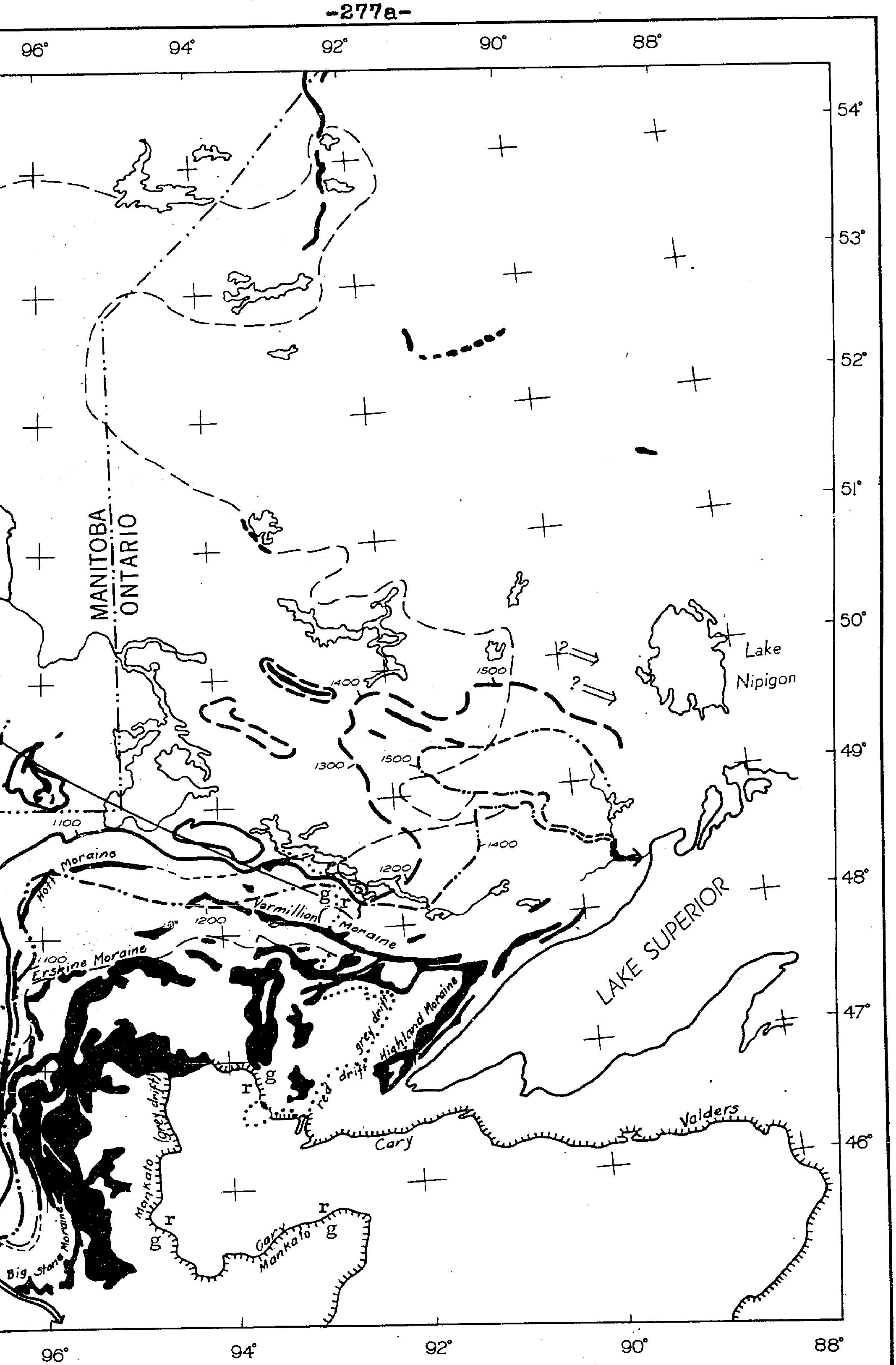
Elk Valley . . . . E

Sheyenne . . . . S





LAKE WINNIPEG
MANITOBA
ONTARIO
Isobase No 6 (W.A. Johnston 1946)
Assiniboine R.
Souris R.
Pembina R.
CANADA
U. S. A.
TIGER HILLS REGION
(Plate 3)
Red River
Holt Moraine
Vermillion
Erskine Moraine
Big Stone Moraine
Mankato (grey drift)
Cary Mankato
Scale of Miles
50 0 50 100 150


96°
94°
92°
90°
88°
54°
53°
52°
51°
50°
49°
48°
47°
46°
MANITOBA
ONTARIO
Lake
Nipigon
LAKE SUPERIOR
1400
1500
1300
1500
1400
1100
1200
1200
1100
Moraine
Vermillion
Moraine
Erskine Moraine
Highland Moraine
grey drift
red drift
Cary
Valders
Mankato
(grey drift)
Cary
Mankato
Big Stone Moraine
96°
94°
92°
90°
88°

Pembina trench downstream from township 2, range 9, by a stream graded to an altitude of about 1,275 feet at Pembina Mountain. The "baselevel" of this stream may have been the apex of the Pembina "delta" (Fig. 5-5; p. 220-222), or it may have been a unilateral spillway.

D. Upper Pembina River phase: The ice front west of Turtle Mountain continued to retreat and Lake Souris expanded northward; north and northwest of Turtle Mountain the front was stationary. A bedrock hill 5 miles north of Ninette obstructed glacier flow and formed a reentrant in the ice margin: a sublobe west of the bedrock hill shrank westward, depositing washboard moraines between Killarney and Ninette; a sublobe east of the hill deposited an end moraine that was partly interlobate in character, parallel to Pelican Lake. East of this moraine (the Tiger Hills moraine) the ice front was stationary and deposited the southern ridge of the Tiger Hills - Darlingford moraine system (Fig. 1-6). Eastward shift of a northern center of outflow caused the margin of the northern ice to advance 1 to 5 miles to the crest of Pembina Mountain. Deposition of the Darlingford moraine began and continued through the next seven phases of deglaciation. The northwestern ice and the northern ice still formed a single sheet north of Treherne, but the influence of northwestern ice on the direction of ice movement in the Tiger Hills was diminishing.

The Whitemud spillway formed the main drainage system, and was joined by a tributary flowing southeastward in the present positions of Pelican Lake and Badger Creek. The upper portion of Pembina River joined this tributary about 10 miles northeast of Killarney.

E. Boissevain lake phase: Continued northwestward retreat of the ice margin west of Turtle Mountain resulted in further expansion of Lake Souris. The ice front on the northwest slope of Turtle Mountain was stationary and deposited end moraine. High ground at the Brandon Hills split the ice sheet and created a reentrant in its margin. The margin west of the Brandon Hills curved south and then west along the base of Turtle Mountain; washboard moraines were deposited during its retreat. Small glacial lakes formed west of Boissevain, in the Whitewater Lake basin, and southeast of Bunclody at the head of Pembina trench. The glacier margin extending eastward from the Brandon Hills was generally stationary and lay along the Tiger Hills - Darlingford moraine. Outwash was deposited as the ice front retreated a short distance north of Neelin. The ice south of Greenway, stagnated, and stratified drift was deposited in openings in it. The northwestern ice had no effect on the direction of flow of the sublobe of northern ice north of the Tiger Hills; the two ice tongues still merged, but the ice in and north of the Tiger Hills was nourished from the Lake Agassiz basin.

Pembina trench was integrated as a spillway during this phase; previously Whitemud Creek spillway had been the main river system in the western part of the Tiger Hills region. The deepening of Pembina trench downstream from Rock

Lake rejuvenated a tributary of the Whitemud spillway that flowed eastward in the position of Rock Lake, and caused it to erode headward and capture another tributary that flowed southward in the positions of Pelican Lake and Badger Creek. This new stream (Pembina trench) received meltwater from both the northwestern ice and the northern ice and deepened its valley rapidly. As a result, the upper portion of Pembina River was rejuvenated and eroded headward and captured the headwaters of Whitemud Creek, which included the Boissevain Lake.

F. Goodlands lake phase: Continued retreat of the margin of the northwestern ice, which now extended southwestward from the Brandon Hills, caused Lake Souris to expand northward west of Turtle Mountain. The glacial lake in the Whitewater Lake basin abandoned its eastern outlet (Pembina River) and discharged westward, into Lake Souris, through lower outlets near Goodlands. Washboard moraines were deposited north of the Goodlands lake. North of the Brandon Hills the northwestern ice still merged with the northern ice. A glacial lake continued to expand in the reentrant in the ice front south of Carroll, and discharged through Pembina trench. East of Carroll, the ice border showed little change from the previous phase except for further stagnation south of Greenway and north of Mariapolis.

The main drainage changes during this phase were (1) transfer of the discharge of the lake north of Turtle Mountain westward from upper Pembina River, and minor channels that flowed northeastward to Pembina trench, to Lake Souris; and (2) reversal of drainage in Badger Creek north of the Whitemud spillway, that resulted in capture of the central part of the Whitemud system by Badger Creek and the abandonment of the portion of the spillway between Badger Creek and Rock Lake.

G. Carroll lake phase: The northwestern ice now was so thin that Moose Mountain (a highland similar to Turtle Mountain in extent and relief, situated about 75 miles west of Virden) created a large reentrant in its margin. As a result, the ice front trended northwestward from about 10 miles west of Lyleton. Broad, shallow valleys containing outwash formed along it during pauses in its retreat and conducted meltwater southeastward into Lake Souris.

The ice margin from Lyleton to Carroll withdrew northwestward. The Goodlands lake was deprived of its glacial source and shrank to a small non-glacial lake without any persistent outlet; alluvial fans deposited by streams flowing down Turtle Mountain began to reduce the depth and extent of the lake basin. Washboard moraines were deposited by the retreating ice between the Carroll lake and Lake Souris. Both these lakes continued to expand, although their landward margins regressed because their water levels lowered as the outlets deepened. Meltwater flowed northeastward along the ice margin from about 3 miles east of Medora to the Carroll lake; a delta was deposited at the mouth of this spillway, about 3 miles southwest of Bunclody.

The sublobe of northern ice north of the Tiger Hills advanced westward against the shrinking northwestern ice lobe, northwest of the Brandon Hills. From the Brandon Hills eastward, the ice margin was stationary except for slow retreat north of Neelin where an outwash plain expanded northward. A small glacial lake formed southeast of Greenway and discharged southeastward through Dry River into Pembina trench. Ice-contact stratified drift was deposited in stagnant ice north of Mariapolis.

H. Dand channel phase: The northwestern ice front withdrew slowly; Lake Souris expanded northward and began to discharge northeastward, through a channel west of Dand, into the Carroll lake near Elgin. A delta was deposited at Elgin when the level of the Carroll lake stood at an altitude of about 1,525 feet. The margin of the northwestern ice extended northward from Dand and passed west of Rivers; the northwestern ice was now separated from the northern ice by the Carroll lake. Minnedosa River flowed southward between the two ice lobes and deposited outwash in the Carroll lake, at Rivers. Northeast and east of Virden, the thinning northwestern ice sheet was fractured by subglacial bedrock hills; the resulting crevasses formed a drainage system in which ice-contact stratified drift that now forms the Arrow Hills was deposited.

East of Rivers, a lateral moraine was deposited along the northwest side of the sublobe of northern ice. This sublobe expanded westward from the Brandon Hills to Alexander, overriding deposits of the Carroll lake. Eastward from Carroll the ice margin was stationary, except for minor retreat 10 to 15 miles west of Greenway, and north of Mariapolis.

I. Glacial Lake Souris phase: The margin of the northwestern ice retreated from the scarp west of Dand; the Dand channel was abandoned, and Lake Souris merged with the Carroll lake. Strandlines along the scarp west of Dand, and terraces in Pembina trench indicate that the lake level stood at an altitude of about 1,495 feet. During this phase meltwater from the ice front extending as far west as central Saskatchewan, and possibly as far west as the Rocky Mountains flowed through Pembina trench.

The northward ice advanced westward from Brandon, probably as far as Griswold, and overrode deposits of the Carroll lake and Lake Souris. Stagnation of ice southwest of Greenway resulted in deposition of ice-contact stratified drift. Minor recession southeast of Greenway enlarged the basin of the Greenway glacial lake, but erosion of the outlet (Dry River) lowered the water level so that the lake did not expand. Farther east, the ice front stood along the Darlingford moraine. Deposition of the Pembina "delta" continued in the reentrant between an ice front and Pembina Mountain.

J. Lake Hind; Melita and Napinka phases: The Melita and Napinka phases of Lake Hind are shown on the same map (Pl. 7J). The ice margins were essentially the same during both lake phases, but Lake Hind was smaller during the Napinka phase.

<u>Melita phase</u>: The transition from glacial Lake Souris to Lake Hind occurred when deepening of Pembina trench lowered the water level and reduced the area of the lake so that its southern end was at Melita, the eastern outlet was at Bunclody, and its northern margin was west of Rivers. The northwestern ice withdrew from the basin so that the lake extended northwest to Virden. A delta deposited by Souris River at Melita, and terraces in Pembina trench near Bunclody indicate that the level of Lake Hind stood at an altitude of about 1,470 feet during the Melita phase. Assiniboine River deposited a delta in it at Virden.

The margin of the sublobe of northern ice that extended westward from Brandon was stationary; stratified drift was deposited north of Griswold. North of Souris the ice front retreated as a result of calving in the lake; north of Carroll the front was stationary and deposited a small end moraine. Stratified drift was deposited in a reentrant northeast of Carroll. A small spillway discharged westward from the Tiger Hills moraine past Carroll to Lake Hind. A general, but minor, retreat of the ice margin between Carroll and Treherne occurred. A small glacial lake formed north of the Tiger Hills moraine and discharged southward into Pembina trench through Souris River gorge. The Dry River spillway deepened, and the Greenway lake continued to subside. Southeast of Treherne the ice front still occupied the Darlingford moraine.

<u>Napinka phase</u>: Deepening of Pembina trench lowered

the level of Lake Hind to an altitude of about 1,460 feet, indicated by a delta deposited by Souris River at Napinka and by terraces in Pembina trench at Bunclody. The north-western ice had retreated from the area, and the northern ice began to wane more rapidly. The ice front northeast of Souris and north of Carroll, no longer standing in water, retreated slowly and deposited a small, discontinuous end moraine.(Pl. 6). The small spillway through Carroll continued to function. Ice-margin retreat enlarged the glacial lake north of the Souris gorge. Near the end of this phase, glacier retreat near Greenway resulted in the ponding of a small glacial lake in the position of the present Cypress River alluvial fan. A channel formed south of St. Alphonse and conducted runoff from the upper watershed of Cypress River westward to Dry River; the channel that trends southward west of the town of Swan River was abandoned. The ice margin occupied the Darlingford moraine southeast of Treherne, and also the end moraine east of Rivers.

K. Lake Hind; Lauder phase: Further deepening of Pembina trench lowered the level of Lake Hind to an altitude of about 1,435 feet, indicated by a delta deposited west of Lauder by Souris River, and by the head of a former channel northwest of Bunclody. Between Treherne and Alexander the ice margin retreated northward, resulting in the ponding of a small glacial lake north of the end moraine southwest of the Brandon Hills, Carroll and Souris, and in the expansion of the lakes north of the Tiger Hills at Souris gorge and between

Hilton and St. Alphonse (Pl. 1). The ice front extending northwest from Methven deposited a small end moraine. An area of stagnant ice occupied a preglacial depression northwest of Alexander. Meltwater flowed westward from Alexander, joined upper Assiniboine and Minnedosa Rivers, and discharged southward into Lake Hind. The glacier continued to deposit end moraine east of Rivers and southeast of Treherne and deposition of the Pembina "delta" (alluvial fan) also continued. Meltwater from an ice front stretching from Treherne westward to central Saskatchewan still discharged through Pembina trench.

L. The Brandon lake; Dry River phase: The margin of the northern ice in the Lake Agassiz basin, east of Pembina Mountain, receded from the Pembina "delta" and the baselevel of Pembina River was lowered suddenly. Pembina trench deepened, Lake Hind was drained, and the present course of Souris River from Melita to Bunclody was established.

A general retreat of the ice margin occurred north of the Tiger Hills. An early phase of this retreat (shown by a dash-dot line on Pl. 7L) opened a channel at Alexander, through which upper Assiniboine River flowed into a small glacial lake between Alexander and the Brandon Hills. This lake discharged eastward through a channel south of the Brandon Hills until the ice-margin retreated northward from the Brandon Hills and opened a lower outlet (a unilateral channel); subsequent ice recession caused the lake to merge with a larger lake north of the Tiger Hills (the Brandon lake).

The Brandon lake formed when ice-margin retreat near

Hilton (pl. 1) caused the lake north of Souris gorge to merge with the lake discharging through Dry River; the Souris gorge outlet was abandoned. Subsequent ice retreat caused the lake west of the Brandon Hills (above) to merge with this larger lake.

End moraine was deposited east of Rivers, east of Alexander, and east of Cardinal. The body of stagnant ice northwest of Alexander continued to melt. Pipestone Creek began to deposit alluvium in the basin of Lake Hind, now occupied only by a small lake (Oak Lake). The Lake Agassiz basis probably was dry.

M. The Brandon Lake; Treherne phase: Continued recession of the glacier northward from Pembina Mountain and the Tiger Hills uncovered a spillway southwest of Treherne. The Brandon lake discharged eastward through this outlet and abandoned the higher Dry River outlet. Cypress River flowed northwestward through the northern part of the Dry River spillway into the Brandon lake. The level of the Brandon lake lowered as its outlet deepened; its southern and western margins of the lake regressed, and the channel of upper Assiniboine River at Alexander extended eastward as the lake subsided. The Treherne outlet was an ice-margin channel that extended eastward around the north end of Pembina Mountain, into the basin of Lake Agassiz.

The stagnant ice in the basin northwest of Alexander separated from the flowing ice farther east. Minnedosa River flowed southwest past Rivers, around the west end of the sublobe of northern ice, and southeast to the Brandon lake near Brandon. The channel along the northwest side of the stagnant ice was abandoned.

Anastomosing channels of Souris River south of Melita were eroded deeper into drift and bedrock.

N. Rise of Lake Agassiz I: Withdrawal of the ice margin northward from the Treherne spillway caused the Brandon lake to drain directly into the Lake Agassiz basin, which probably was dry at the beginning of this phase. The stagnant ice northwest of Alexander continued to melt and formed a basin into which early Assiniboine River shifted; the Alexander channel was abandoned. Assiniboine River deposited sand and gravel on the stagnant ice, and flowed eastward to join Minnedosa River about 6 miles west of Brandon. Thus, the present course of Assiniboine River upstream from Brandon was established; at this time the river probably headed at an ice front north of Moose Mountain.

Lake Agassiz I formed as a result of an ice advance in western Ontario blocking eastern outlets of the Red River basin. Ice recession in the Lake Agassiz basin east of the Manitoba Escarpment accellerated when the waters of rising Lake Agassiz initiated retreat by calving. The advance of the ice across northwestern Ontario was represented only by a halt in recession in the western part of the Lake Agassiz basin, where glacier flow balanced wastage by calving. The ice margin extended southeastward from Riding Mountain to the Vermillion moraine in northern Minnesota (Fig. 6-1).

During this phase Lake Agassiz I rose to its highest level. Simultaneously, glacier retreat in Saskatchewan uncovered the Qu'Appelle valley, and all glacier meltwater from the Prairies west of Brandon discharged through Assiniboine River. The sudden increase in discharge caused Assiniboine River to erode its valley deeply, and the resulting sediment was deposited in Lake Agassiz I as a delta.

Discharge through the Souris - Pembina River system was reduced to the runoff from about 22,500 square miles. Pembina River alluviated Pembina trench downstream from La Riviere, as a result of the rise of its baselevel (Lake Agassiz I); the trench continued to deepen upstream from La Riviere.

O. Lake Agassiz I; Assiniboine delta: Deposition of the Assiniboine delta in Lake Agassiz I was complete by the time the lake level rose to an altitude of about 1,250 feet and subsided to about 1,200 feet. At this time Assiniboine River, no longer carrying glacier meltwater, flowed eastward from Brandon to Douglas Station, then southeastward to the present valley. A small tributary of early Assiniboine River eroded headward through Souris gorge and captured Souris River. The resulting increase in discharge accellerated the deepening of the Souris-Assiniboine valley, and another small tributary eroded northwestward from the present junction of Assiniboine and Little Souris Rivers, and captured the main Assiniboine River just east of Brandon; thus, the present course of Assiniboine River was established across the delta.

A pause in the subsidence of Lake Agassiz I occurred when the Tintah level (altitude about 1,135 feet) obtained, and the lower portion of the Assiniboine valley was widened by lateral stream erosion. Subsidence of the lake also was halted at the Campbell level, because the southern outlet (Lake Traverse, Minnesota) eroded down to a bedrock sill. Further subsidence of Lake Agassiz I only occurred when glacier recession in western Ontario opened lower outlets.

Pembina River aggraded its valley downstream from La Riviere until Lake Agassiz subsided to the Norcross level (altitude about 1,150 feet at Walhalla).

South of Melita, the easternmost of the anastomosing channels of Souris River was abandoned because discharge, much reduced when its glacier source was captured by Assiniboine River, was inadequate to erode two channels. The eastern channel, in bedrock, was abandoned for the western channel which was in more easily eroded drift.

Deposition of the basal gravelly alluvium in the Cypress River alluvial fan may have occurred at this time.

P. Erosional interval following Lake Agassiz I: General shrinking of the Laurentide ice sheet opened eastern outlets north of Lake Superior and lowered Lake Agassiz to an altitude of about 890 feet or lower (p. 123), and thus lowered the baselevels of Pembina and Assiniboine Rivers. Pembina River eroded the alluvial fill it had deposited prior to and during the Norcross phase of Lake Agassiz. Assiniboine River eroded its valley to a depth of at least 150 feet and a width of 1 to 2 miles north of Treherne. Souris River incised its meanders about 65 feet near Wawanesa, and abandoned a high-level channel east of Treesbank.

Several deep ravines were eroded in the Assiniboine delta west of the Campbell scarp and north of Assiniboine River. Windblown sand was deposited on the delta and on the high-level terraces in the Assiniboine valley.

Q. Lake Agassiz II: Readvance of an ice front north of Lake Superior blocked the lowest eastern outlets of the Lake Agassiz basin and resulted in the ponding of Lake Agassiz II, which rose to the Campbell strandline and discharged through the southern outlet (Lake Traverse). A freshwater gastropod fauna from the Mississippi River entered southern Manitoba by this route. The deep ravines in the Assiniboine delta west of the Campbell strandline were alluviated, and an estuarine-like sediment was deposited in the Assiniboine valley, which was flooded as far west as Glenboro.

Northwest of Alexander, Assiniboine River had two channels, one on each side of the gravelly alluvium previously deposited on stagnant ice. A small stream flowing southward past Brawardine (Pl. 6) deposited an alluvial fan that blocked the north channel of Assiniboine River, which assumed its present course. Souris River cut through several meander necks and abandoned incised meanders near Wawanesa.

During this phase grasses and conifers, including *Larix* grew on the Assiniboine delta. Human occupations included Folsom, Scottsbluff, Plainview, and Agate Basin cultures.

One of these cultures may have migrated southeast from Alaska following the spread of Bison occidentalis, an extinct form that developed into the living race Bison (B.) bison bison. Terrestrial gastropods that appeared in the region at this time represented the genera Discus, Gastrocopta, and Vallonia; Retinella and Zonitoides appeared later.

The distribution of Plainview artifacts suggests that Lake Agassiz II was partly contemporary with Lake Algonquin III.

Retreat of the ice front north of Lake Superior reopened the eastern outlets of the Lake Agassiz basin; the Lake Traverse outlet was abandoned and Lake Agassiz II began to subside. A series of abandoned strandlines mark pauses in the lowering of the lake level. Lake Agassiz II may have drained during the altithermal, at which time southern Manitoba was occupied by people of the Lake Shore culture. Probably at this time a soil, now buried, formed on Cypress River alluvial fan, and terrestrial snails of the genera Cionella, Deroceras, and Hawaiia appeared in the region. Drainage of Lake Agassiz was complete by the time people of the Larter culture occupied southern Manitoba.

R. Present drainage system: The present streams and lakes were established when Lake Agassiz II was drained. Deposition of alluvium on various alluvial fans, including those of Assiniboine River at Portage la Prairie, Pipestone Creek at Oak Lake, Cypress River (upper alluvium), and of streams flowing down Pembina and Turtle Mountains continues

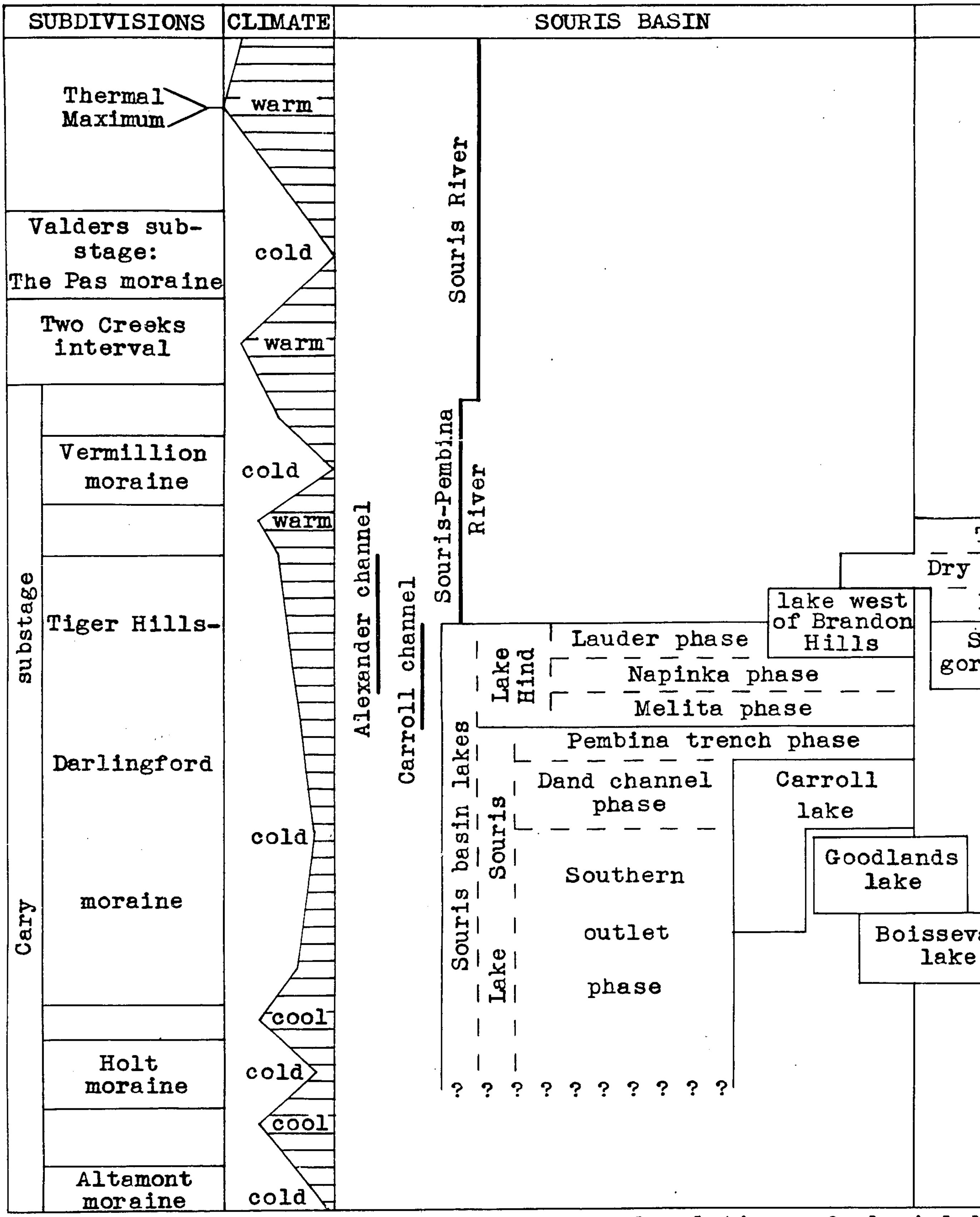
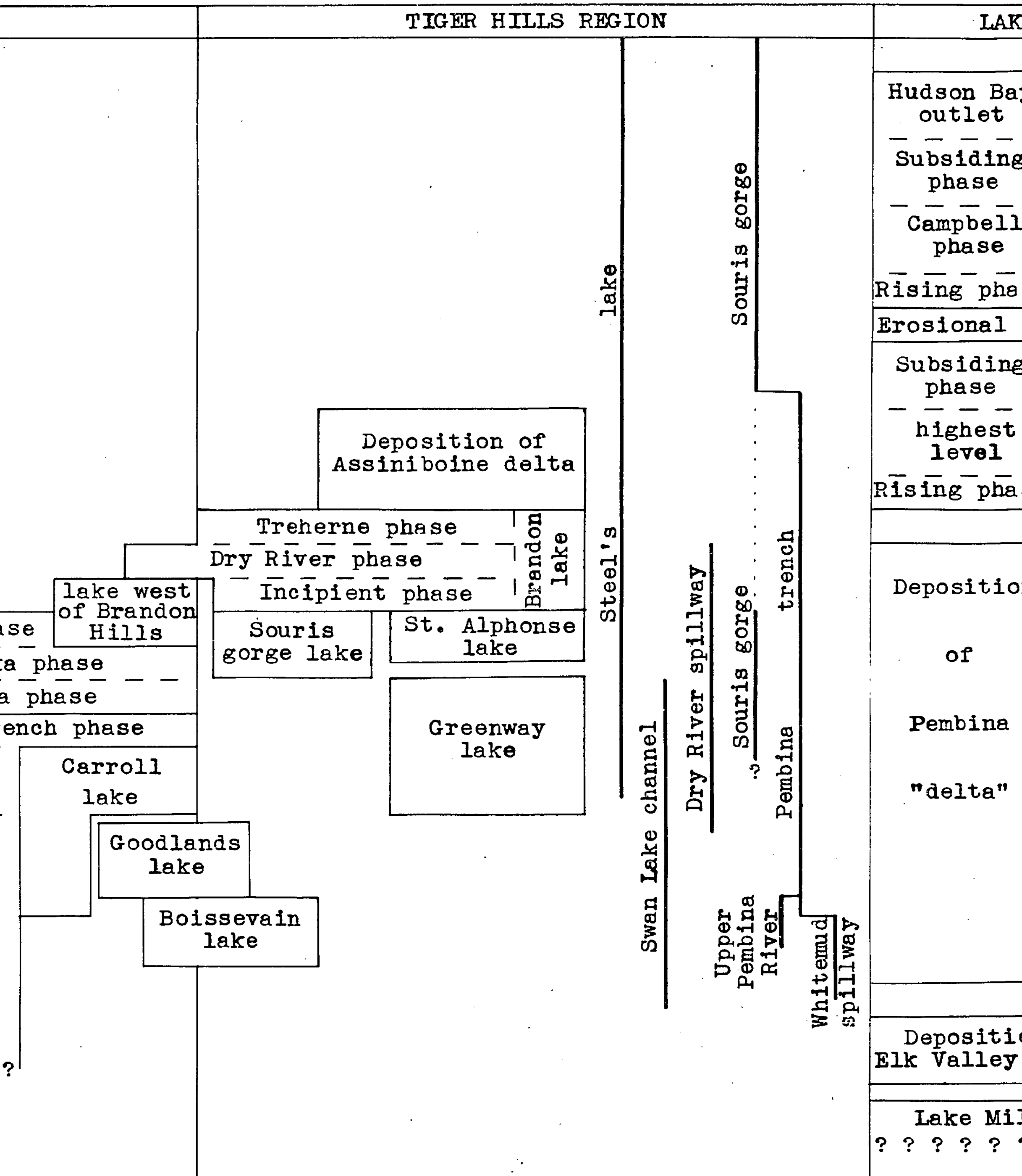
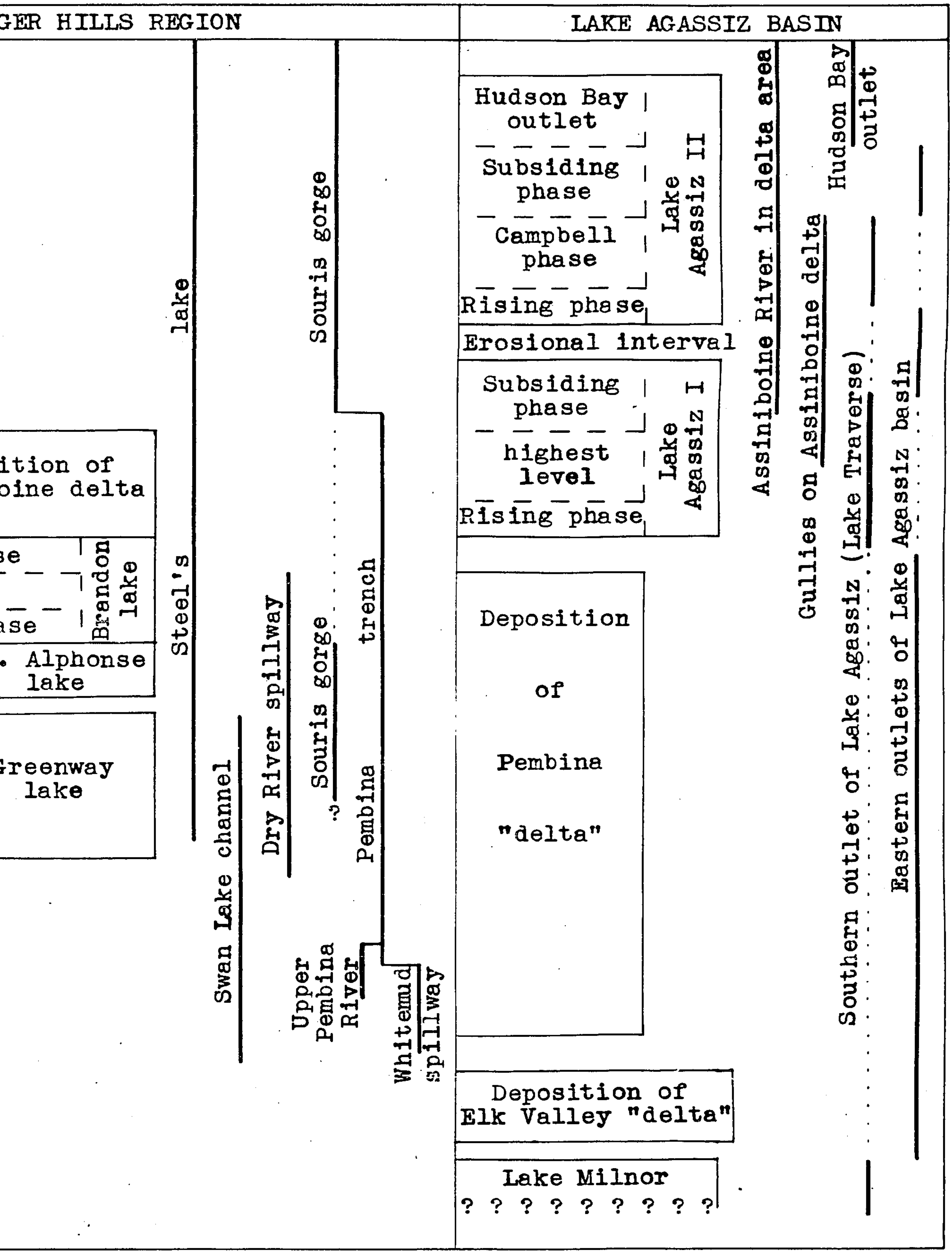


Table 6-1. Chart showing sequence and mutual relations of glacial l



ations of glacial lakes and related features in southwestern Manitoba.



ated features in southwestern Manitoba.

at present. Alluvial fans of its tributaries blocked Pembina trench and formed a series of lakes, the largest of which are Pelican Lake, Rock Lake, and Pembina Lake. Most of the gullies in the Assiniboine delta are now occupied by marsh, except near the Campbell strandline where they contain small underfit streams. Apparently the present runoff is substantially less than it has been at one or more times since deglaciation.

Terrestrial snails that have appeared since the present drainage was established include members of the genera Succinea, Carychium, and Helicodiscus.

. . . .

The foregoing sequence of glacial lakes, channels, and related features, summarized graphically in Table 6-1 and Plate 7, is based on inferences and hypotheses set forth earlier in the text, and is believed to conform to the present data. Undoubtedly several inaccuracies are present: their correction must await the collection of more data.

ORIGIN OF GLACIAL LAKE AGASSIZ

Previous interpretations

N.H. Winchell, in 1873, apparently was the first to point out that Lake Agassiz was a glacial lake ponded between an ice margin in the north and high ground in the south (Leverett, 1932, p. 119). Subsequently American workers, first of whomwas Upham (1895), conceived that the lake formed as an ice front retreated northward in the Red River basin; on the other hand Canadian workers, first of whom was Tyrrell (1896), conceived that the lake formed when an ice advance blocked the northern outlet of the basin so that it filled with meltwater and runoff and overflowed southward. The writer attempts to show that both theories are partly correct. A lake must have been ponded between the ice margin and a height of land to the south during glacier recession in the United States; but there is evidence in Canada that Lake Agassiz had a rising phase, and that there was an interval of subaerial erosion during which the lake was dry or at least greatly reduced in size. Clearly, the history of Lake Agassiz is more complex than is generally supposed.

American theory of origin (ice recession)

Warren Upham (1895, p. 208-244) noted that the highest strandlines of Lake Agassiz extend northward 250 miles from the southern outlet to the latitude of Winnipeg. He stated that Lake Agassiz formed as an ice margin withdrew northward, and he cited the small end moraines, weak strandlines, and the steep northeast sides of the deltas suggestive of ice-contact faces, as evidence of very rapid glacier retreat. The strandlines were tilted southward as the ice withdrew. Upham (Idem., p. 253) observed organic matter in and underlying sediments that were deposited in Lake Agassiz II, but he thought that these sediments were of fluvial origin.

T.C. Chamberlin (1895) agreed that Lake Agassiz formed as a result of ice margin retreat, but suggested that the earth's crust was warping downward as the ice withdrew so that the upper strandlines extended farther northward and modified older moraines: when the ice withdrew completely the crust warped upward and the strandlines assumed their present attitudes. Chamberlin thought that the steep north sides of the deltas resulted from undercutting by waves generated by north winds prevailing during deglaciation, and that the shore features of the lake are small because it was frozen most of the year.

Frank Leverett (1932, p. 119-140) upheld Upham's theory except concerning the moraines in western Minnesota. Upham thought that these moraines were deposited by an ice front retreating northeastward, and that the western moraines were the oldest. Leverett showed that the moraines were deposited concentrically around an ice lobe in the Lake Agassiz basin, so that the western moraines in Minnesota are the youngest. Hence, he tacitly shifted the general direction of ice retreat from northeastward (according to Upham) to north or northwestward. Leverett (Idem., p.126-127) emphasized that the shapes of the deltas in Lake Agassiz indicate that ice margins formed their northeast sides during deposition. He thought that the deltas were mainly glacial deposits in ponded water, and not the deposits of inflowing streams.

C.C. Nikiforoff (1947) attempted to show that the apparent slope of Lake Agassiz strandlines was due not to crustal warping, but to slow subsidence of the lake as the ice margin withdrew. He stated that Lake Agassiz began as embayments in the ice sheet that contained lakes which merged to form a southeast-trending lake in Manitoba and Minnesota. This lake was bordered by ice on the north and south sides.

When ice on the south side melted the lake expanded southward and was ultimately drained through the Lake Traverse outlet. Nikiforoff's interesting theory is based on misconceptions of the relationships of earlier glacial lakes (Lakes Souris and Saskatchewan) to Lake Agassiz (Idem. p. 224). He made no use of stratigraphic data. Furthermore, if the northern part of Lake Agassiz formed in the same way as the southern part, as is implied, the strandlines north of the latitude of Winnipeg should slope northward instead of southward.

Canadian theory of origin (ice advance)

J.B. Tyrrell (1896) used the evidence of till sheets and striations to infer that only the northwest part of the Lake Agassiz basin was occupied by an ice lobe, which flowed southward from the Keewatin center of glaciation, and that the lake basin drained northward into Hudson Bay. The Keewatin ice began to retreat and simultaneously an ice sheet began to advance from Labrador. The two ice sheets joined when the Keewatin lobe had retreated into northern Manitoba, blocked the northern drainage of the lake basin, and ponded Lake Agassiz. Later, continued retreat of the Keewatin ice opened the northern outlet to Hudson Bay, and the lake was drained.

W.A. Johnston (1916) based support of Tyrrell's theory on evidence of an unconformity at the base of the Lake Agassiz lacustrine sediments. Johnston (Idem., p. 638) stated

"An earlier glacial marginal lake, which is herein referred to as Early Lake Agassiz, was associated with a lobe of the Keewatin glacier; but this lake was largely if not wholly drained before Lake Agassiz came into existence. The latest advance of the ice into the Lake Agassiz basin did not extend farther south than the southern portion of Lake Winnipeg, so that the ice border of Lake Agassiz was at least 250 miles north of the southern end of the lake during the entire existence of the lake."

Evidence of the Keewatin and Labradorean "glaciers" consists of the patterns of striations that radiate outward from poorly defined central areas. Rather than representing the separate ice sheets interpreted by Tyrrell, the patterns of striations probably represent centers of outflow within the Laurentide ice sheet. The theory of separate glaciers was rejected by Flint (1943) and was tacitly rejected by T. C. Chamberlin as early as 1895. Episodes of northward drainage of the Lake Agassiz basin were impossible without separation of the Keewatin and Labradorean glaciers, hence, the Tyrrell-Johnston theory of the origin of Lake Agassiz is not acceptable.

The present hypothesis

Both the American and Canadian explanations of the origin of Lake Agassiz are partly correct. The following data and inferences are added to evidence amassed by Upham, Tyrrell, Johnston, and Leverett: (1) Alluvial fills in the Pembina and Assiniboine valleys represent two phases of rising water level in the Lake Agassiz basin. (2) Glaciofluvial sand and gravel underlying the basal lake deposits and overlying till indicate that an interval of subaerial deposition occurred after deposition of the till and before deposition of the lake clay. (3) The structure, shape, and position of the Pembina "delta" with respect to the Darlingford moraine indicate that it is an alluvial fan that was deposited in a reentrant between Pembina Mountain and an ice tongue in the Lake Agassiz basin. (4) The character of the Assiniboine delta indicates that it was deposited in a rising lake or in a lake with a constant level, but not in a subsiding lake. (5) Kaministiquia River, north of Lake Superior, is a possible eastern outlet of a lake with a level at or higher than the Norcross strandline. Outlets of lakes with levels lower than the Campbell water plane probably were west of Lake Nipigon near latitude 50°. (6) Centers of outflow shifted from west to east during the waning of the Laurentide ice sheet. The writer does not accept Tyrrell's concept of separate Keewatin and Labradorean glaciers, and a preliminary phase of drainage of the Lake Agassiz basin northward into Hudson Bay.

Deglaciation of the Lake Agassiz basin and the formation of Lake Agassiz probably occurred as follows: The ice sheet shrank northward from the southern part of the Lake Agassiz basin in Minnesota and North Dakota; an early high-level lake (Lake Milnor) formed between the ice margin and higher ground to the south, and discharged southward through the Lake Traverse outlet. The glacier margin extended generally northeastward from the southern part of the Lake Agassiz basin to Lake Nipigon (Figs. 6-1, 6-2). When the ice front retreated to the Holt moraine (Fig. 6-1) a lower outlet, probably Kaministiquia River, was uncovered and the lake discharged into the Lake Superior basin. Further glacier recession opened lower outlets west of Lake Nipigon, Lake Milnor(?) was

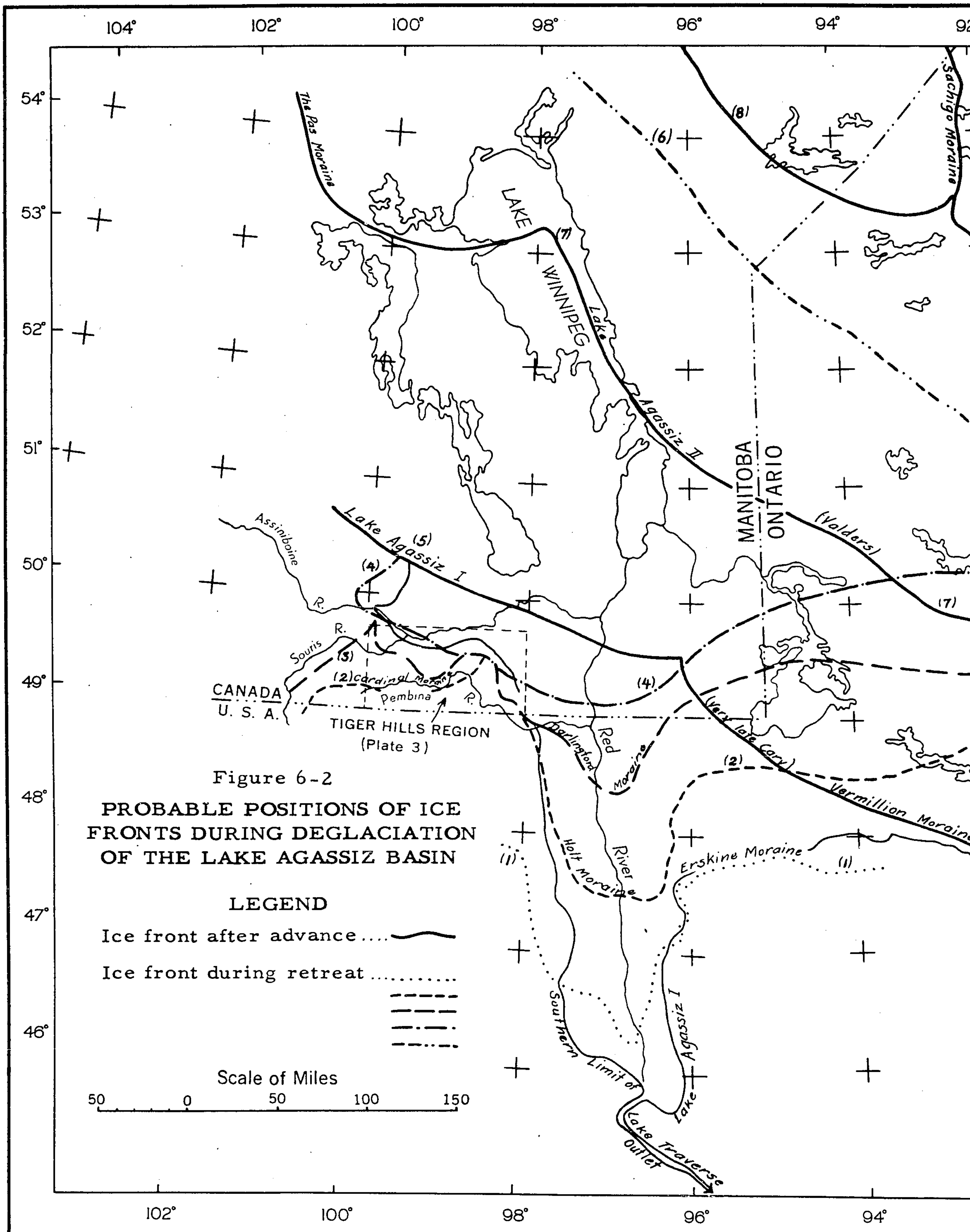
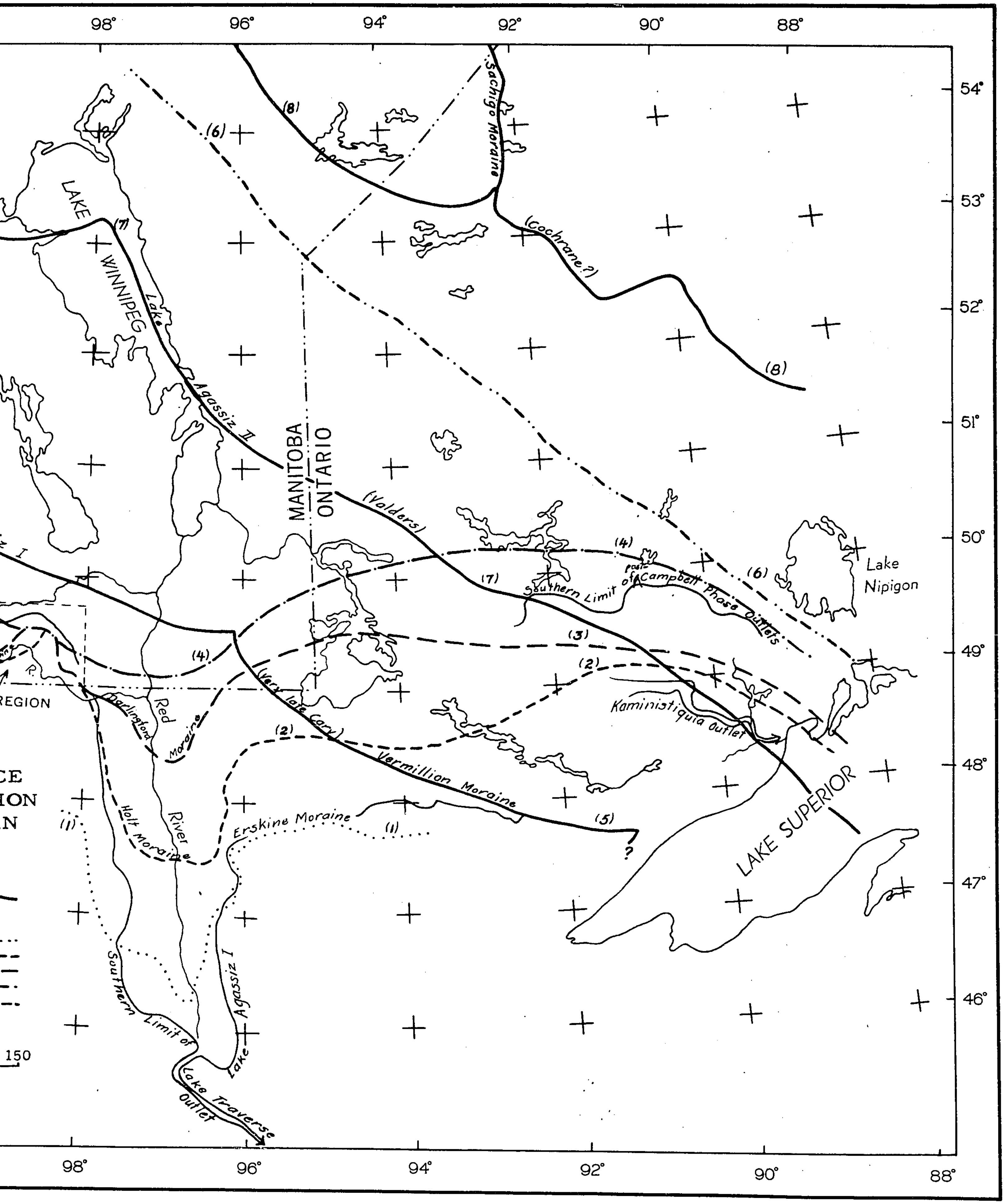


Figure 6-2

PROBABLE POSITIONS OF ICE FRONTS DURING DEGLACIATION OF THE LAKE AGASSIZ BASIN



98°
96°
94°
92°
90°
88°
54°
53°
52°
51°
50°
49°
48°
47°
46°
LAKE WINNIPEG
Sachigo Moraine
(Cochrane?)
(6)
(8)
(7)
Lake Agassiz II
MANITOBA
ONTARIO
(Valders)
(4)
(6)
Lake Nipigon
Southern Limit of Post-Campbell Phase Outlets
(3)
(2)
Kaministiquia Outlet
(Very late Cary)
Vermillion Moraine
(5)
Erskine Moraine
(1)
LAKE SUPERIOR
REGION
Darlington Moraine
Red River
Holt Moraine
Southern Limit of Lake Agassiz I
Lake Traverse Outlet
150

drained, and glaciofluvial sand and gravel was deposited in the Lake Agassiz basin as recession continued. Meanwhile the centers of outflow in northern Saskatchewan and Manitoba gradually shifted from west to east, and although the ice front receded in Saskatchewan and western Manitoba, it advanced in Northern Ontario. Shortly after the glacier receded from the Darlingford moraine, but before it shrank to the latitude of Winnipeg, the eastern outlets of the Lake Agassiz basin were blocked, and Lake Agassiz I began to form. The Assiniboine delta was deposited while the lake level rose to the altitude of the southern (Lake Traverse) outlet. At the time of the highest level of Lake Agassiz I the ice margin probably extended southeastward from the north side of the Assiniboine delta to the Vermillion moraine in northern Minnesota. Lake Agassiz I subsided as the southern outlet was eroded, deepened until a bedrock sill retarded erosion of the outlet, and the first (upper) Campbell strandline formed. Concurrently the ice margin continued to recede and eventually uncovered eastern outlets low enough to drain the lake, as indicated by an erosion and drying surface within the lake deposits. The northwestern center of outflow probably vanished at this time, and there may have been an opening northward from the Lake Agassiz basin into Hudson Bay.

Reactivation of the Laurentide ice sheet resulted in an advance that blocked the eastern outlet a second time, and created Lake Agassiz II, which rose to the level of the Campbell strandline and discharged southward through the Lake

Traverse outlet. Final recession of the Laurentide ice re-opened the eastern outlets near Lake Nipigon, and later, the northern outlets to Hudson Bay.

These events and possible correlations with events in the Great Lakes basin are summarized in Table 6-2.

Conclusion

The sequence of events described in the foregoing text, the inferred ice margins shown in Figure 6-2, and the correlations in Table 6-2 constitute a working hypothesis that is believed to fit the data from the sedimentary record in the Lake Agassiz basin and its tributary valleys, the strandlines of Lake Agassiz, the moraines in and near the lake basin, and the known and inferred outlets. More data on the strandlines and outlets of the Lake Superior basin and the history of Lake Duluth and its successors may alter the hypothesis or the correlation with the glacial predecessors of the Great Lakes. The writer has been unable to find in the geological literature any reference to low-water phases in the Lake Superior basin that might correlate with the glacier recessions that opened the eastern outlets of Lake Agassiz. It is anticipated that eventually evidence will appear in the form of alluvial fills in tributary valleys of Lake Superior, and as differences in the slope of older and younger abandoned strandlines (Fig. 5-14 (b)) that might account for the contrast between the strandline interpretations of Leverett (1929) and Sharp (1953).

The present hypothesis reconciles the American view

Table 6-2. Events in the history of Lake Agassiz and suggested correlation with events in the Great Lakes basin.

Lake Agassiz basin		Great Lakes basin
Final (present) drainage to Hudson Bay		Present Great Lakes
• • • • • • • • • • • • • • •		• • • • • • • • • • • • • • •
Lake Agassiz II	crustal uplift	
Hudson Bay outlet		Nipissing Great Lakes
Lake Nipigon outlets		Lake Chippewa low-water phase
		Lake Algonquin
Lake Traverse outlet		Lake Algonquin
		Lake Duluth (II?)
- - - - - - - - - - -Valders substage- - - - - - - - - - - - - -		
Erosional interval; Lake Agassiz basin drained via Lake Nipigon outlets (?)	crustal uplift	Two Creeks interglacial interval; Bowmanville low-water phase of Great Lakes
• • • • • • • • • • • • • • •		• • • • • • • • • • • • • • •
Lake Agassiz I		
Lake Nipigon outlets		Lake Duluth (I?)
Lake Traverse outlet		Lake Duluth (I?)
- - - - -very late Cary (post-Mankato) advance- - - - - - - - (Vermillion moraine)		
Subaerial interval; Lake Agassiz basin drained via Kaministiquia River (?)		Early Lake Duluth
• • • • • • • • • • • • • • •		• • • • • • • • • • • • • • •
Lake Milnor (Lake Traverse outlet)		???
- - - - - - -late Cary advance (Mankato?)- - - - - - - - - - (Altamont moraine)		

that Lake Agassiz formed by ice margin retreat with the Canadian view that it formed by ice advance.

GENERAL CONCLUSION

The structure of the washboard moraines in the Tiger Hills region and their relationship to eskers indicate that they formed subglacially near the ice margin. They may be cyclical and possibly annual phenomena.

Striated boulder pavements apparently form by selective subglacial erosion of till, and may be the subglacial expression of a change in the regimen of an ice sheet involving margin retreat and advance of substage magnitude.

The last ice sheet flowed southeastward across southwestern Manitoba. During deglaciation, a southeast-flowing glacier lobe (northwestern ice) retreated northwestward, while another glacier lobe (northern ice) flowed southward in the Lake Agassiz basin. A sublobe of the northern ice advanced westward up the preglacial Assiniboine valley. The northern ice flowed vigorously, and its margin advanced slightly while the northwestern ice retreated; this activity was due to a shift of centers of outflow in the Laurentide ice sheet eastward from northern Saskatchewan to northern Manitoba, and to the splitting of the waning ice sheet by highlands such as Moose Mountain and Riding Mountain.

Former lakes, including (1) glacial Lake Souris and its proglacial successor, Lake Hind, (2) the Brandon glacial lake, and (3) a portion of Lake Agassiz, occupied parts of southwestern Manitoba. Lake Souris, Lake Hind, and subsequently the Brandon lake discharged through Pembina trench, and antedated Lake Agassiz. The Lake Agassiz basin was dry during most of the deglaciation of southwestern Manitoba; and drained eastward into Lake Superior. The eastern outlet may have been Kaministiquia River which, owing to crustal warping, was at least 700 feet lower than its present altitude. Readvance of the Laurentide ice sheet north of Lake Superior closed the eastern outlet and formed Lake Agassiz I, after the Pembina "delta" (alluvial fan) had been deposited in a reentrant between an ice margin and Pembina Mountain, and after the glacier had receded to the north side of the Assiniboine delta. The Assiniboine delta was deposited during the rising and the high-level phases of Lake Agassiz I. The lake level fell as the southern outlet was deepened through drift, and then stood at the Campbell strandline when further deepening of the outlet was retarded by a bedrock sill. Subsequently, recession of the ice margin north of Lake Superior uncovered lower outlets to the east through which the lake was drained. Closing of the eastern outlets by another glacier advance formed Lake Agassiz II, which filled to the Campbell strandline and discharged southward through the Lake Traverse outlet into the Mississippi River system. A freshwater molluscan fauna migrated into Lake Agassiz II and its tributaries by this route. Early man spread into southwestern Manitoba at this time. Final retreat of the Laurentide glacier again opened eastern outlets north of Lake Superior and then the present outlets to Hudson Bay.

Buried soil profiles in sand dunes and in the Cypress

River alluvial fan, the history of Steel's Lake and Morris (Boyne) River, the succession of terrestrial snails in Pembina trench alluvium, and the forms of valleys containing underfit streams, together show that at least two dry intervals and two or three humid intervals (including the present) have occurred since deglaciation. The last major dry interval, represented by the buried soil profile in the Cypress River alluvial fan, may have been the Thermal Maximum.

Correlation of events in southwestern Manitoba with late-Wisconsin events in eastern North America (Antevs, 1931; Flint, 1953) depends mainly upon the distribution of human cultural materials, radiocarbon dates, and tentative interpolations of ice fronts between widely separated segments of moraines. The present data suggest that the Mankato drift, including the Altamont moraine, was deposited during the general retreat of the Cary ice sheet; thus, the surficial drift in southwestern Manitoba belongs to the Cary substage, and the striated boulder pavement may represent the Tazewell-Cary interval. Then, Lake Agassiz I was formed by a minor readvance near the end of Cary time, the erosional interval between Lakes Agassiz I and II is the Two Creeks interval, and Lake Agassiz II resulted from the Valders advance (which should not be thought of as contemporary with the Mankato "glaciation"). Lake Agassiz II lasted through Lake Algonquin time, and at one time probably discharged through an eastern outlet into Lake Chippewa, the low-level lake that existed in the interval between Lakes Algonquin and Nipissing. Lake Agassiz II finally drained northward into Hudson Bay, probably during the Thermal Maximum.

R.F. Flint (oral communication) suggested that Lake Agassiz II was the result of the Cochrane glaciation. If so, Lake Agassiz I is of Mankato age and the striated boulder pavement is of Cary-Mankato age. Although the data are sparse, the distribution of human cultural materials and the present radiocarbon dates militate against this hypothesis.

APPENDIX

LIST AND DESCRIPTION OF FOSSIL MOLLUSK OCCURRENCES

Lake Agassiz sediments

1. SW 35-9-9 W. Prin. (3 miles south of Rossendale): About 14 feet of silty and sandy clay alluvium overlie a bed of peat (Y165). Fossils are from a spoil pile, and may represent fauna ranging from the time of the peat deposition to the present. Altitude of the fossil bed is 1,050 to 1,060 feet.

2. "Approximately 3 miles south of Lavenham, near Assiniboine River in a moderately good section of one of the Lake Agassiz beaches contains 15 or more species of fresh-water molluscs all of which are lacustrine forms. Altitude of the deposit is approximately 1,160 feet and the deposit is almost certainly older than Campbell beaches; it is not far below the Upper Tintah or Norcross beaches" (Mozley, 1934, p. 375). The writer was unable to find a "beach" (alluvial fill?) deposit at 1,160 feet in the area described. Alluvial fill in a small tributary valley of Assiniboine River containing abundant fossils occurs in NE 22-9-10 W. Prin. at an altitude of about 1,065 feet and represents the Campbell phase of Lake Agassiz.

3. "Several miles south of Lavenham and one-quarter mile west of .... ((No. 2)), and 60 feet lower is a deposit of sand on the eastern bank of Assiniboine River ((SE 22-9-10 W. Prin. ?)) evidently younger than No. 2" (Mozley, 1934, p. 378). These are probably the lower (sand) beds of the alluvial fill and are actually older than No. 2.

4. SW 13-9-9 W. Prin. in gulley in alluvial fill: fossils from the base of silt beds in Assiniboine valley, at an altitude of about 1,035 feet. Clams collected here were submitted for radiocarbon dating (Y166).

5. NE 11-9-8 W. Prin.: Sand dunes at an altitude of about 1,025 feet.

6. West half, section 16-9-9 W. Prin. in road cut in alluvial fill in Assiniboine valley, at an altitude of about 1,040 to 1,050 feet: silt and clay beds.

Pembina trench alluvium

7. NE 24-1-9 W. Prin. in younger alluvium in Pembina trench: Cut bank 30 feet high (above water level); fossils 4 to 6 feet above water, about 25 feet below surface of terrace, in clayey sandy silt.

8. NE 24-1-9 W. Prin.: Same locality as No. 7 but 12 to 15 feet below surface of terrace (about 11 feet above No. 7) in clayey silt.

9. NE 24-1-9 W. Prin.: Same cut as No. 7 but 6 to 12 feet below surface (about 15 feet above No. 7) in gravel and silt above clay bed 2 feet thick.

10. NE 24-1-9 W. Prin.: Vicinity of No. 7 but 5 feet below surface of flood plain just east of the main cut bank, in sandy silt.

11. SW 4-2-7 W. Prin.: Younger alluvium (flood plain) of Pembina River, in upper 2 feet of alluvium.

12. SW 13-3-15 W. Prin.: Alluvial fan of Badger Creek in Pembina trench. New ditch in silty sandy younger alluvium, 2 to 4 feet below surface.

Cypress River alluvial fan

13. SW 9-6-12 W. Prin.: Sandy silty alluvium below soil-peat-gyttja horizon.

14. NW 8-6-12 W. Prin.: Buried gyttja in soil-peat-gyttja horizon between upper and lower alluvia.

15. NW 8-6-12 W. Prin.: Charcoal-bearing horizon about 6 feet below surface, in sandy, silty alluvium.

16. SW 9-6-12 W. Prin.: Alluvium above soil-peat-gyttja horizon of Cypress River alluvial fan.

17. SW 17-6-12 W. Prin.: Alluvium above soil-peat-gyttja horizon of Cypress River alluvial fan.

Recent alluvium

18. SE 36-3-6 W. Prin.: Sandy alluvium containing a little charcoal near tributary of Dead Horse Creek.

19. SW 36-5-7 W. Prin.: Clayey silt alluvium of Tobacco Creek, 1 to 2 feet below surface in new cut.

20. West half, section 21-5-6 W. Prin.: From surface to 1.5 feet below surface in a ditch cut in clayey silty alluvium of tributary of Tobacco Creek.

21. NE 1-4-6 W. Prin.: Clayey alluvium near tributary of Dead Horse Creek.

22. NE 36-10-10 W. Prin.: Very fine sand underlying 2 feet of silt (alluvium?) on Assiniboine delta.

23. SW 31-6-6 W. Prin.: Sandy alluvium of Morris River near Stephenfield, 12 feet below surface.

Assiniboine River alluvium (younger)

24. SE 20-9-9 W. Prin.: Younger alluvium, about 40 feet above Assiniboine River.

25. West half, section 21-9-9 W. Prin.: Younger alluvium 10 to 20 feet above Assiniboine River, above flood plain.

Miscellaneous Deposits

26. NW 24-8-9 W. Prin.: Shallow abandoned channel containing silt and peat. Snails from surface to a depth of 2 feet, in Carex peat.

27. East half, section 13-11-8 W. Prin.: Sand containing black organic matter, 1 to 2 feet below surface of former lake bottom (Lizard Lake).

28. North half, section 36-6-7 W. Prin.: Sand of the lower Assiniboine delta, 0.25 mile north of Morris River near Stephenfield; 4 feet below surface, altitude about 975 feet; may be recent fauna buried by windblown sand.

The fossil mollusks from the above localities are listed in the tables following this page.

APPENDIX: Molluscan fa

	Lake Agassiz II						Pembina		
PELECYPODA Locality:	1	2	3	4	5	6	7	8	9
1. Anodonta sp.		M							
2. Lampsilinae									
Lampsilis siliquoidea rosacea (DeKay)		M							
3. Pisidium sp.	R	M	M	L		R			
4. Sphaerium sp.		M	M	L					
Sphaerium simile (Say)	R	M							
Sphaerium striatinum (Lamarck)					R	R			
GASTROPODA									
1. Amnicola sp.		M							
Amnicola leightoni Baker						R			
Amnicola limosa (Say)		M							
Amnicola porata (Say)	R								
Amnicola walkeri Pilsbry				L					
2. Aplexa hypnorum (Linné)									
3. Armiger crista (Linné)									
4. Ferrissia parallela (Haldeman)									
Ferrissia rivularis Say									
5. Gyraulus sp.									
Gyraulus altissimus (Baker)	R					R			
Gyraulus parvus (Say)									
6. Helisoma antrosa (Say)*	R	M	M			R			R
Helisoma campanulatum (Say)									
Helisoma trivolis (Say)									
7. Lymnaea sp.		M							
Lymnaea abrussa decampi (Streng)		M							
Lymnaea caperata (Say)									
Lymnaea parva (Lea)				L					
Lymnaea stagnalis jugularis Say	R								
8. Menetus exacuous (Say)									

*. Called Helisoma antrosa Conrad by Leonard and Russel, and Planorbus antrosa Conrad

Identifications by A. Byron Leonard = L; by Alan Mozley (1934) = M; by L. S. Russell = R.

ENDIX: Molluscan fauna of the Tiger Hills region: Freshwater species.

	Pembina Trench						Cypress River					Recent alluv			
	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
R							L			L					
						L				L					
R															
R															
										L					
							L								
R										L	L				
						L	L			L	L				
R			R			L									
										L					
														R	
											L				
							L			L	L				L

rbus antrosa Conrad by Mozley; listed as Helisoma anceps anceps Menke by LaRocque.
y L. S. Russell = R.

s region: Freshwater species.

Cypress River					Recent alluvium						As. R.		Misc.		
3	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
											R				
L			L							L				R	
			L							L					
												R			
													R		
													R		
										L					
			L												
L															
			L	L					R					R	R
L			L	L									R		
										L					
			L												
							R						R		
				L											
L			L	L				L							
										L					
													R		
													R		

Helisoma anceps anceps Menke by LaRocque.

APPENDIX: Mollusca

GASTROPODA (cont'd)	Lake Agassiz II						I	
Locality:	1	2	3	4	5	6	7	8
9. Physa sp.								
Physa ancillaria Say								
Physa gyrina Lea								
Physa sayi crassa (Walker)								
? Planorbidae			M					
10. Planorbula armigera (Say)	R							
Planorbula crassilabris Walker			M					
Planorbula jenksii (Carpenter)								
Planorbus arcticus ("Beck" Möller)		M						
11. Promenetus exacuous (Say)	R							
12. Stagnicola sp.	R					R	R	R
Stagnicola elodes (Say)	R							
Stagnicola palustris elodes (Say)								
Stagnicola palustris? nuttalliana (Lea)								
Stagnicola palustris palustris (Müller)	R							
Stagnicola cf. vahlii (Möller)								
13. Valvata bicarinata (Say)						R		
Valvata lewisi Currier?			M					
Valvata sincera Say	R							
Valvata tricarinata Say	R	M	M					

Identifications by A. Byron Leonard = L; by Alan Mozley (1934) = M; by L. S. Russ

ENDIX: Molluscan fauna of the Tiger Hills region: Freshwater species (cont'd).

	Pembina Trench						Cypress River						
6	7	8	9	10	11	12	13	14	15	16	17	18	1
								R					
						L				L			
										L			
			R										
								R					
				R									
R	R	R	R										
				R									
								R					
R													
											L		

I; by L. S. Russell = R.

water species (cont'd).

River			Recent alluvium						As. R.		Misc.		
5	16	17	18	19	20	21	22	23	24	25	26	27	28
					R								
	L							L					
	L												
										R	R		
						L							
							R						R
											R		
											R		
					R								
											R		
		L						L					

APPENDIX: Moll

GASTROPODA	Locality:	Lake Agassiz II					I
	1	2	3	4	5	6	7	8
1. Carychium exile canadense Clapp								
2. Cionella lubrica (Müller)	R							
3. Deroceras laeve (Müller)								
4. Discus sp.								R
Discus cronkhitei (Newcomb)	R			L				
5. Gastrocopta armifera (Say)		M						
Gastrocopta armifera abbreviata (Sterki)							R	R
Gastrocopta armifera armifera (Say)				L			R	
Gastrocopta pentadon (Say)								
6. Hawaiia minuscula (Binney)								
7. Helicodiscus parallelus (Say)								
8. Retinella sp.							R	
Retinella binneyana (Morse)								
Retinella electrina (Gould)								
9. Succinea sp.	R							R
Succinea avara (Say)								
Succinea decampii Tyron								
Succinea ovalis (Say)								
Succinea retissa Loa								
10. Vallonia albula Sterki								
Vallonia costata (Müller)				L				
Vallonia gracilicosta Reinhardt							R	R
11. Zonitoides arboreous (Say)								
Zonitoides nitidus (Müller)	R							R

Identifications by A. Byron Leonard = L; by Alan Mozley (1934) = M; by L. S. Russ

APPENDIX: Molluscan fauna of the Tiger Hills region: Terrestrial species.

	Pembina Trench						Cypress River					Re	
6	7	8	9	10	11	12	13	14	15	16	17	18	19
									L				R
									L				
		R											
			R	R		L			L				R
	R	R											
	R												
									L				
				R									
	R												
													R
					R				L		L		
		R											
										L			
				R	R								R
				R									
									L				
	R	R			R								R
							L					R	R
		R	R	R									

M; by L. S. Russell = R.

rrestrial species.

River		Recent alluvium						As. R.		Misc.		
16	17	18	19	20	21	22	23	24	25	26	27	28
					L							
			R		L		L					
			R						R			
					L	R	L		R			
							L					
									R			
	L		R		L		L		R			
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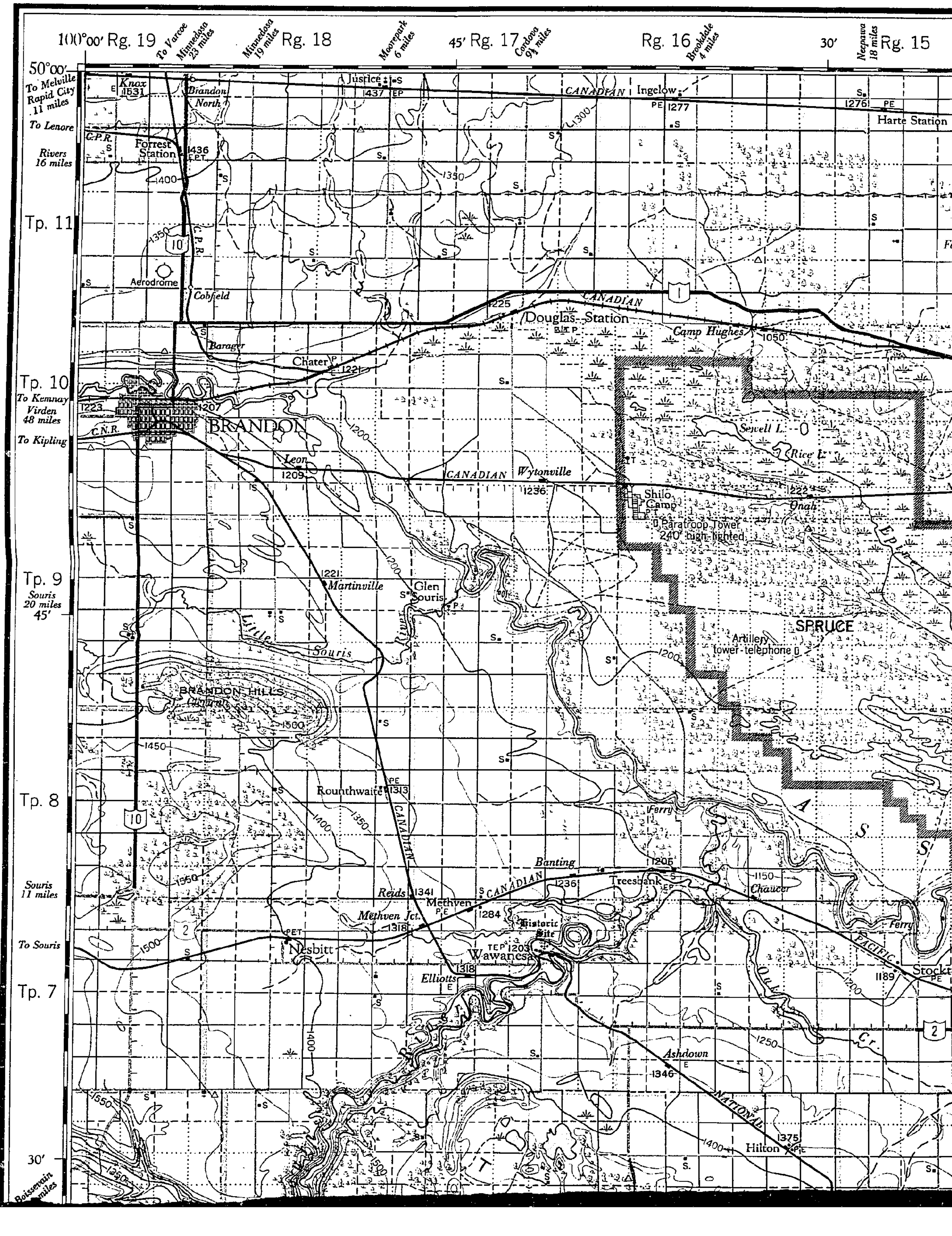

Canada

Department of Mines and Resources

MINES, FORESTS AND SCIENTIFIC SERVICES BRANCH

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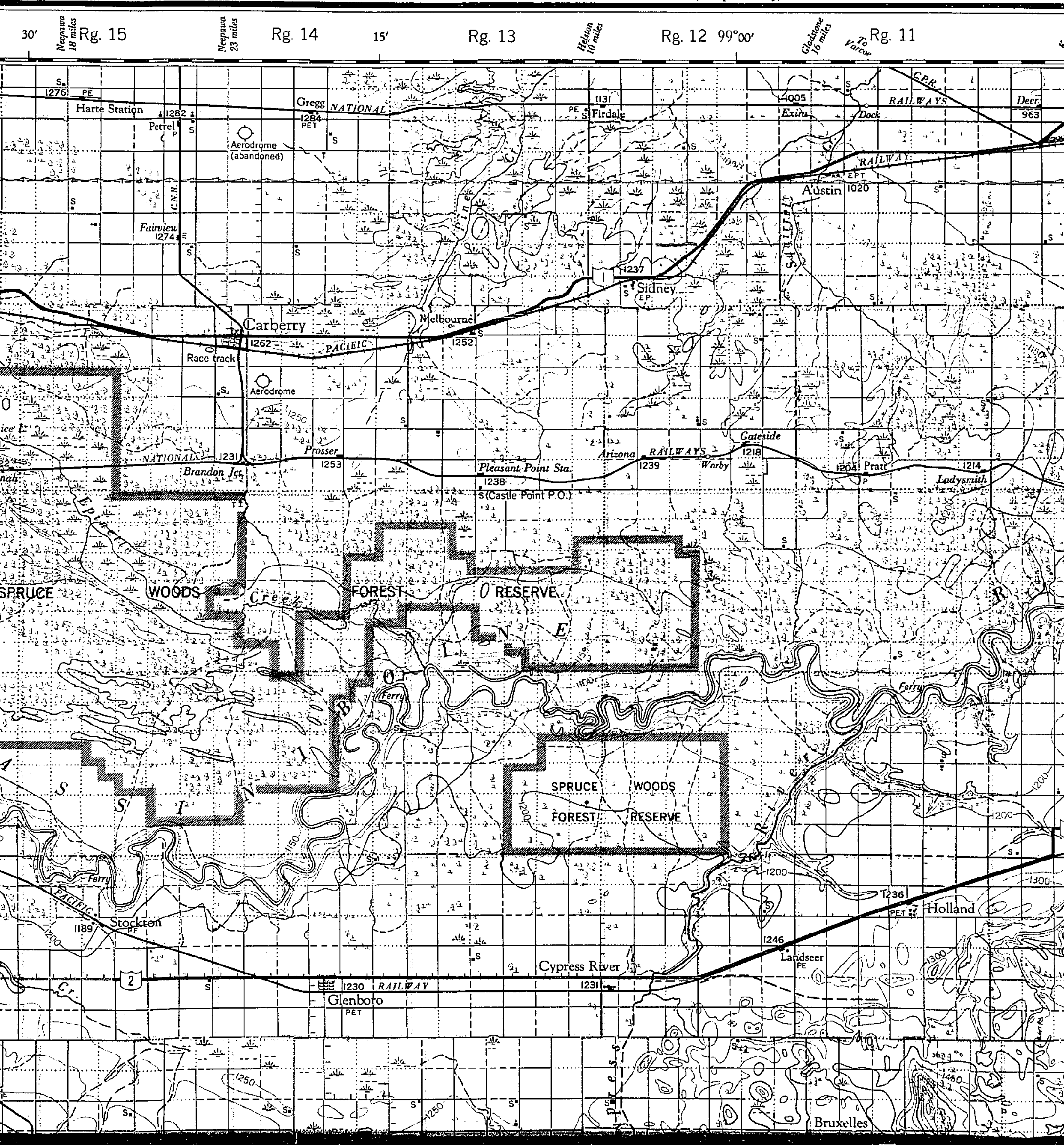

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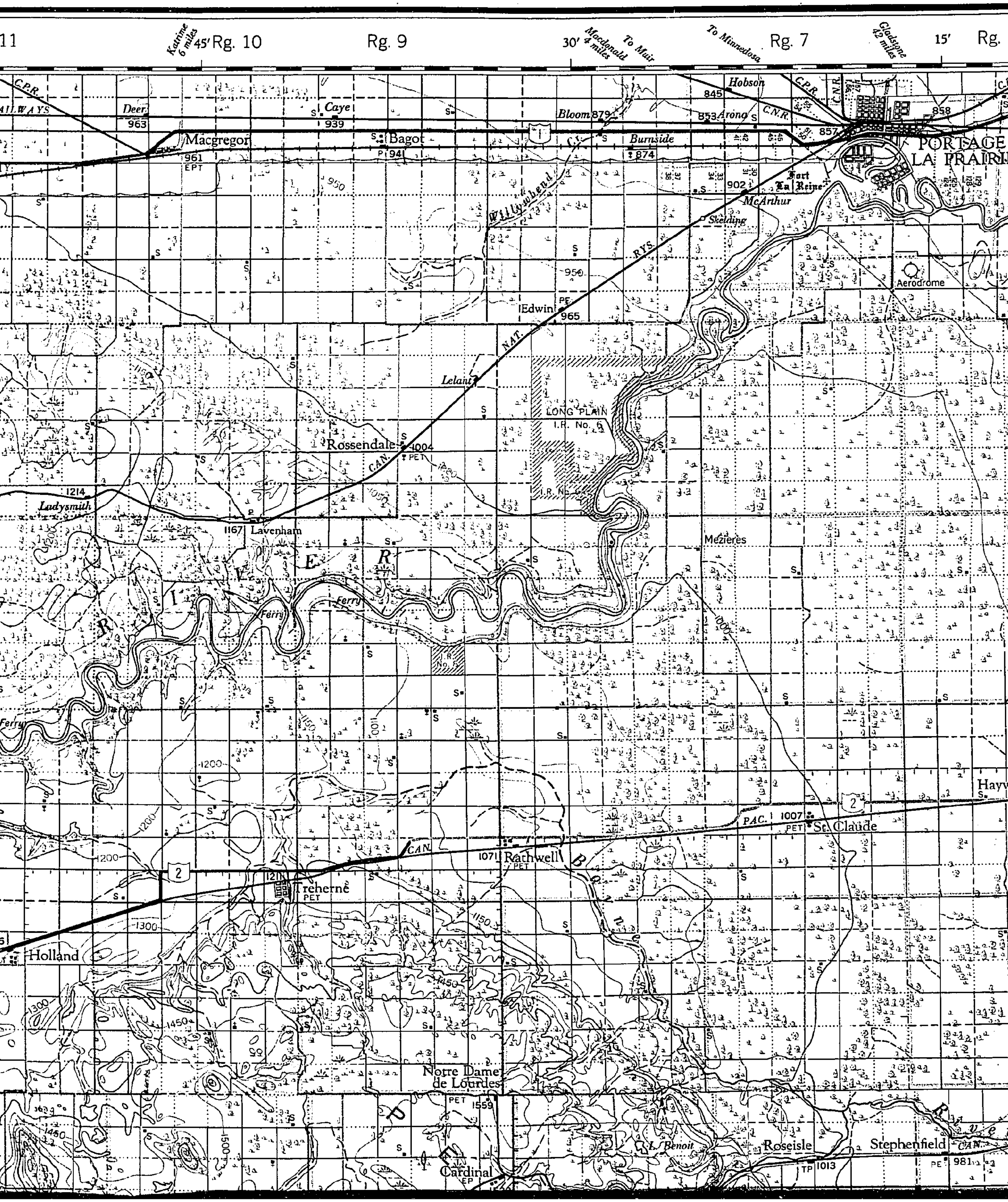
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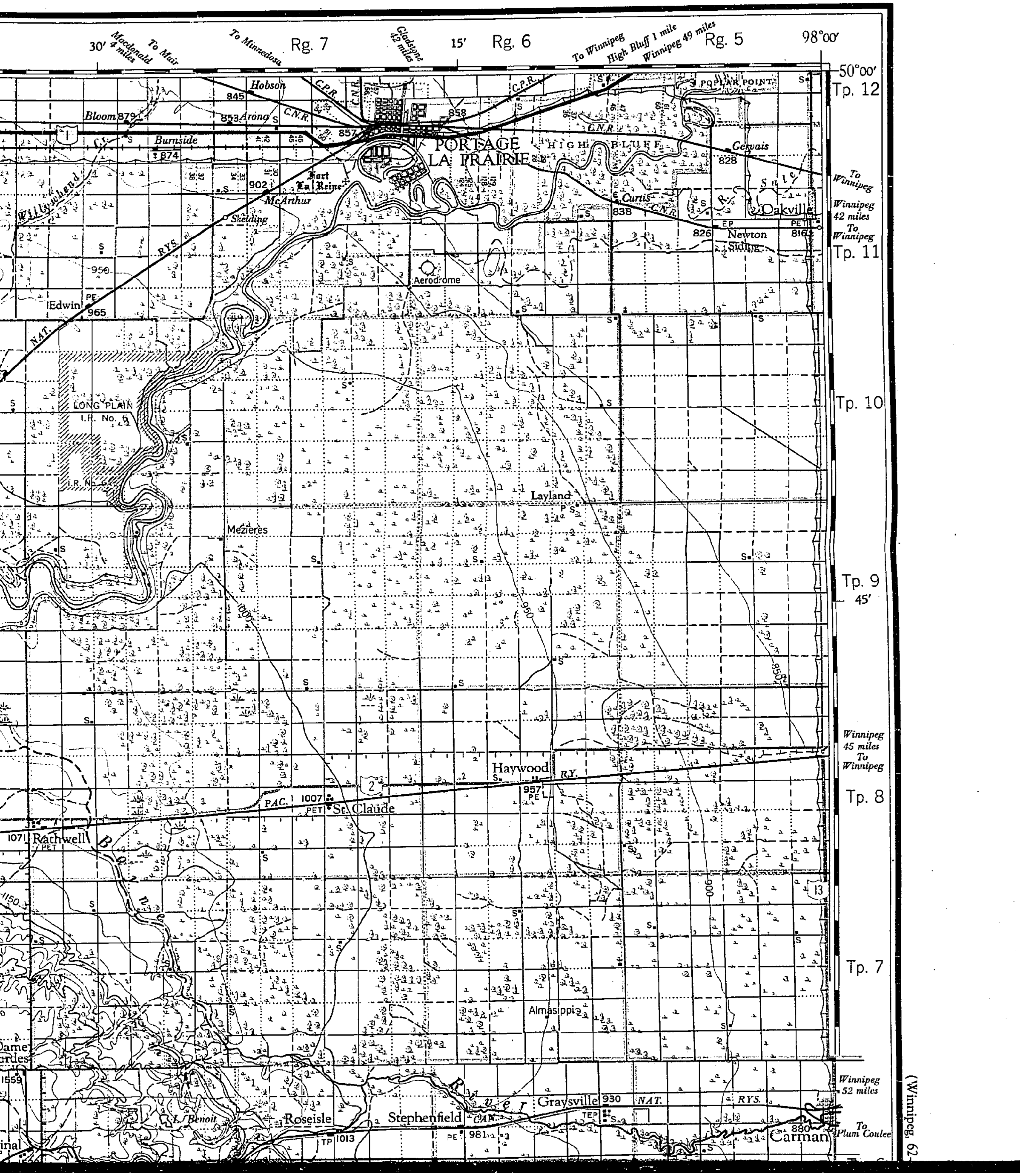
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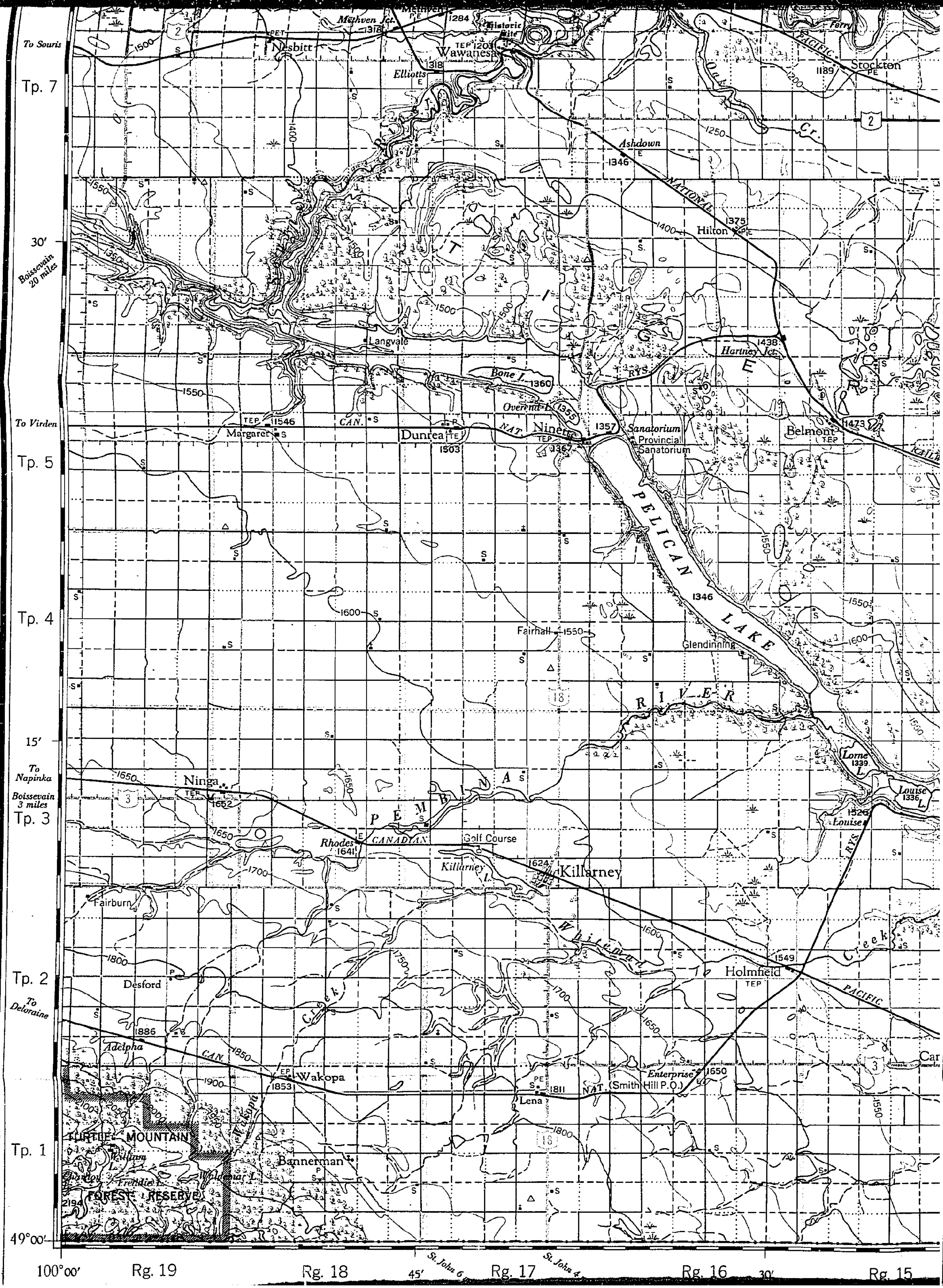
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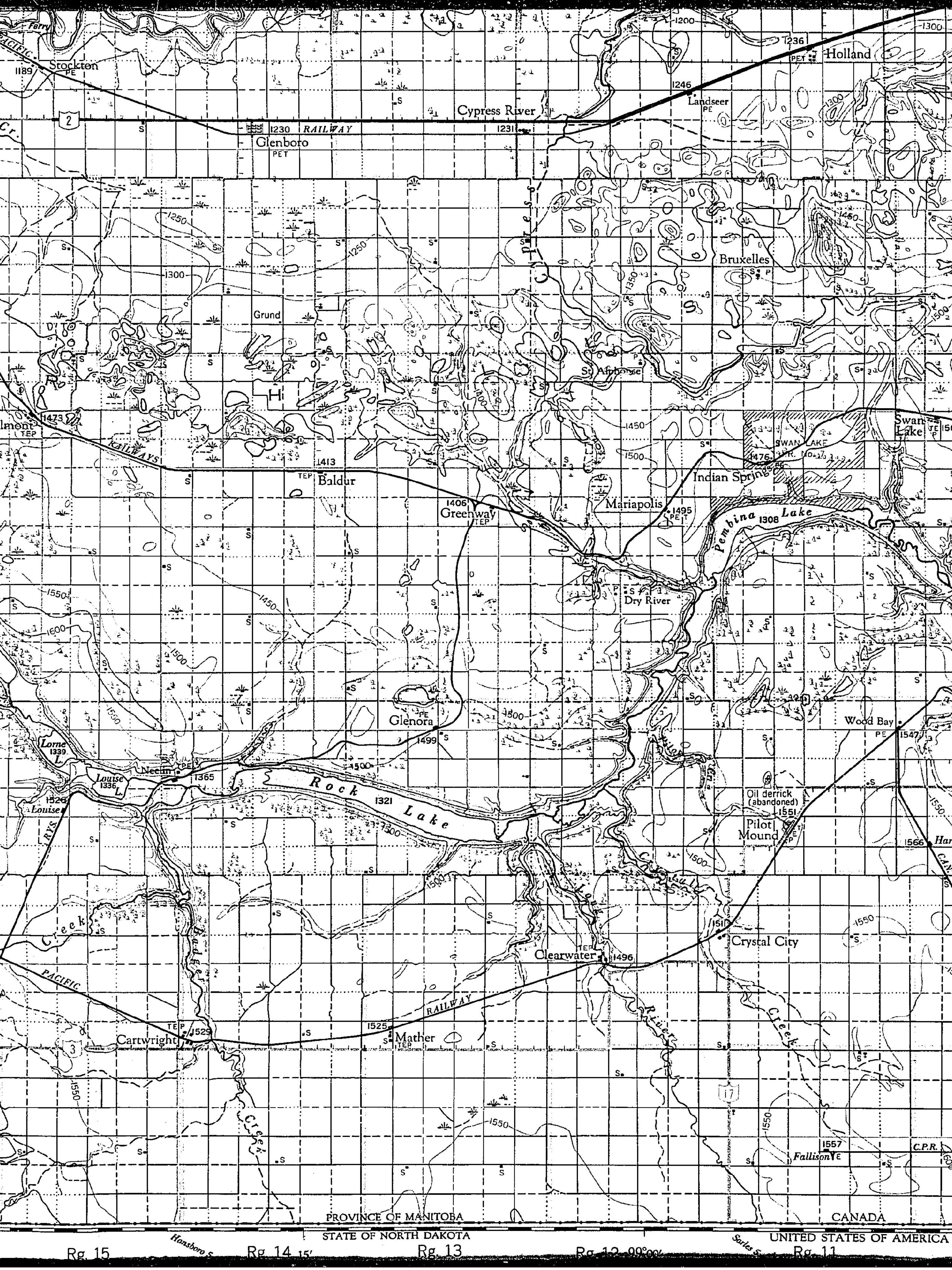
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Dry River
Wood Bay
La Riviere
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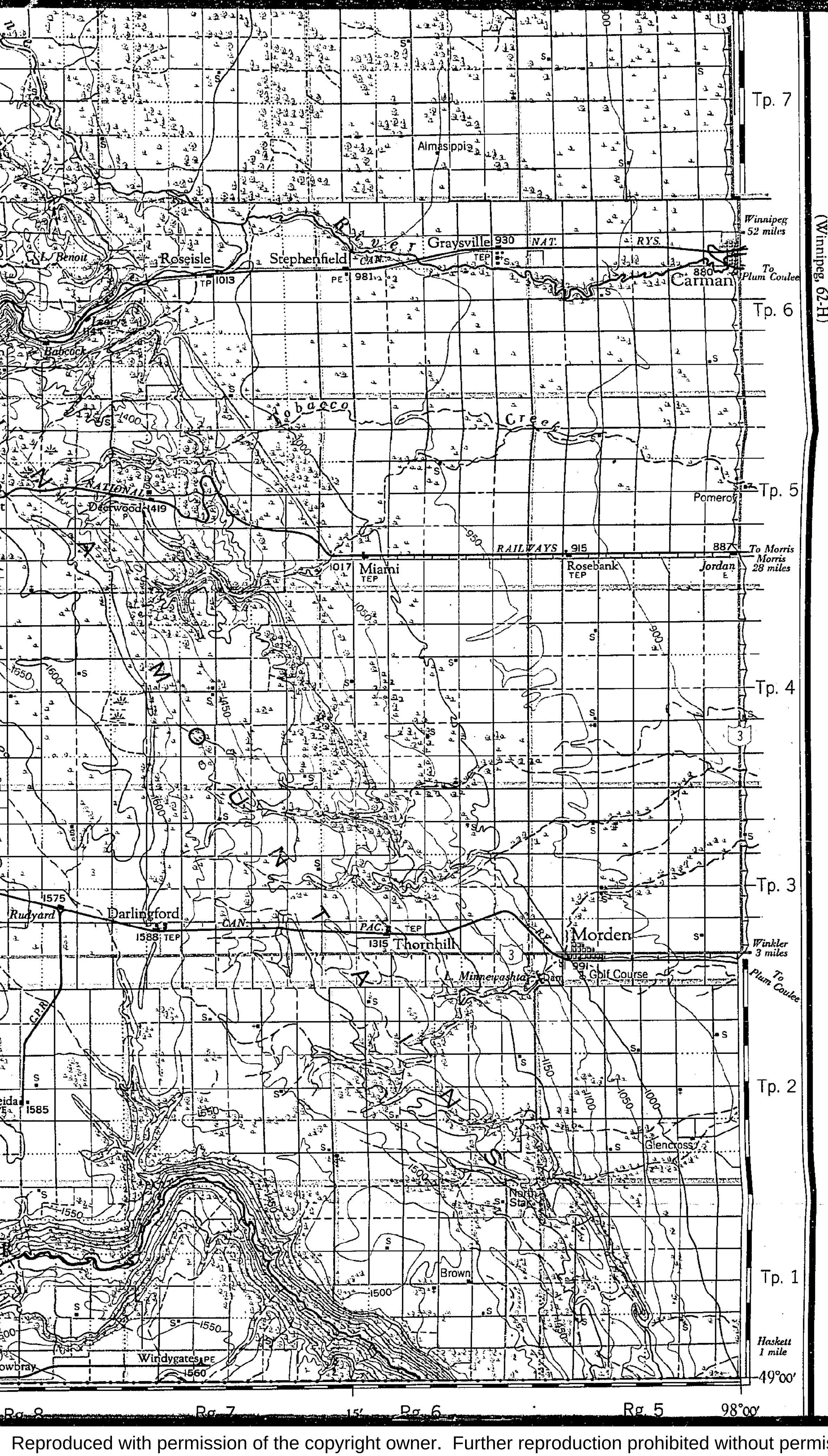
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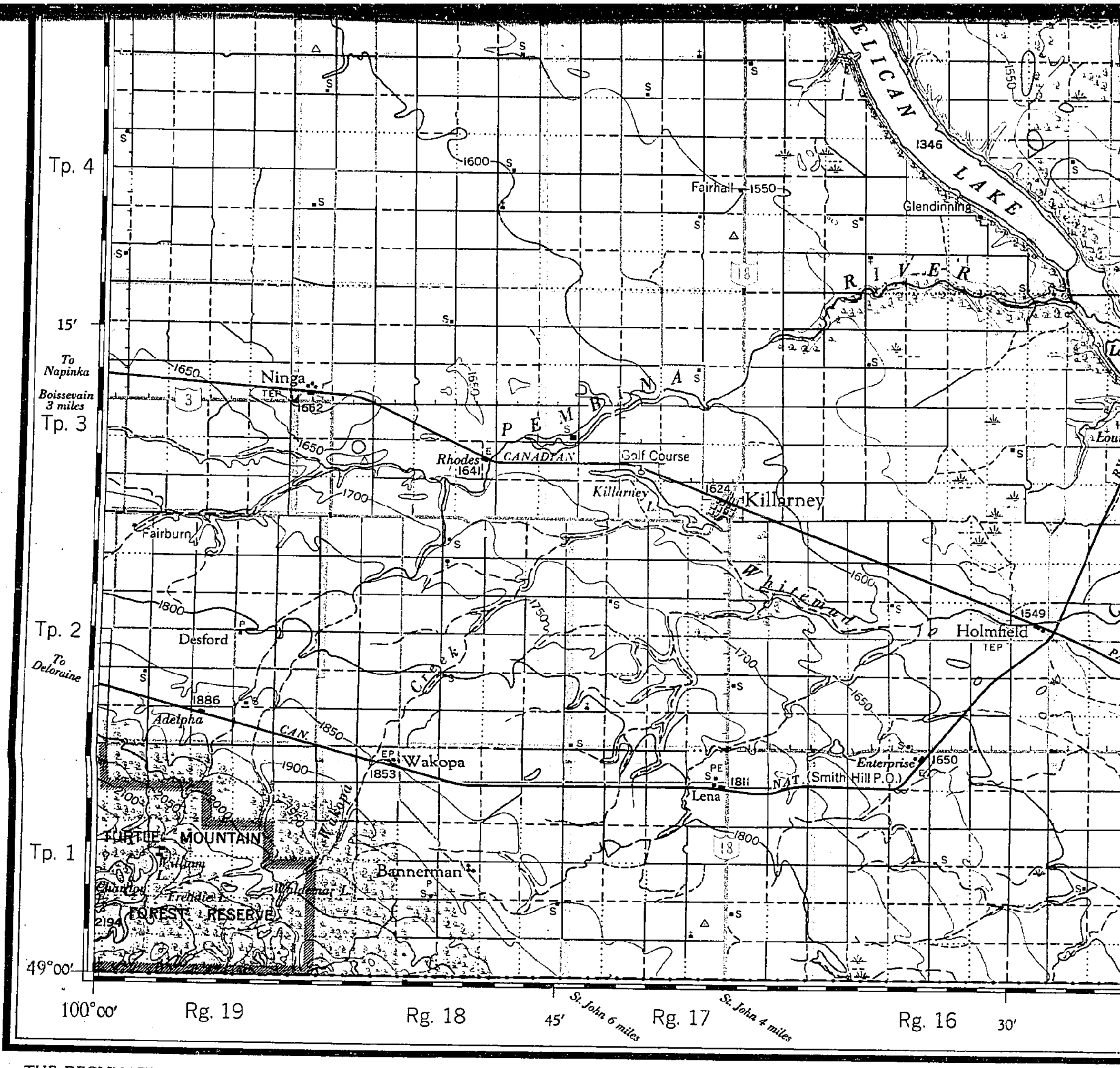
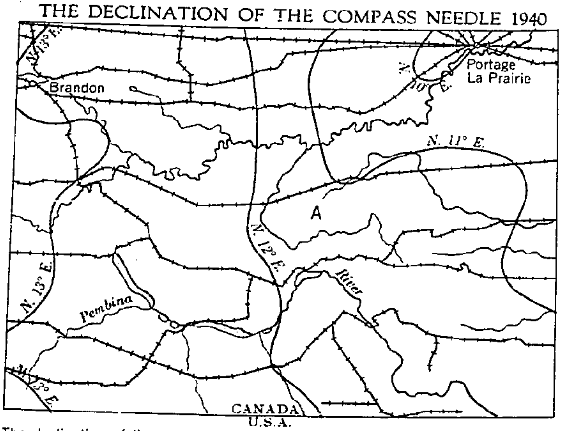


THE DECLINATION OF THE COMPASS NEEDLE 1940



The declination of the compass needle at any place along a red line is the declination given on that red line. At other places the declination is between those given on the neighbouring red lines; thus at the place marked A. the declination is between N. 11° E. and N. 12° E.

The declination of the compass needle is decreasing 3′ annually.

DIAGRAM OF TOWNSHIP

31	32	33	34	35	36
30	29	28	27	26	25
19	20	21	22	23	24
18	17	16	15	14	13
7	8	9	10	11	12
6	5	4	3	2	1

Reference

Railway, steam, double track ....

" " single track ....

Boundary: international ....

" township ....

" forest reserve ....

" Indian reserve...............

Surveyed line...............

Main highway ....

Secondary highway ....

Other roads...............

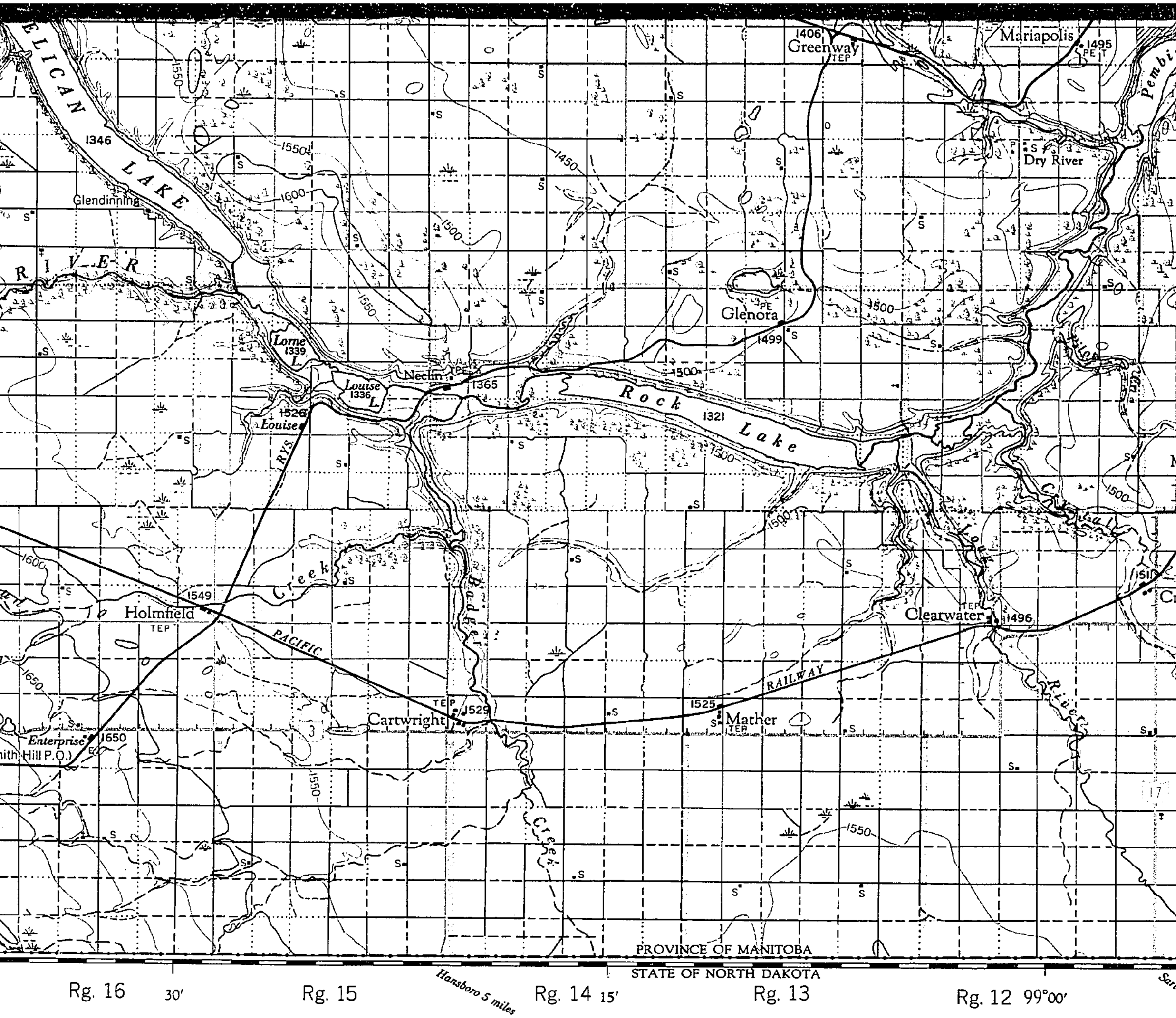
Highway route number ....

Electric power line { on steel or wood towers... / on wooden poles.........

Non-perennial stream ....

Drainage ditch...............

Marsh or open muskeg...............



Reference

Railway, steam, double track

" " single track — Station, Siding or stop

Boundary: international

" township

" forest reserve

" Indian reserve

Surveyed line

Main highway — Paved, Gravel

Secondary highway — Gravel or Improved Earth

Other roads — Wagon road

Highway route number — 2

Electric power line — on steel or wood towers; on wooden poles

Non-perennial stream

Drainage ditch

Marsh or open muskeg

BRANDO

MANITOBA

Scale 4 Miles to 1 Inch or 1:25

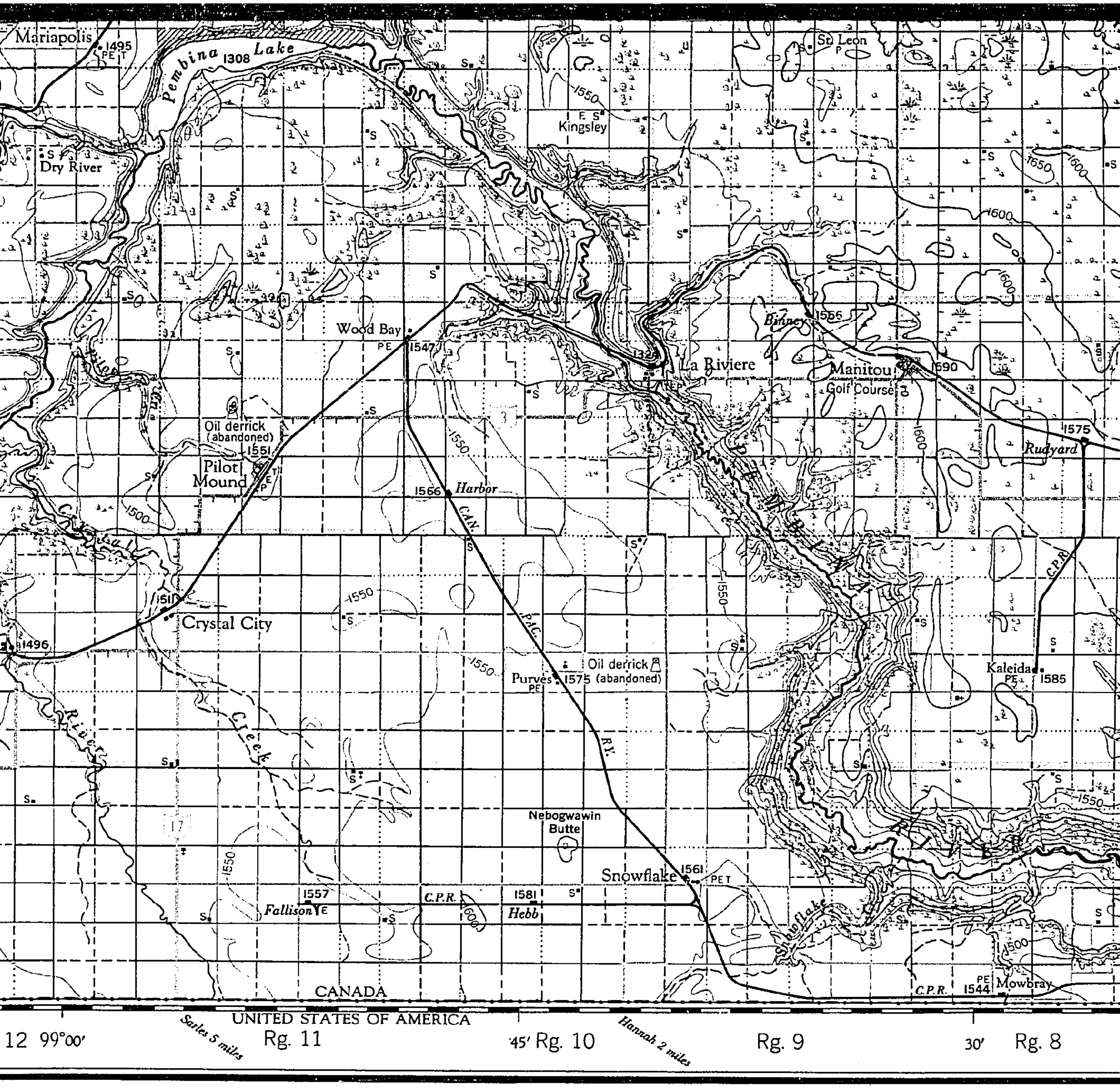
Miles 2 1 0 2 4 6

Contour interval 50 feet.

Datum is mean sea level.

PLATE I

Price 25 cents



ANDON

ANITOBA

s to 1 Inch or 1:253,440

4 6 8 10 Miles

ntour interval 50 feet.

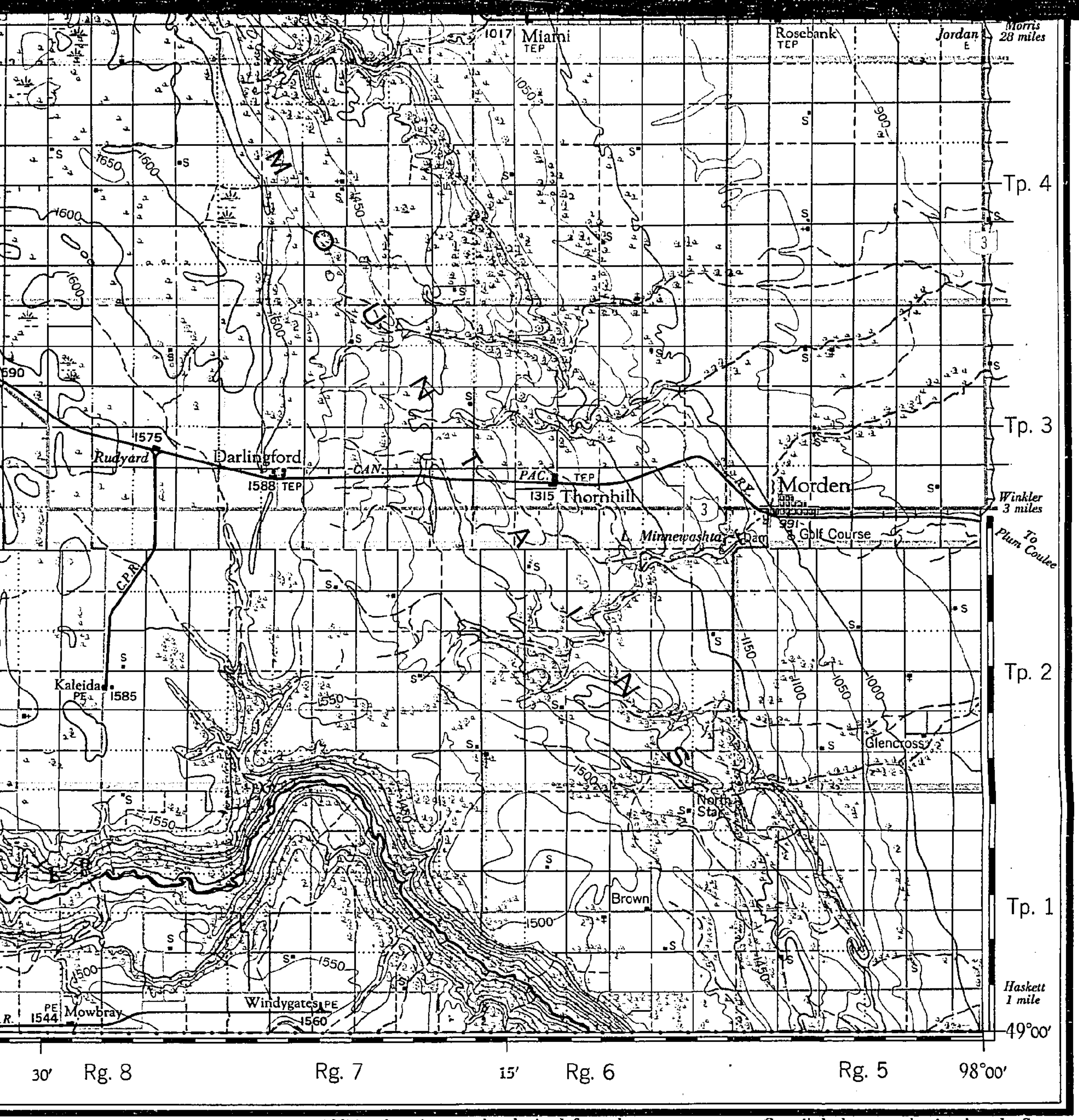
tum is mean sea level.

LATE I

Price 25 cents

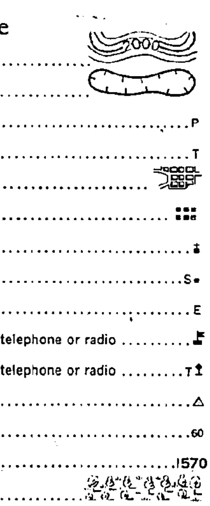
Reference

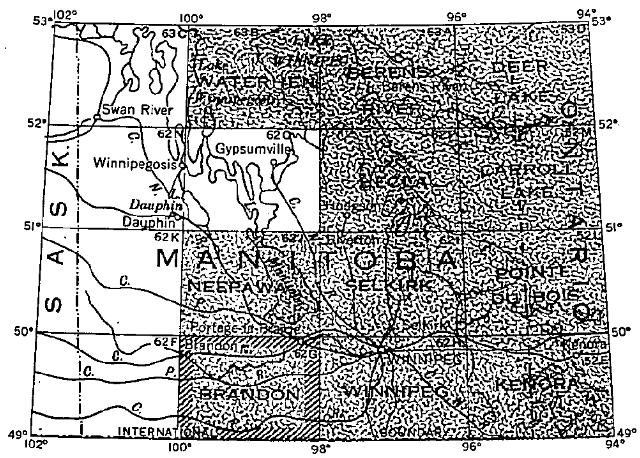
Contours
Depression contours
Post office .... P
Telegraph office .... T
Cities or large towns
Small towns or villages
Church
School .... S
Elevator or elevators .... E
Ranger cabin .... with telephone or radio
Forestry tower .... with telephone or radio
Geodetic triangulation station .... △
Lot number 60
Height in feet 1570
Woods, bush, scrub



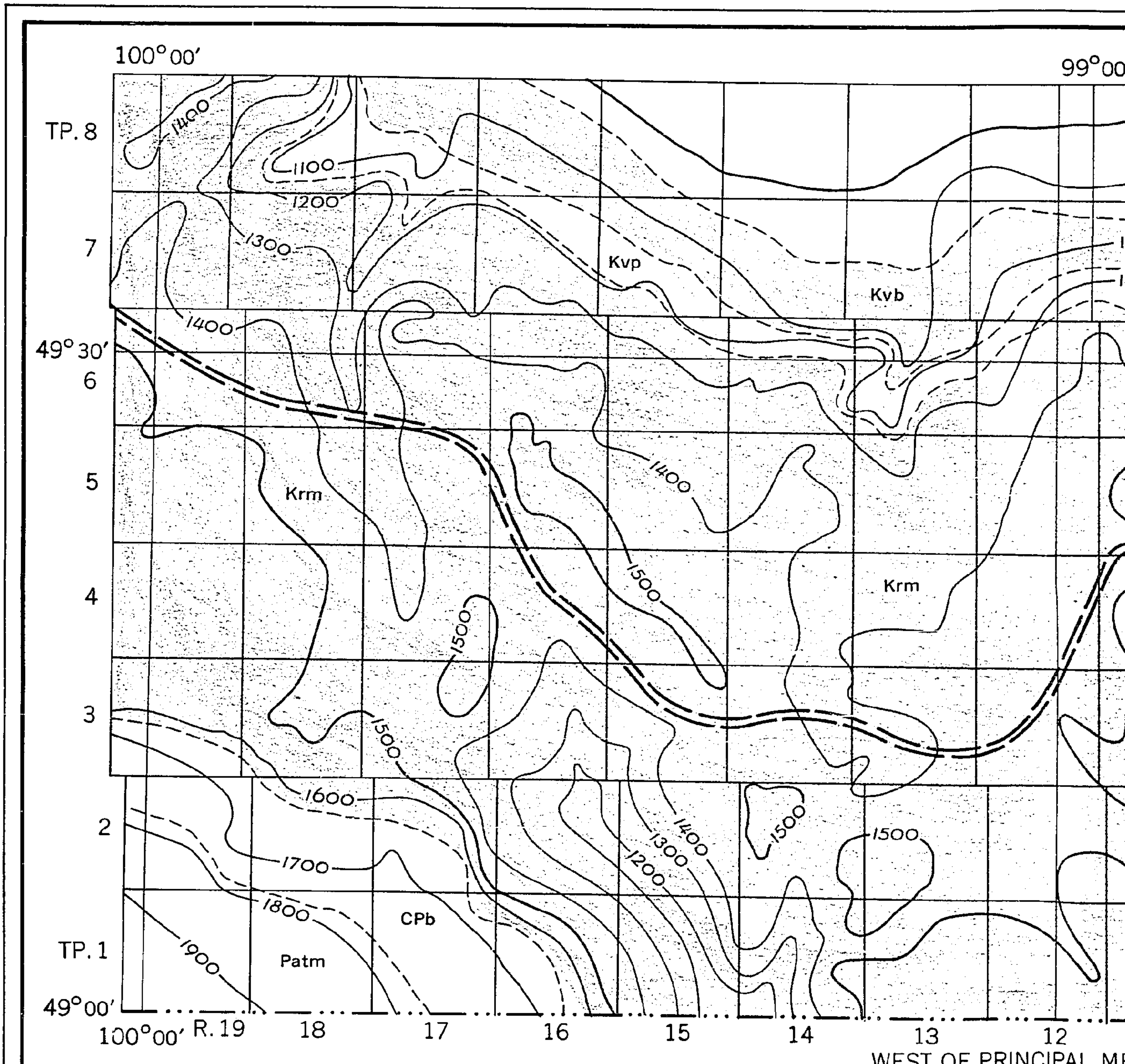
Additional copies may be obtained from the Surveyor General, Department of Mines and Resources, Labelle Building, Ottawa, Canada.

Compiled, drawn and printed at the Surveys and Mapping Bureau, Ottawa, 1948.





NOTE: On the above index the sheets published are shown in colour.



LEGEND

CENOZOIC

PALEOCENE

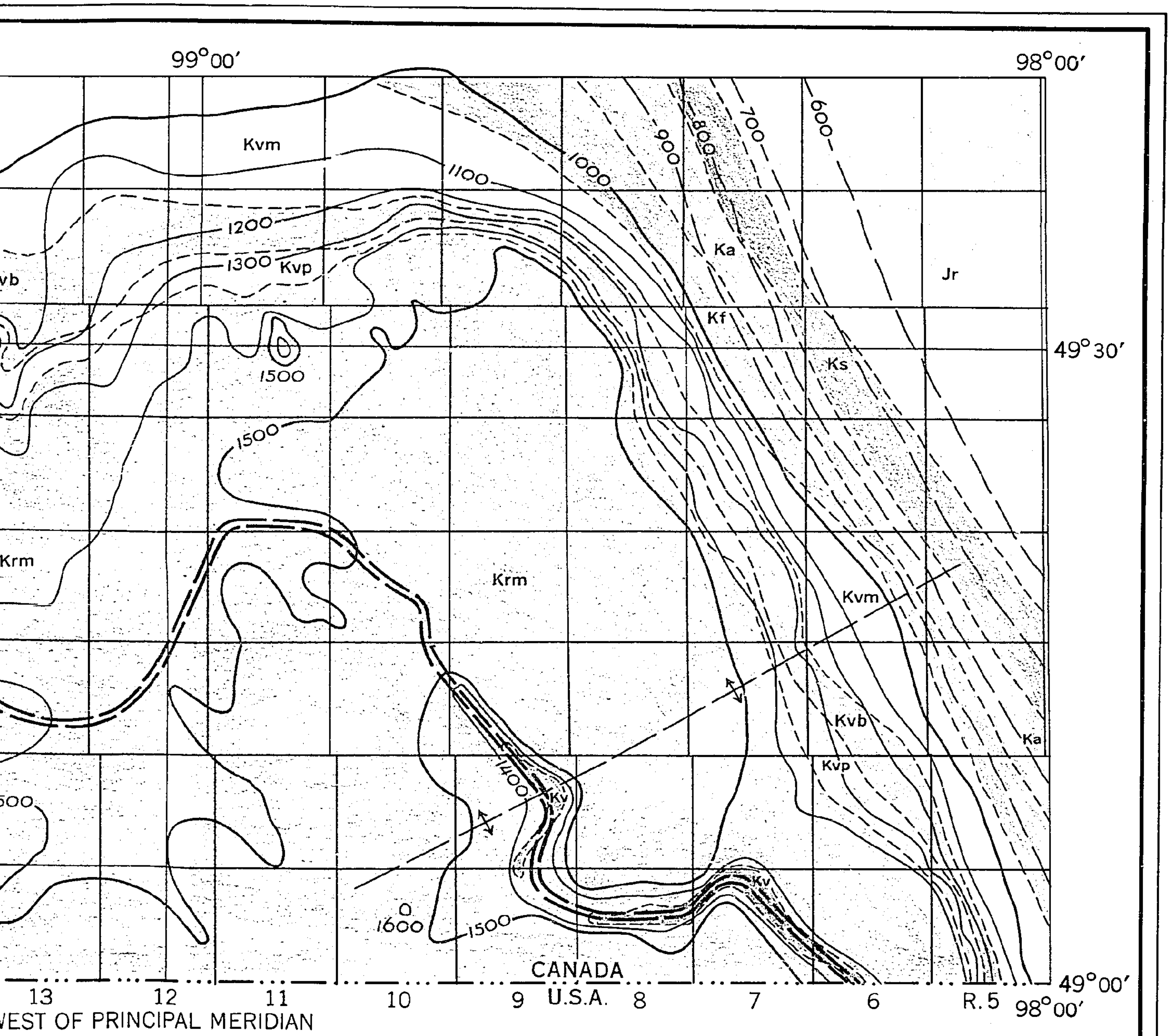
Patm — *TURTLE MOUNTAIN FORMATION: clay, sand, sandstone, coal*

CRETACEOUS OR PALEOCENE

CPb — *BOISSEVAIN FORMATION: sand, sandstone*

UPPER CRETACEOUS

Krm — *RIDING MOUNTAIN FORMATION: grey*



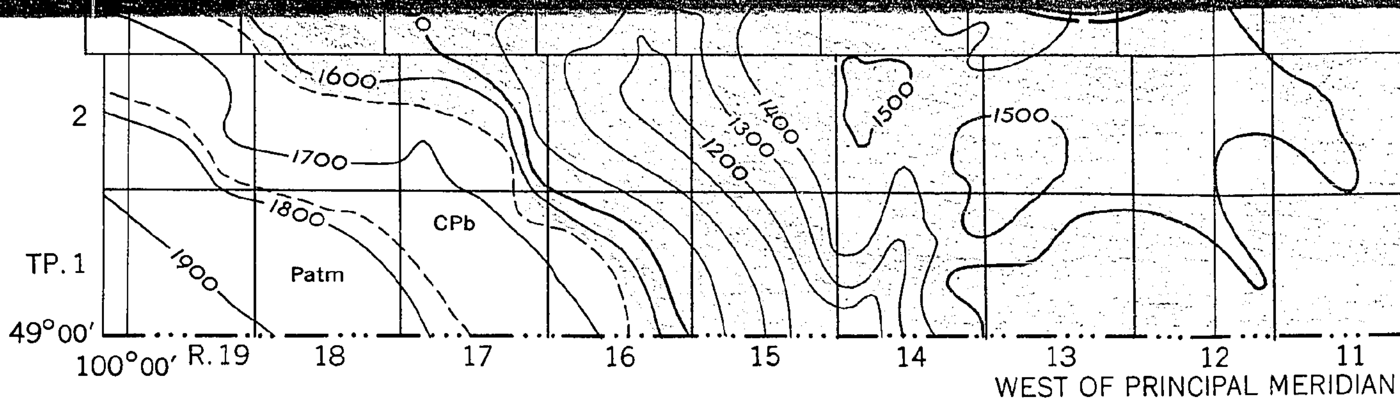
Township boundary. . . . .

Geological boundary (assumed). . . . .

Anticline . . . .

Altitude of bedrock surface
(contour interval 100 feet) 900

Axis of Pembina Trench



LEGEND

CENOZOIC

PALEOCENE

Patm — *TURTLE MOUNTAIN FORMATION:* clay, sand, sandstone, coal

CRETACEOUS OR PALEOCENE

CPb — *BOISSEVAIN FORMATION:* sand, sandstone

MESOZOIC

UPPER CRETACEOUS

Krm — *RIDING MOUNTAIN FORMATION:* grey and greenish grey shale; siliceous shale

Kv — *VERMILION RIVER FORMATION:* dark grey shale, clay, calcareous speckled shale, bentonite

Kvp — *Pembina Member:* grey to black soft shale, bentonite

Kvb — *Boyne Member:* calcareous shale, a little bentonite

Kvm — *Morden Member:* grey shale, septarian concretions

Kf — *FAVEL FORMATION:* calcareous speckled shale, limestone, bentonite

LOWER (?) AND UPPER CRETACEOUS

Ka — *ASHVILLE FORMATION:* dark grey shale; minor silt, sand, limestone and bentonite

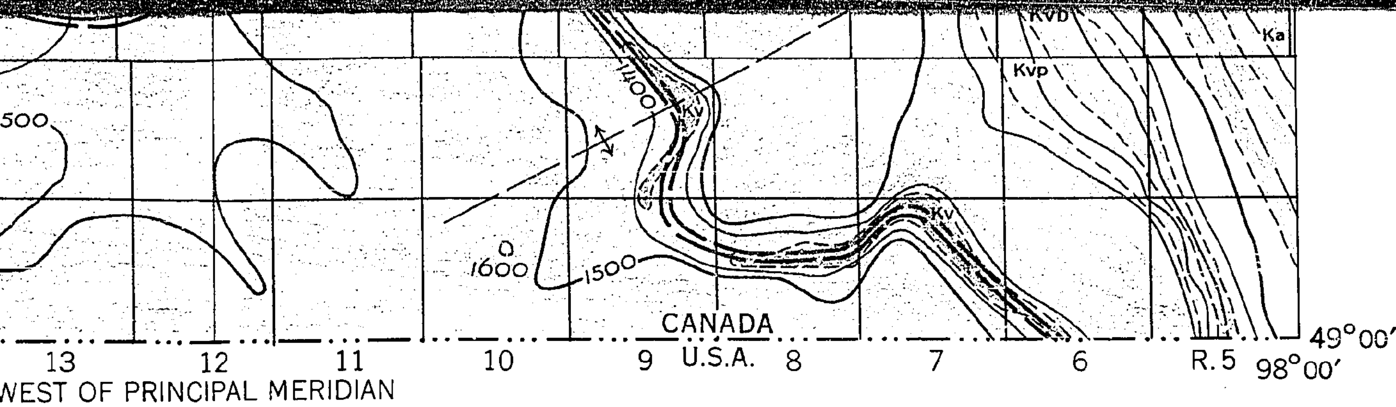
LOWER CRETACEOUS

SWAN RIVER GROUP

Ks — Sand, sandstone, shale

JURASSIC

Jr — Grey shale, calcareous shale, variegated shale



Township boundary . . . .

Geological boundary (assumed) . . . .

Anticline . . . .

Altitude of bedrock surface (contour interval 100 feet) 900

Axis of Pembina Trench . . . .

Compiled by J.A. Elson

BEDROCK GEOLOGY

TIGER HILLS REGION

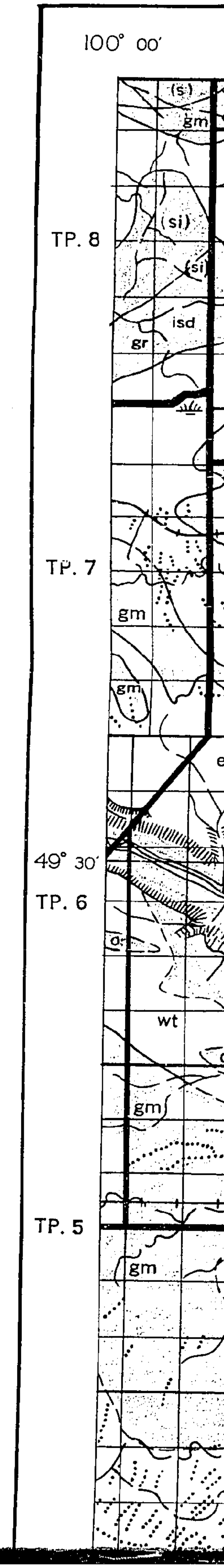
MANITOBA

Scale of Miles

10 5 0 10 20

PLATE 2

PLATE 3



LEGEND

CENOZOIC

PLEISTOCENE (WISCONSIN)

POST-GLACIAL DEPOSITS

ya	*Younger alluvium: Poorly sorted sand, silt, clay and gravel; includes some undifferentiated alluvium*
es	*Windblown sand: well-sorted medium to fine sand*

LATE-GLACIAL AND EARLY POST-GLACIAL DEPOSITS

oa	*Older alluvium: poorly sorted sand and gravel; includes some outwash*
lc	*Delta and lake deposits; coarse: well sorted sand and coarse silt*
lf	*Delta and lake deposits, fine: fine silt and clay*
wt	*Waterworked drift: 1 to 4 foot lag concentrate of poorly sorted silt, gravel, sand and boulders overlying glacial drift (mainly till)*
si	*Poorly sorted very fine sand and silt with rare pebbles; problematic origin (outwash or eolian?)*

GLACIAL DEPOSITS

o	*Outwash: sand and gravel, sorting variable but generally poor*
isd	*Ice-contact stratified drift; sand, gravel and silt, sorting variable; includes eskers*
gm	*Ground moraine; mostly compact silty-sandy till, locally silty till and silty-clayey till; topography smooth*

avel;

EPOSITS

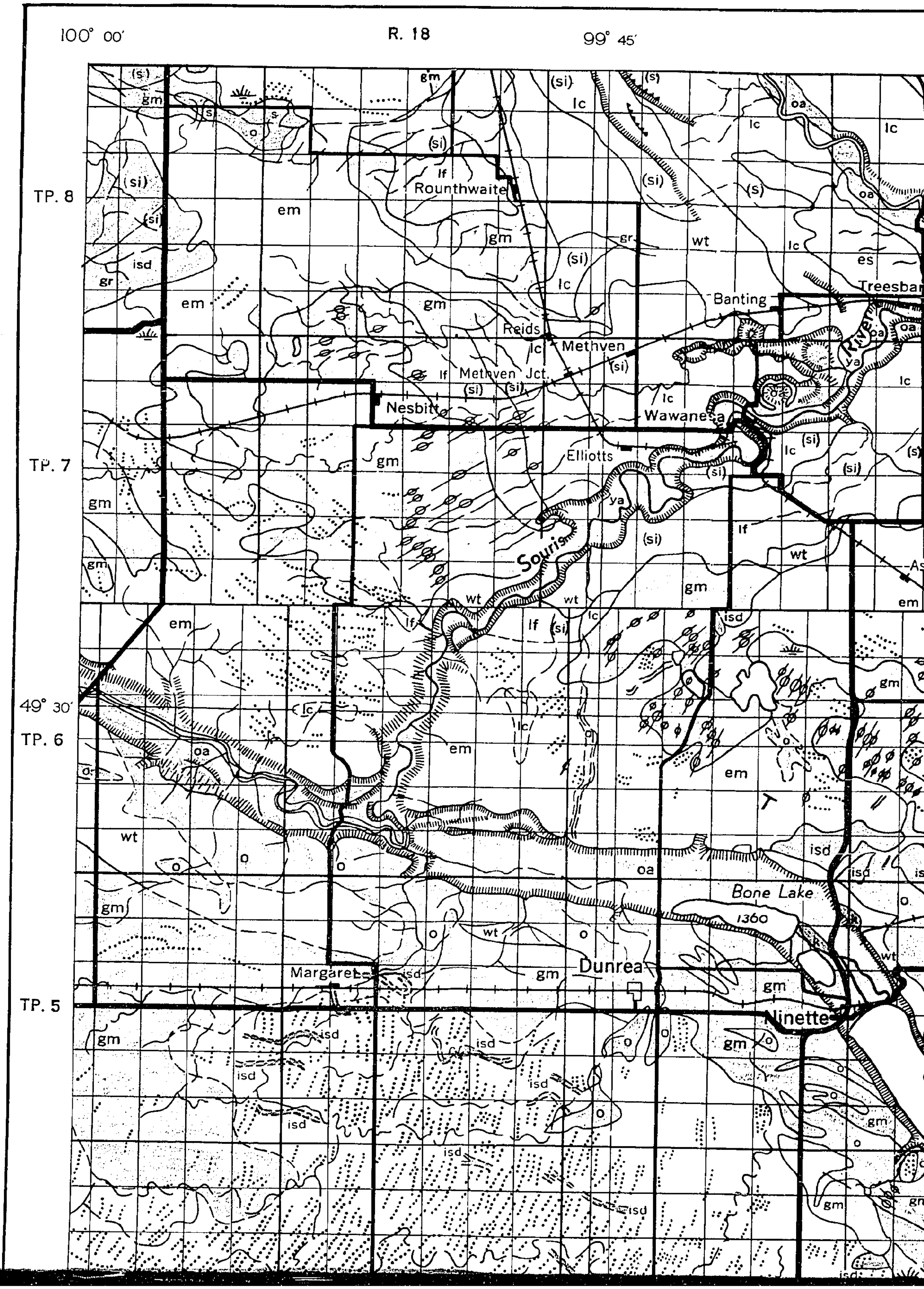
s

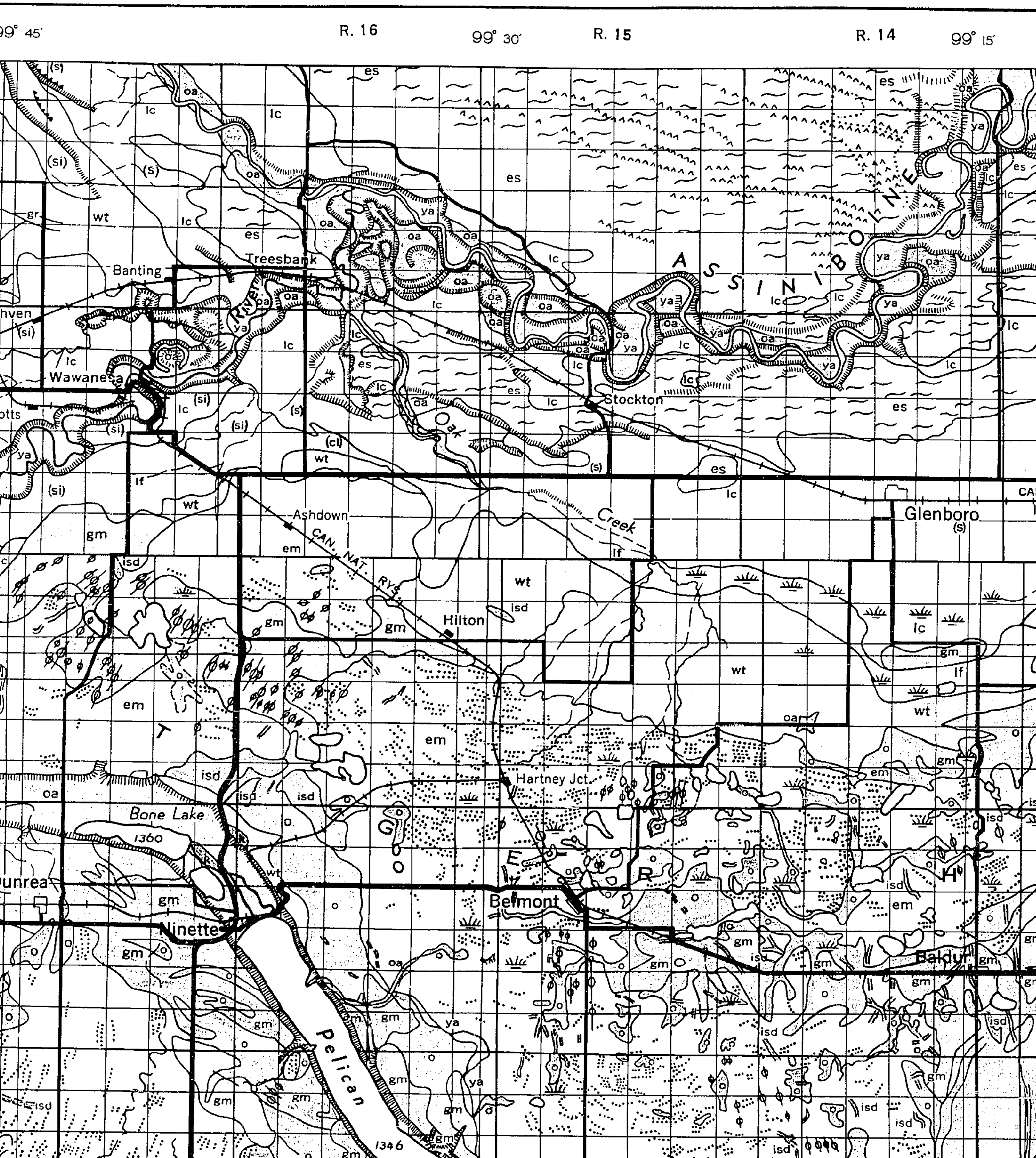
ly sorted
ainly till)

y poor

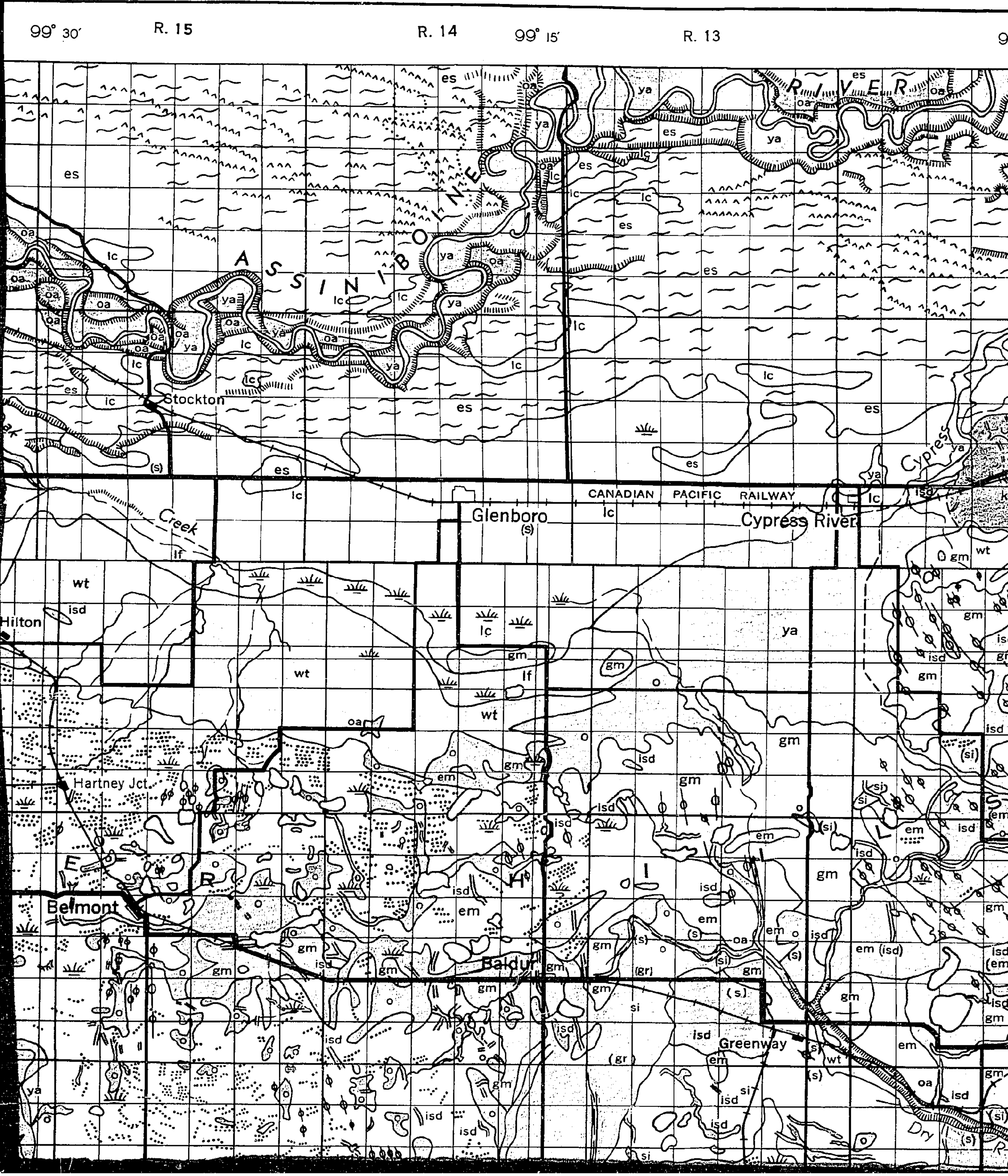
variable;

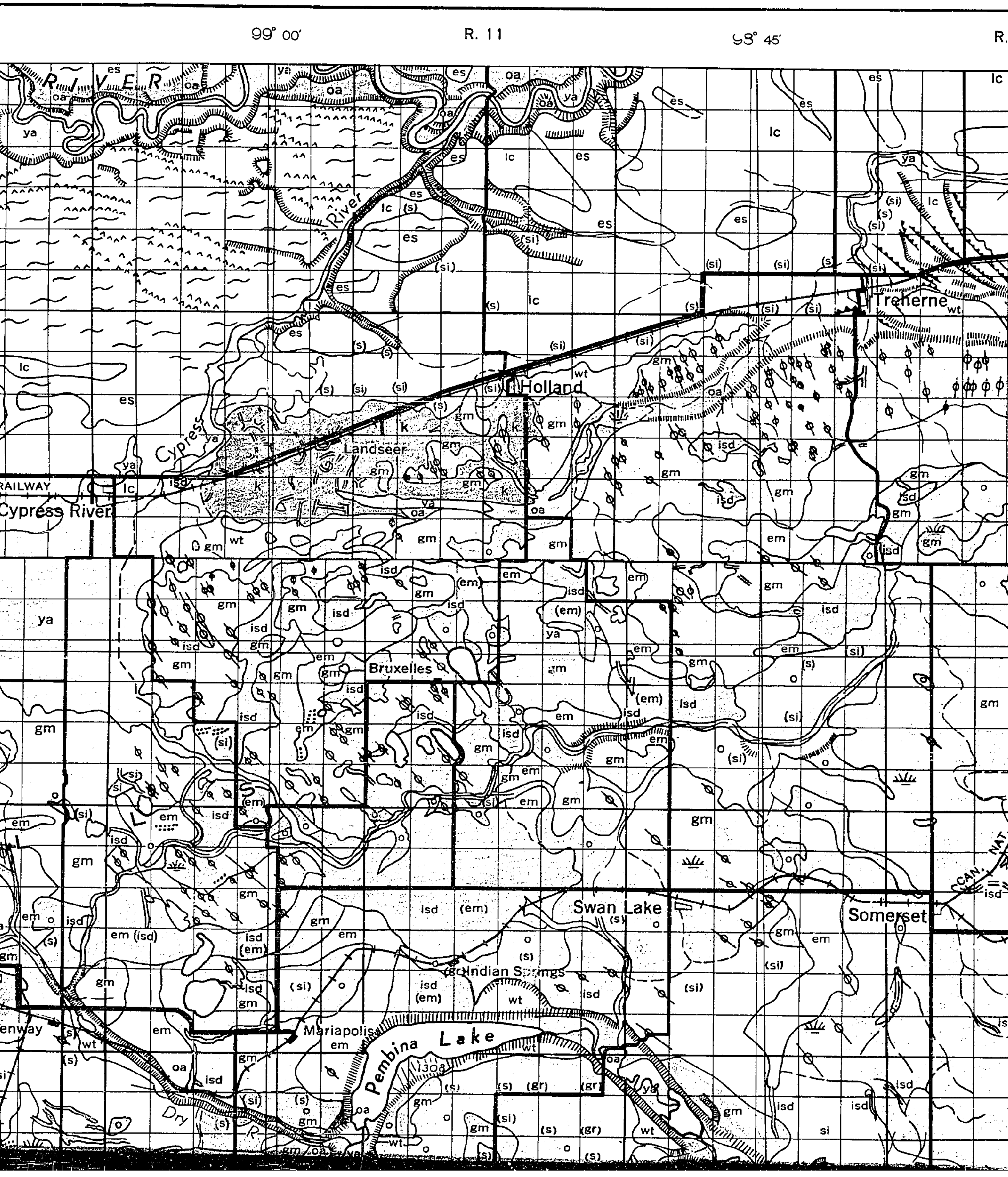
silty till

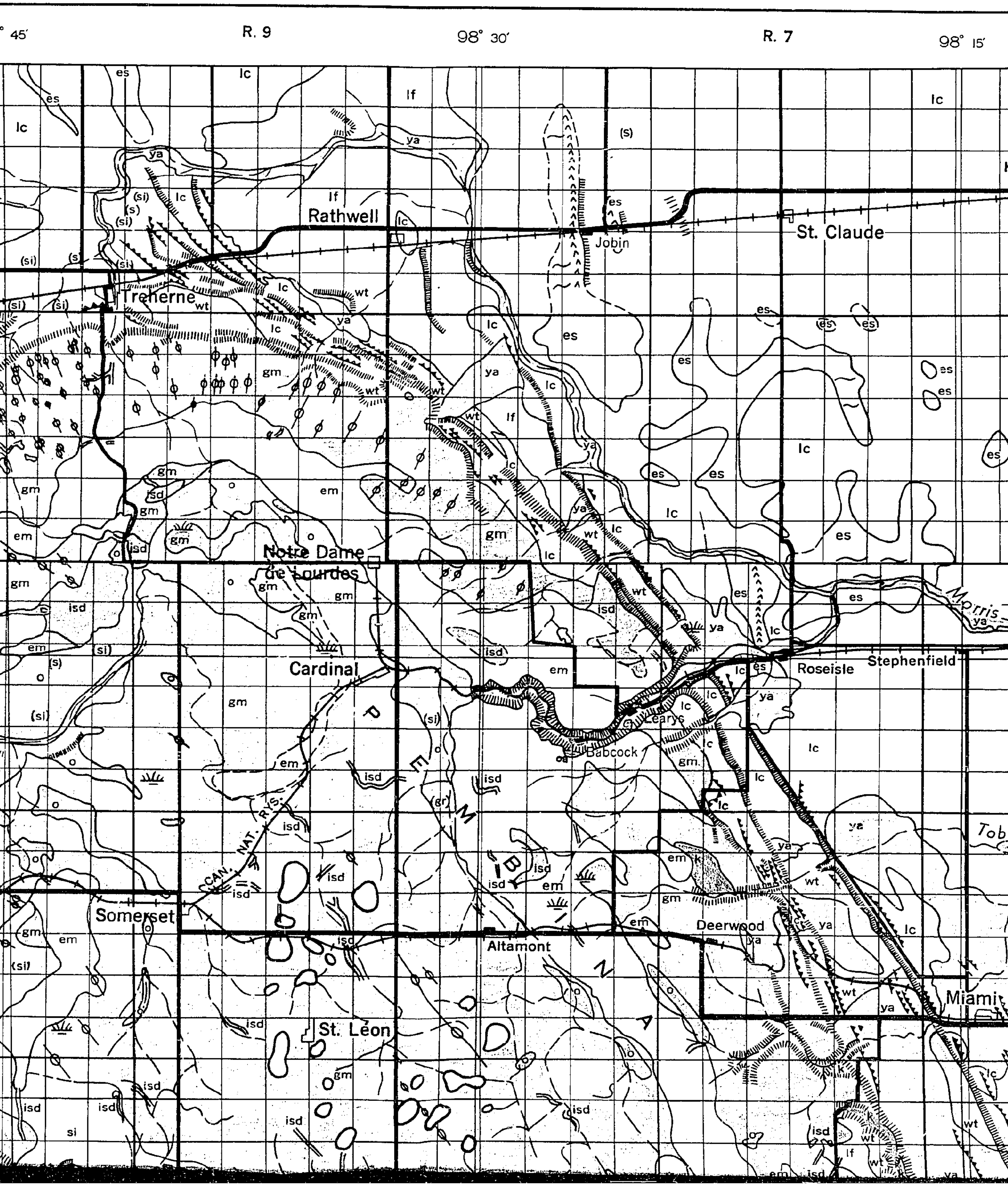



99° 45′
R. 16
99° 30′
R. 15
R. 14
99° 15′
Banting
Treesbank
Wawanesa
Stockton
Ashdown
CAN. NAT. RYS.
Oak Creek
Glenboro
Hilton
Hartney Jct.
Bone Lake
1360
Belmont
Ninette
Baldur
Pelican
1346
ASSINIBOINE
River
es
lc
oa
ya
wt
gm
em
isd
lf
(si)
(s)
(cl)
gr

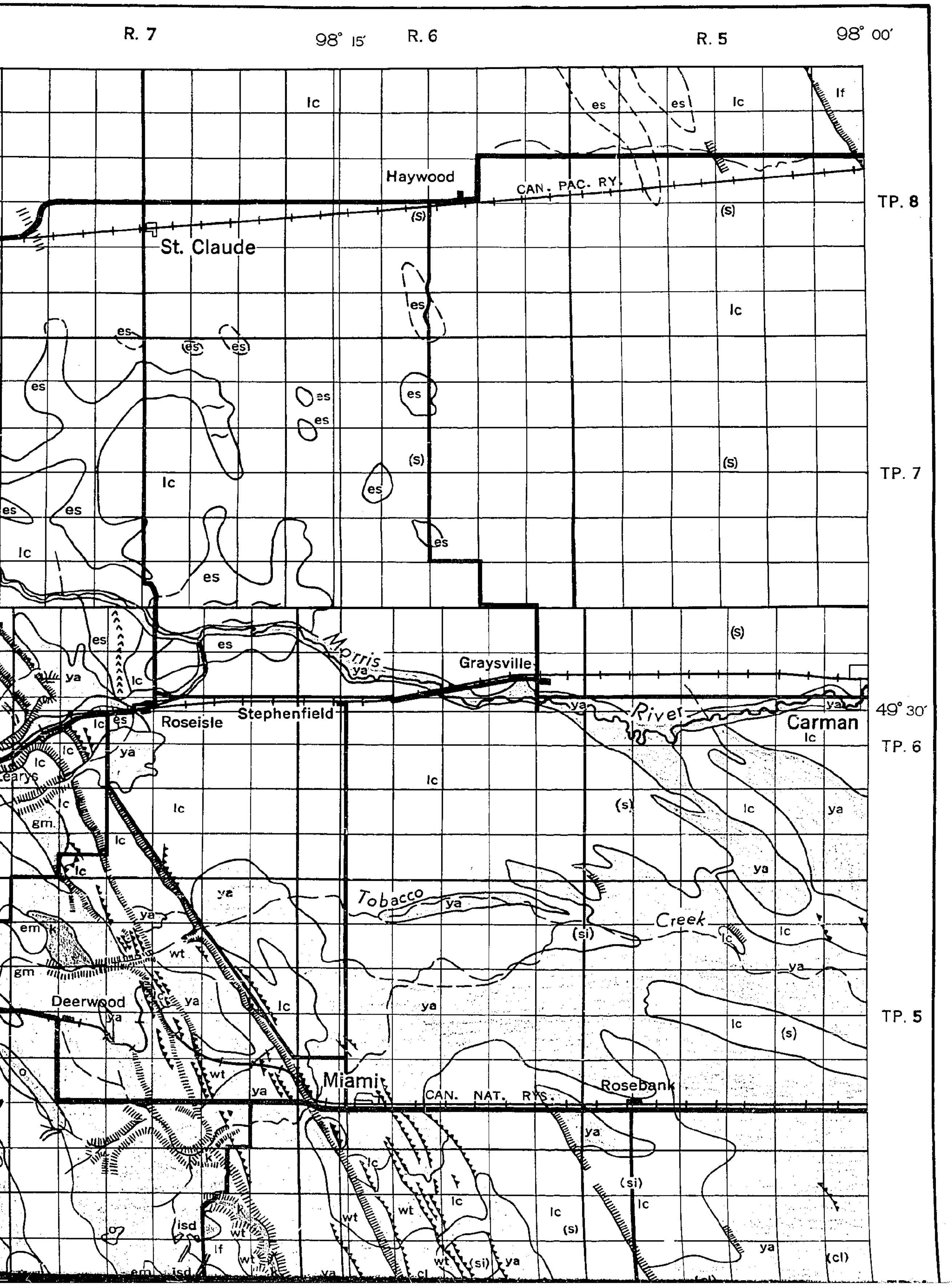

R. 14
99° 15′
R. 13
99° 00′
R. 11
RIVER
Cypress River
CANADIAN PACIFIC RAILWAY
Glenboro
Cypress River
Landseer
Bruxelles
Baldur
Greenway
Mariapolis
Pembina Lake
Dry


99° 30′
R. 15
R. 14
99° 15′
R. 13
ASSINIBOINE
RIVER
Stockton
CANADIAN PACIFIC RAILWAY
Glenboro
Cypress River
Cypress
Creek
Hilton
Hartney Jct.
Belmont
Baldur
Greenway
Dry


99° 00′
R. 11
98° 45′
R I V E R
River
Cypress
RAILWAY
Cypress River
Landseer
Holland
Treherne
Bruxelles
Swan Lake
Somerset
Indian Springs
Mariapolis
Pembina Lake
1308
Dry R
CAN. NAT



98° 45′
R. 9
98° 30′
R. 7
98° 15′
Rathwell
St. Claude
Jobin
Treherne
Notre Dame de Lourdes
Cardinal
Roseisle
Stephenfield
Learys
Babcock
Somerset
Altamont
Deerwood
Miami
St. Léon
CAN. NAT. RYS.
P E M B I N A
Morris


R. 7
98° 15'
R. 6
R. 5
98° 00'
TP. 8
TP. 7
TP. 6
TP. 5
49° 30'
Haywood
CAN. PAC. RY.
St. Claude
Morris
River
Graysville
Roseisle
Stephenfield
Carman
Tobacco
Creek
Deerwood
Miami
CAN. NAT. RYS.
Rosebank

GLACIAL DEPOSITS

o — *Outwash: sand and gravel, sorting variable but generally poor*

isd — *Ice-contact stratified drift; sand, gravel and silt, sorting variable; includes eskers*

gm — *Ground moraine; mostly compact silty-sandy till, locally silty till and silty-clayey till; topography smooth*

em — *End moraine: unsorted deposits of variable texture ranging from sandy till to sand and gravel; less compact than ground moraine with rougher topography*

MESOZOIC

UPPER CRETACEOUS

More or less continuous exposures of bedrock, mostly soft shale

Geological boundary (assumed, approximate) . . . .

General area of sand dunes . . . .

Dune ridge . . . . ^^^^^^^^

Beach bar of Lake Agassiz (sand and gravel ridge) . . . .

Scarp (strandlines and terraces) . . . .

Steep slope . . . .

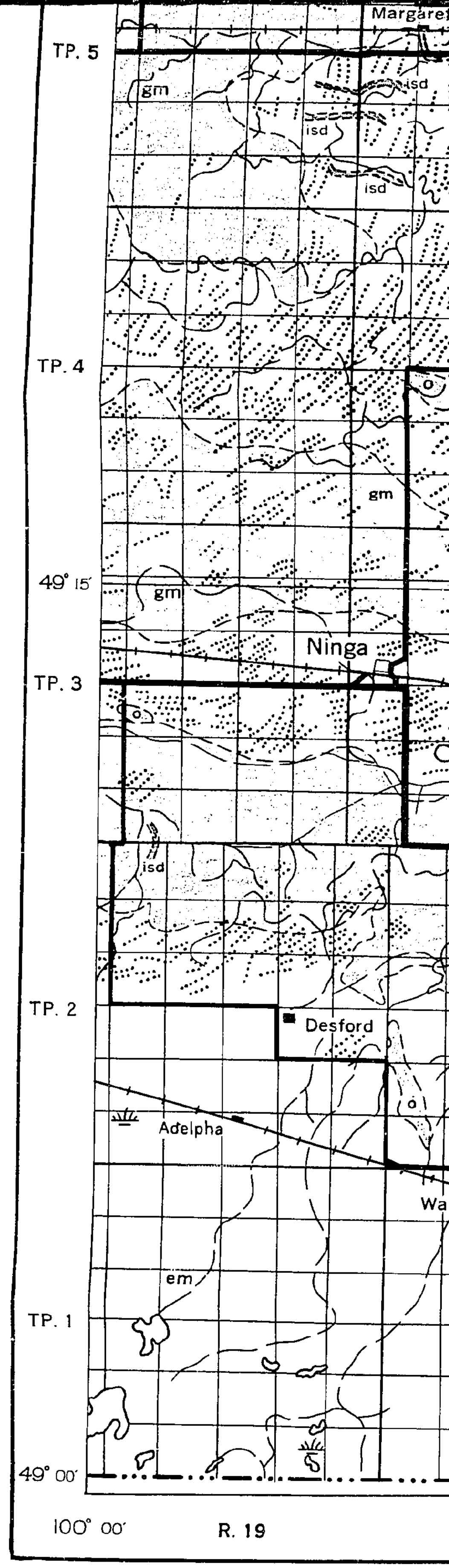
Glacially streamlined feature (mainly drumlinoids, some grooves) . . .

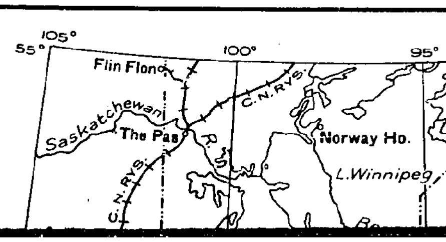
Trend of moraine ridge . . . .

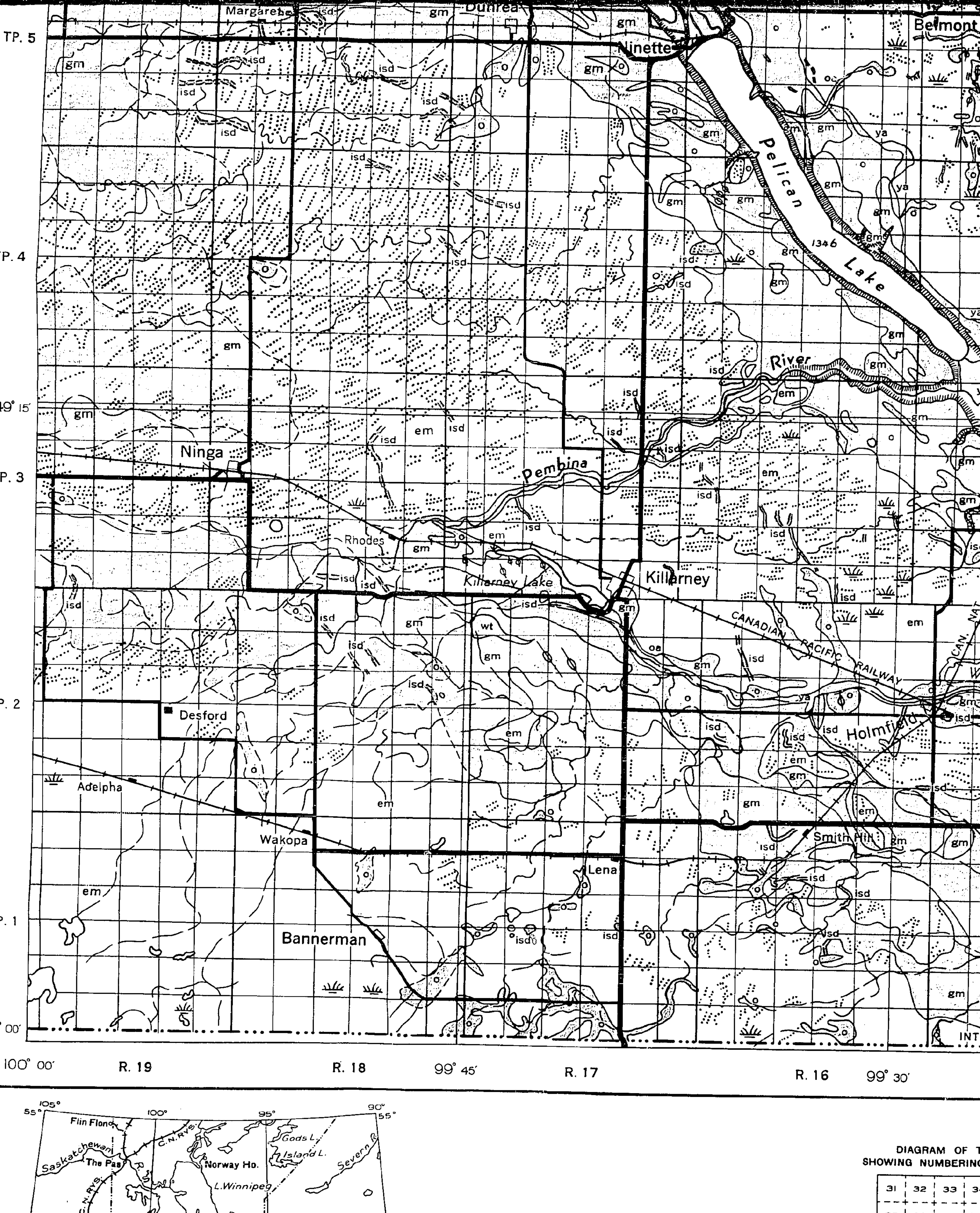
Symbols describing nature of sediments are in parentheses:
gr - *gravel*, s - *sand*, si - *silt*, cl - *clay*

Cartography by the Geological Survey of Canada

Geology by J. A. Elson, 1948 to 1951







TP. 5
TP. 4
TP. 3
TP. 2
TP. 1
49° 15′
49° 00′
Margaret
Dunrea
Ninette
Belmont
Pelican Lake
1346
River
Pembina
Ninga
Rhodes
Killarney Lake
Killarney
CANADIAN PACIFIC RAILWAY
CAN. NAT.
Holmfield
Desford
Adelpha
Wakopa
Smith Hill
Lena
Bannerman
100° 00′
R. 19
R. 18
99° 45′
R. 17
R. 16
99° 30′
105°
55°
100°
95°
90°
Flin Flon
C.N.RYS.
Saskatchewan
The Pas
R.
Gods L.
Island L.
Severn R.
Norway Ho.
L. Winnipeg
DIAGRAM OF T
SHOWING NUMBERING
31 32 33 34
30 29

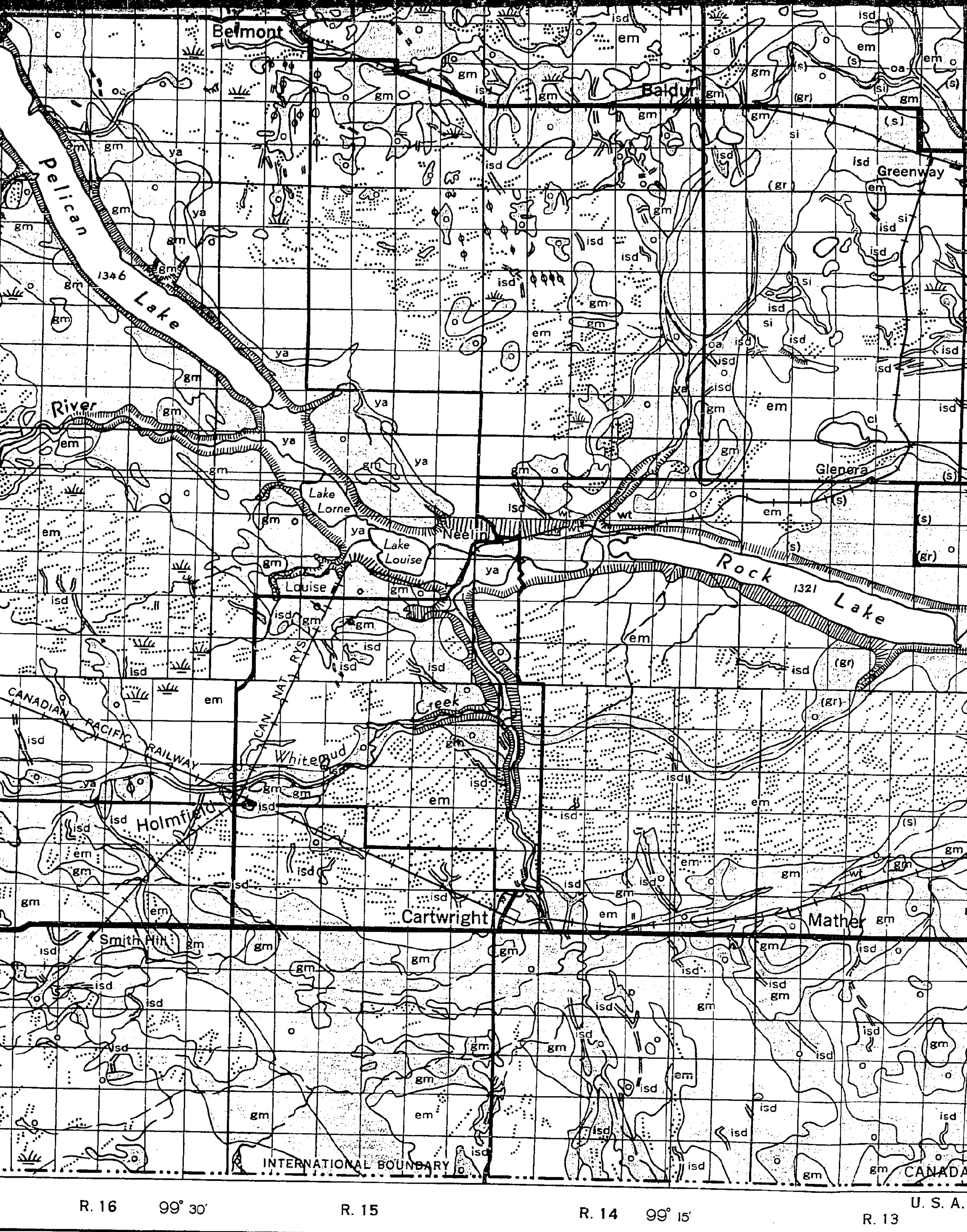
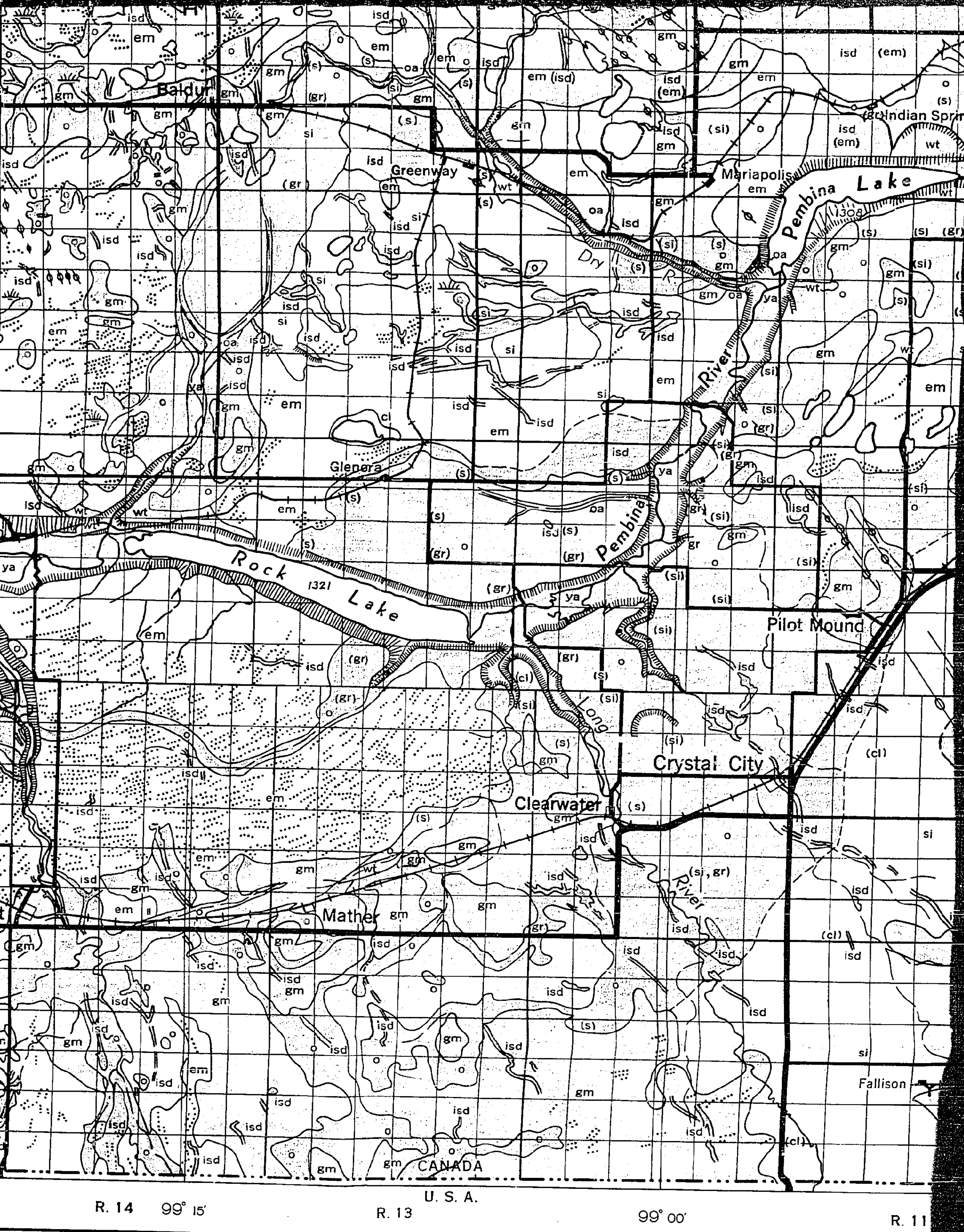


DIAGRAM OF TOWNSHIP
SHOWING NUMBERING OF SECTIONS

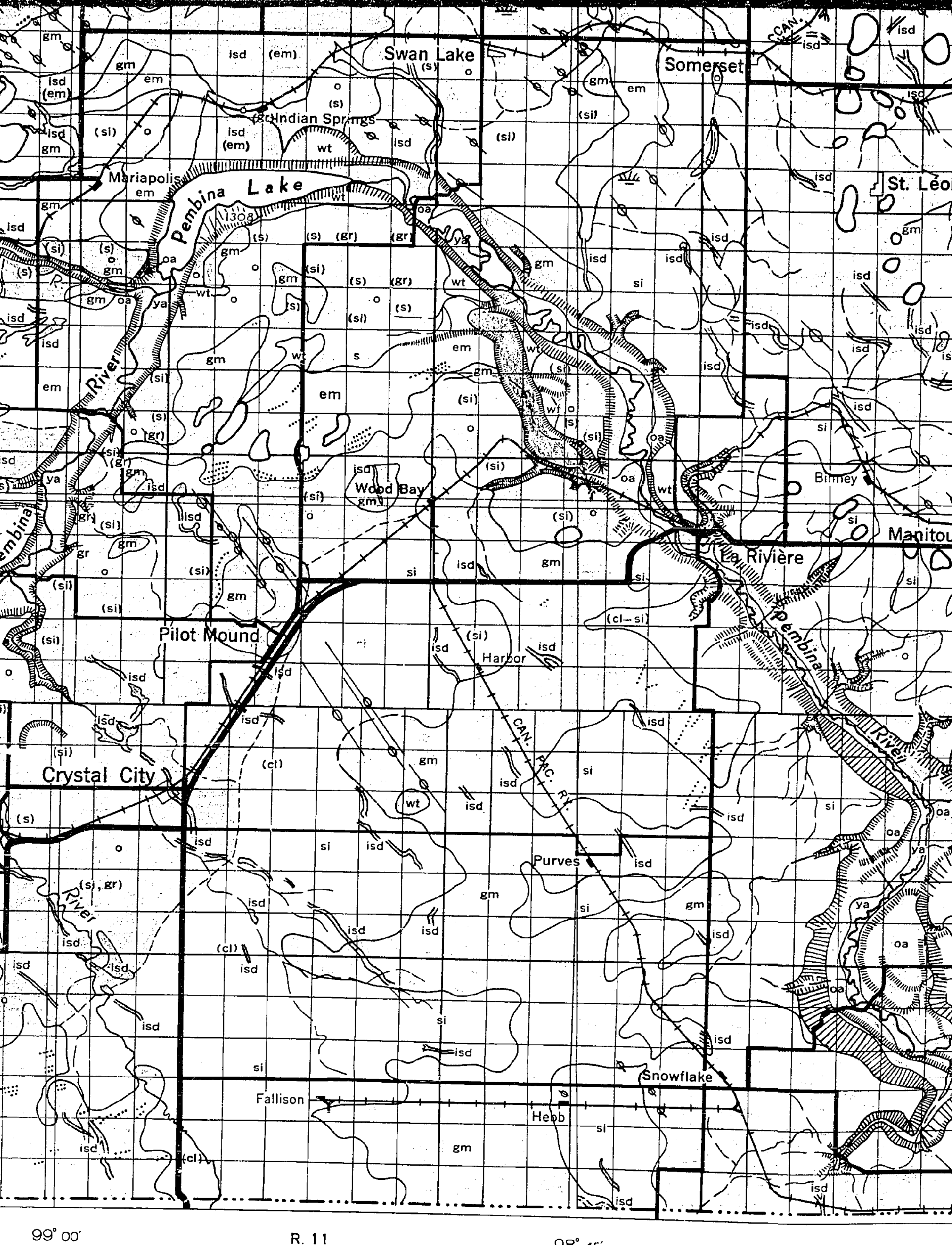
31	32	33	34	35	36
30	29				

TIG



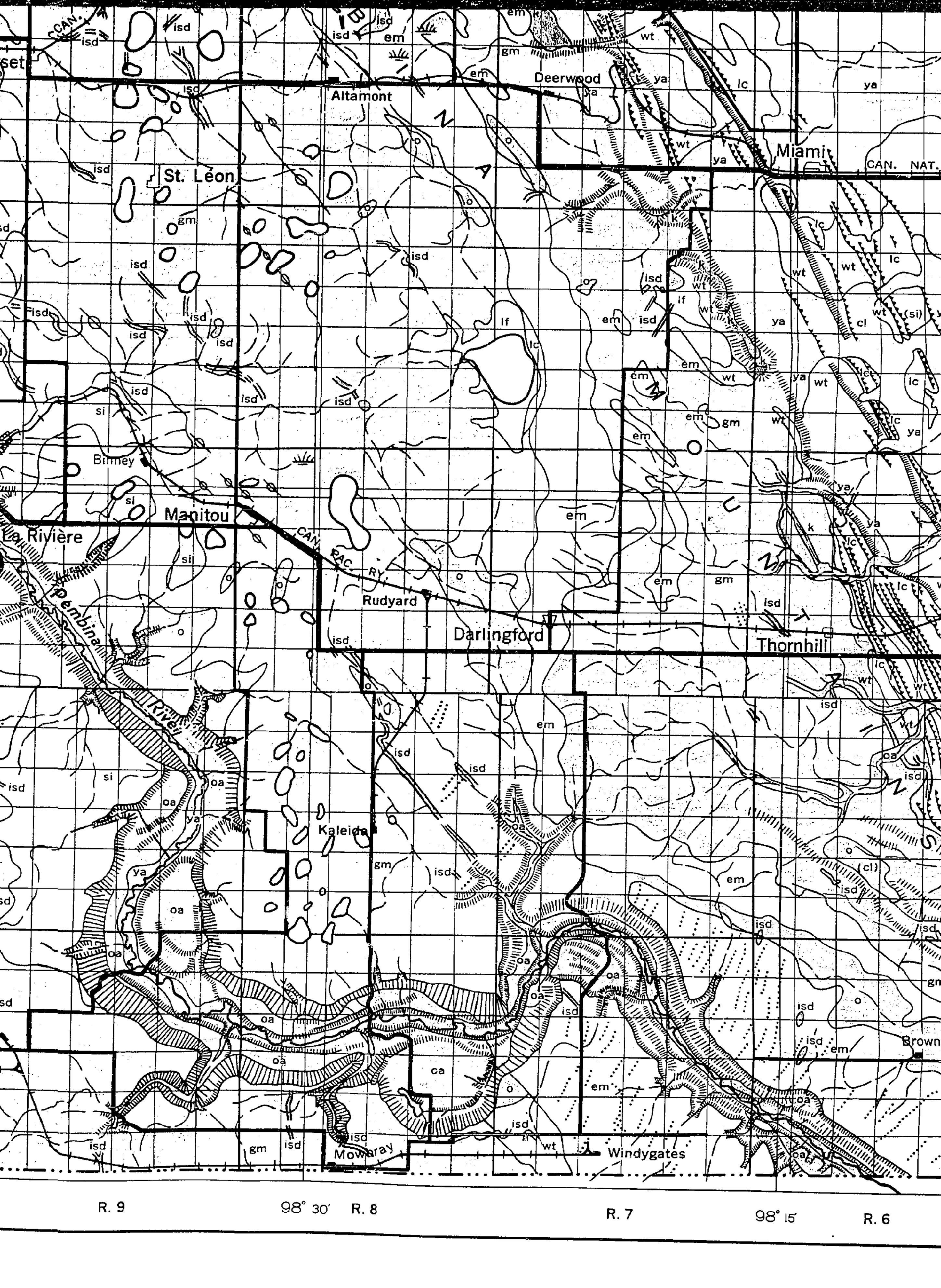
SURFICIAL GEOLOGY

TIGER HILLS REGION

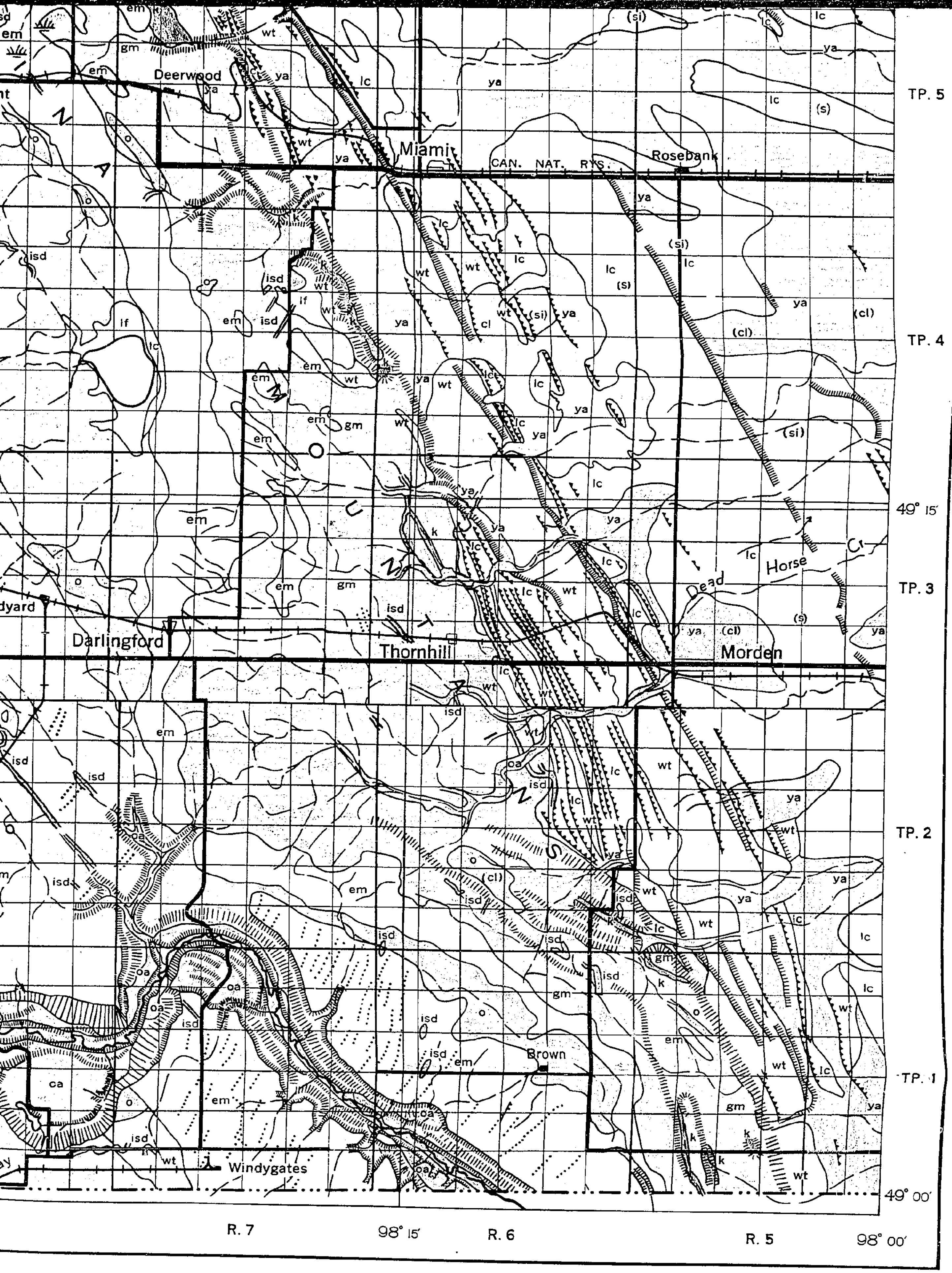


CIAL GEOLOGY

ILLS REGION


Altamont
Deerwood
Miami
St. Leon
Binney
Manitou
La Rivière
Pembina River
Rudyard
Darlingford
Thornhill
Kaleida
Mowbray
Windygates
Brown
CAN. PAC. RY.
CAN. NAT.
R. 9
98° 30′
R. 8
R. 7
98° 15′
R. 6

LEGEND


Deerwood
Miami
CAN. NAT. RYS.
Rosebank
Darlingford
Thornhill
Morden
Dead Horse Cr.
Brown
Windygates
TP. 5
TP. 4
TP. 3
TP. 2
TP. 1
49° 15′
49° 00′
R. 7
98° 15′
R. 6
R. 5
98° 00′

LEGEND

moraine with rougher topography

MESOZOIC

UPPER CRETACEOUS

More or less continuous exposures of bedrock, mostly soft shale

Geological boundary (assumed, approximate) ....

General area of sand dunes ....

Dune ridge ....

Beach bar of Lake Agassiz (sand and gravel ridge) ....

Scarp (strandlines and terraces) ....

Steep slope ....

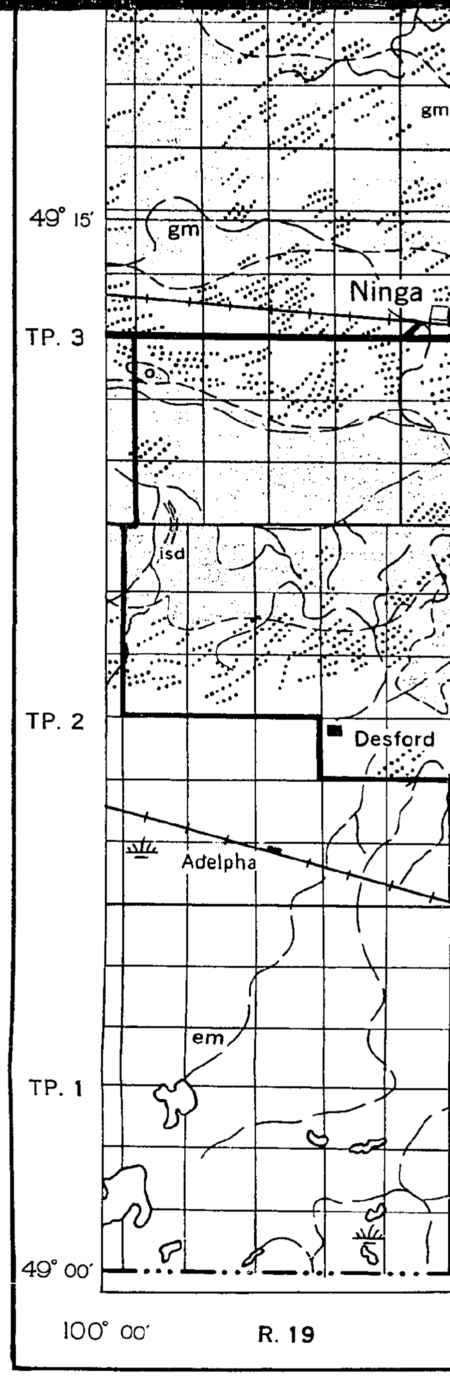
Glacially streamlined feature (mainly drumlinoids, some grooves)...

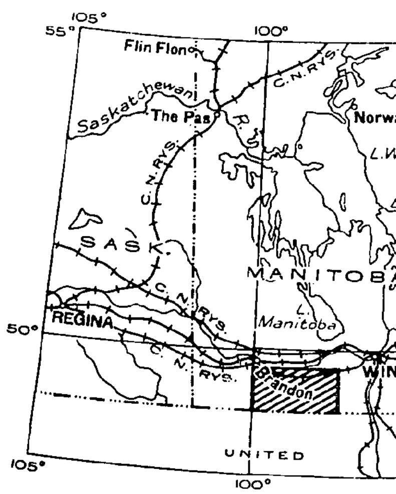
Trend of moraine ridge ....

Symbols describing nature of sediments are in parentheses:
gr - *gravel*, s - *sand*, si - *silt*, cl - *clay*

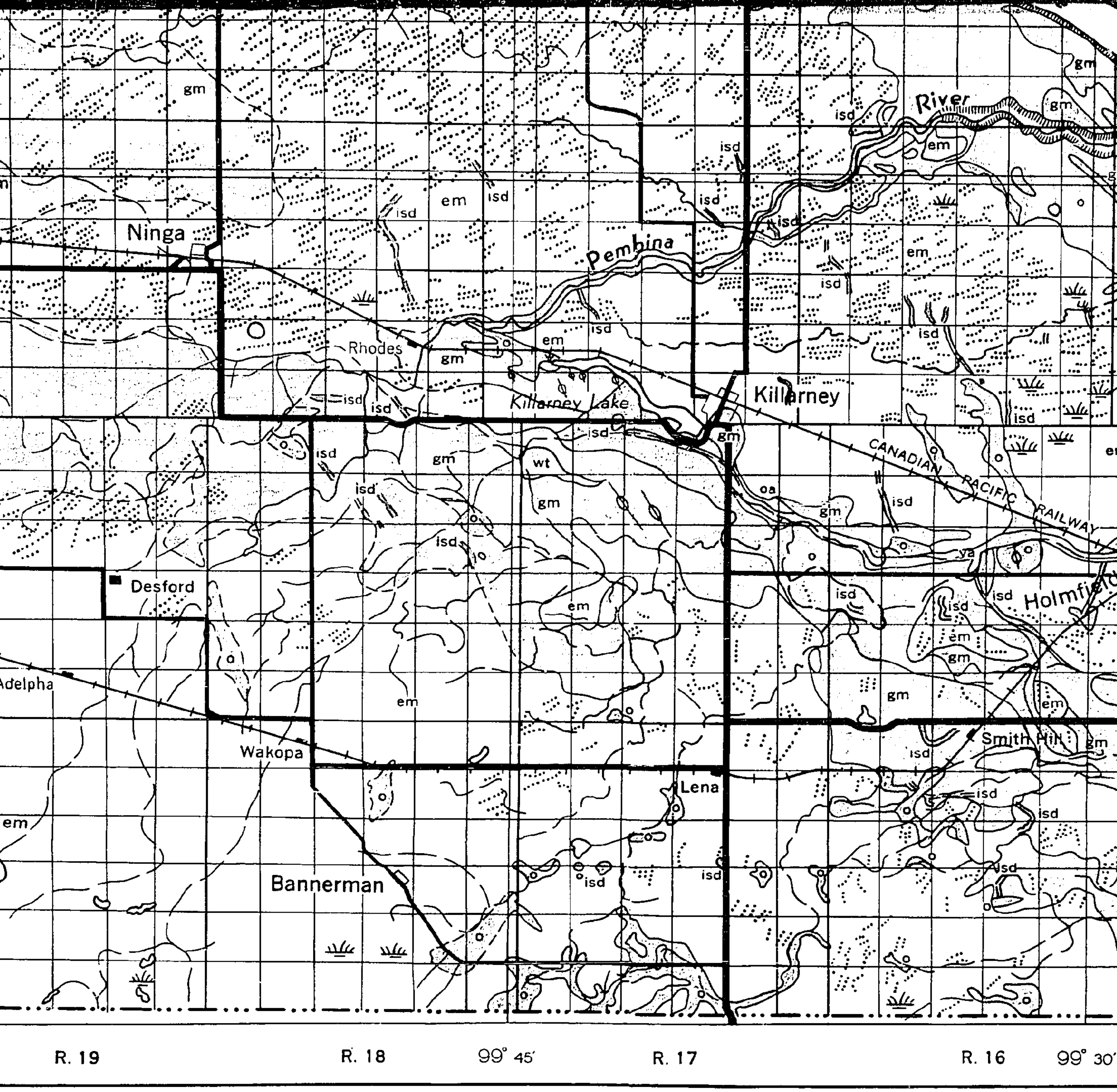
Cartography by the Geological Survey of Canada

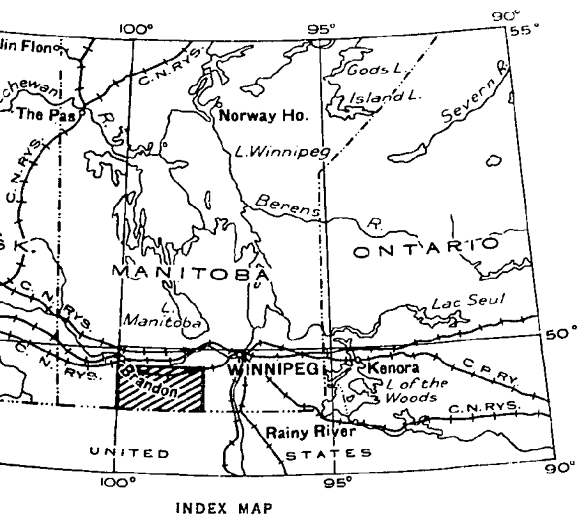
Geology by J. A. Elson, 1948 to 1951



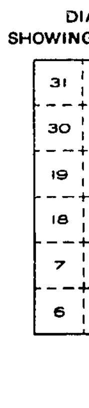


INDEX MA


Ninga
Pembina
River
Rhodes
Killarney Lake
Killarney
CANADIAN PACIFIC RAILWAY
Desford
Adelpha
Wakopa
Bannerman
Lena
Smith Hill
R. 19
R. 18
99° 45'
R. 17
R. 16


100°
95°
90°
55°
50°
The Pas
Norway Ho.
Gods L.
Island L.
Severn R.
L. Winnipeg
Berens R.
ONTARIO
MANITOBA
L. Manitoba
Lac Seul
WINNIPEG
Kenora
L. of the Woods
C.N.RYS.
C.P.RY.
Rainy River
UNITED
STATES

INDEX MAP



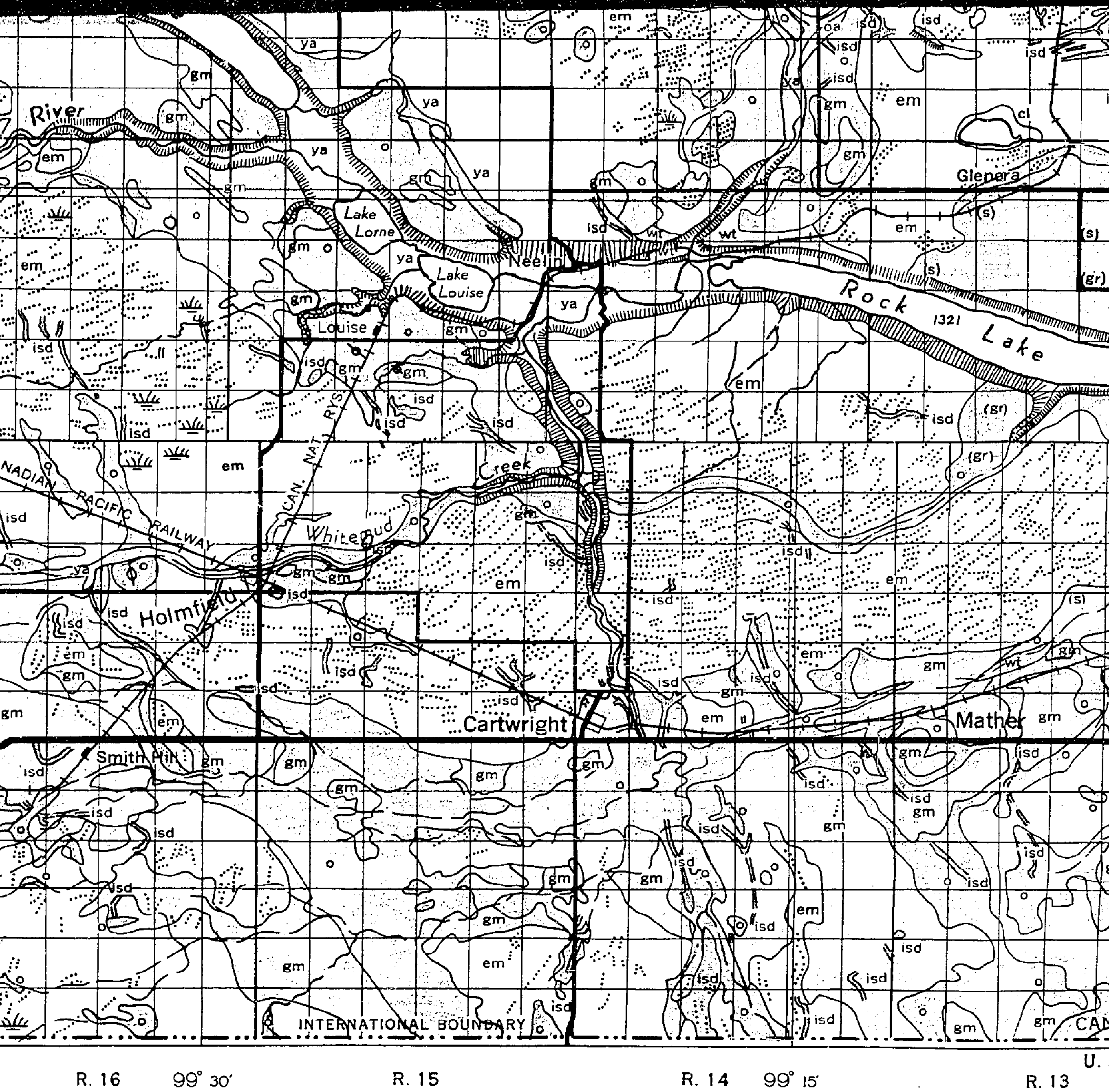
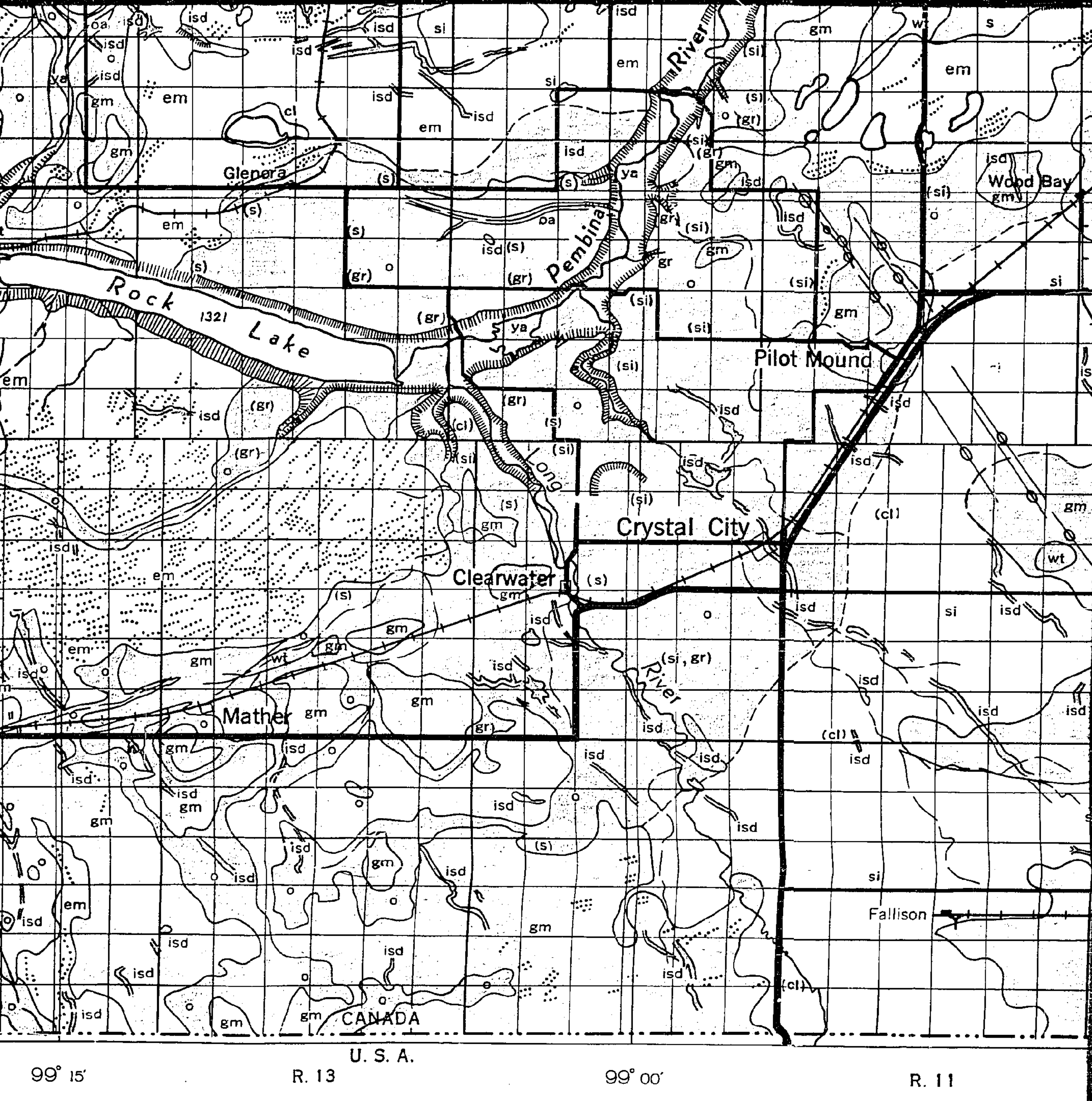


DIAGRAM OF TOWNSHIP
SHOWING NUMBERING OF SECTIONS

31	32	33	34	35	36
30	29	28	27	26	25
19	20	21	22	23	24
18	17	16	15	14	13
7	8	9	10	11	12
6	5	4	3	2	1



SURFICIAL GEOLOGY

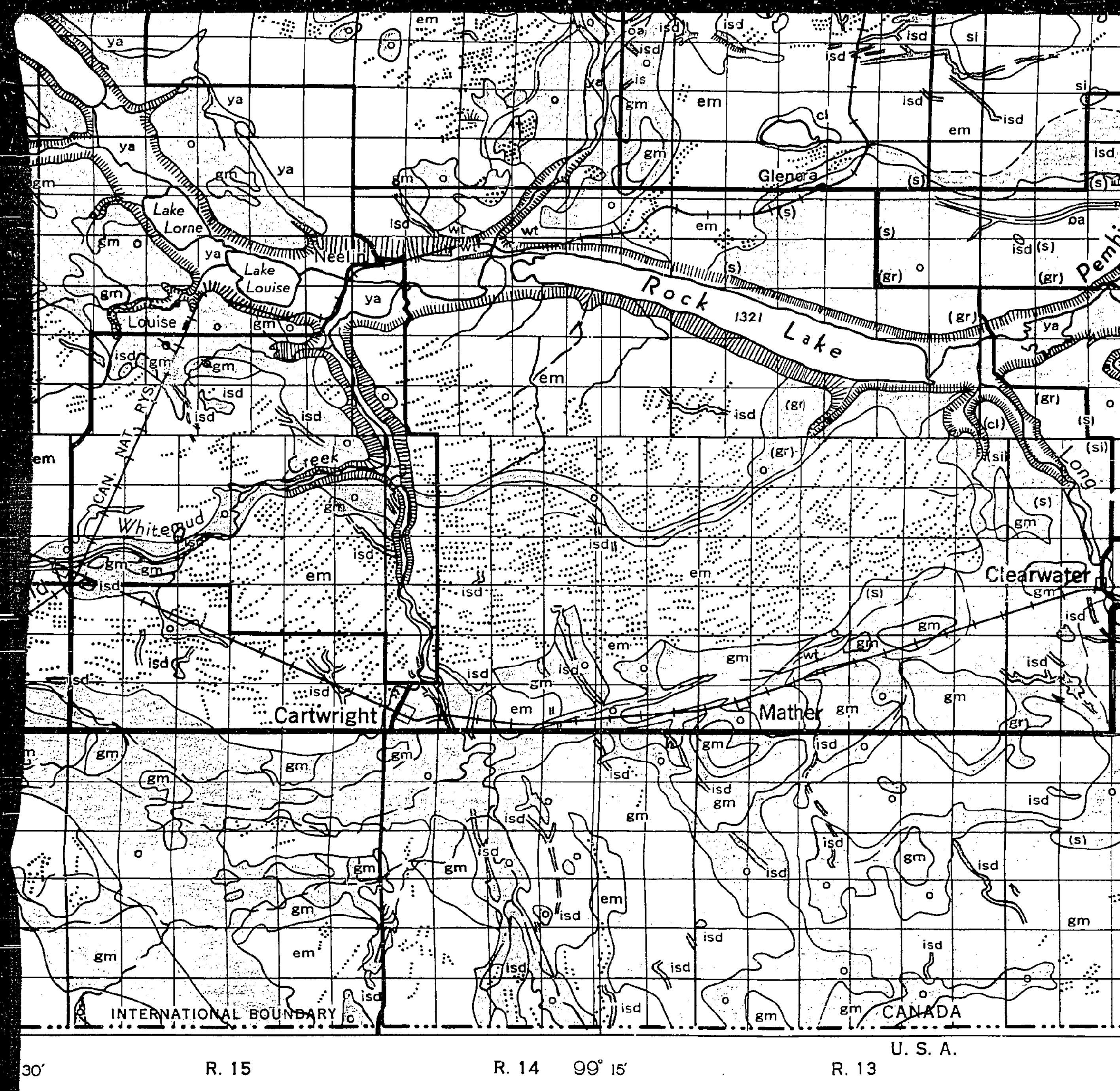
TIGER HILLS REGION
MANITOBA

Scale: One Inch to Three Miles $= \frac{1}{190,080}$

Miles

3 0 3 6 9

PLATE 3



SURFIC

TIGER HI

MA

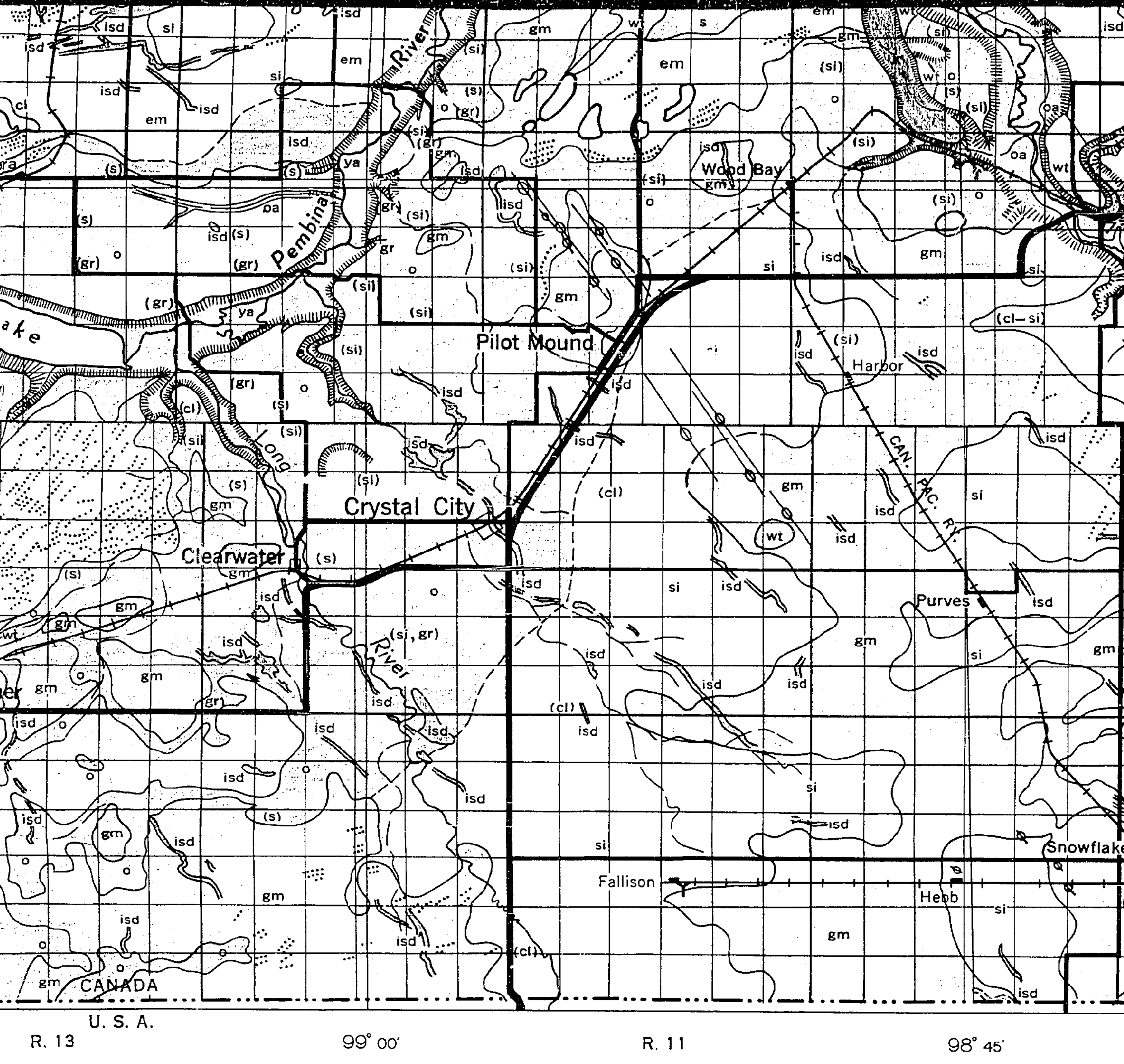
Scale: One Inch

3 0

PI

DIAGRAM OF TOWNSHIP
ING NUMBERING OF SECTIONS

32	33	34	35	36
29	28	27	26	25
20	21	22	23	24
17	16	15	14	13
8	9	10	11	12
5	4	3	2	1



SURFICIAL GEOLOGY

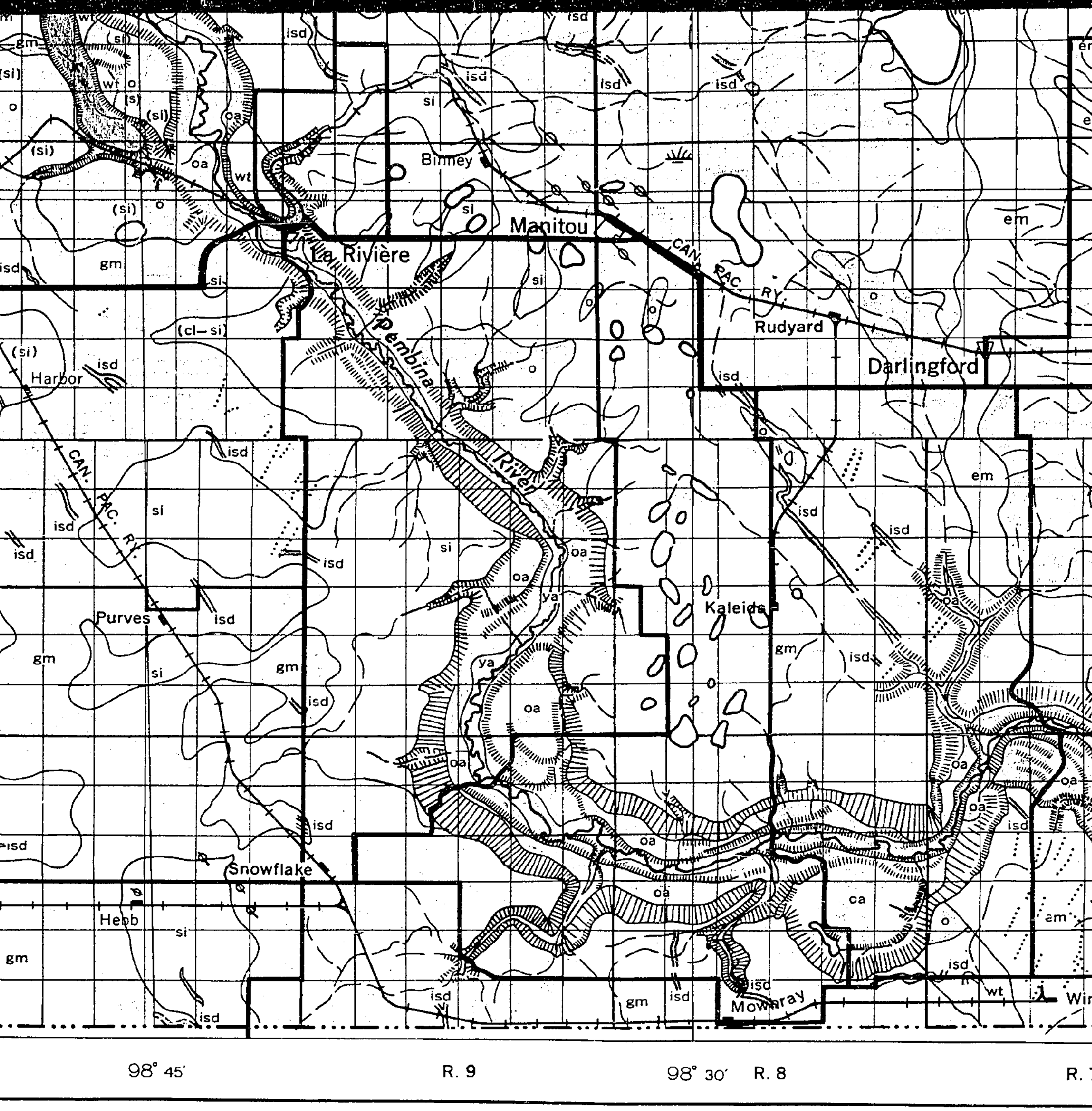
TIGER HILLS REGION
MANITOBA

Scale: One Inch to Three Miles = $\frac{1}{190,080}$

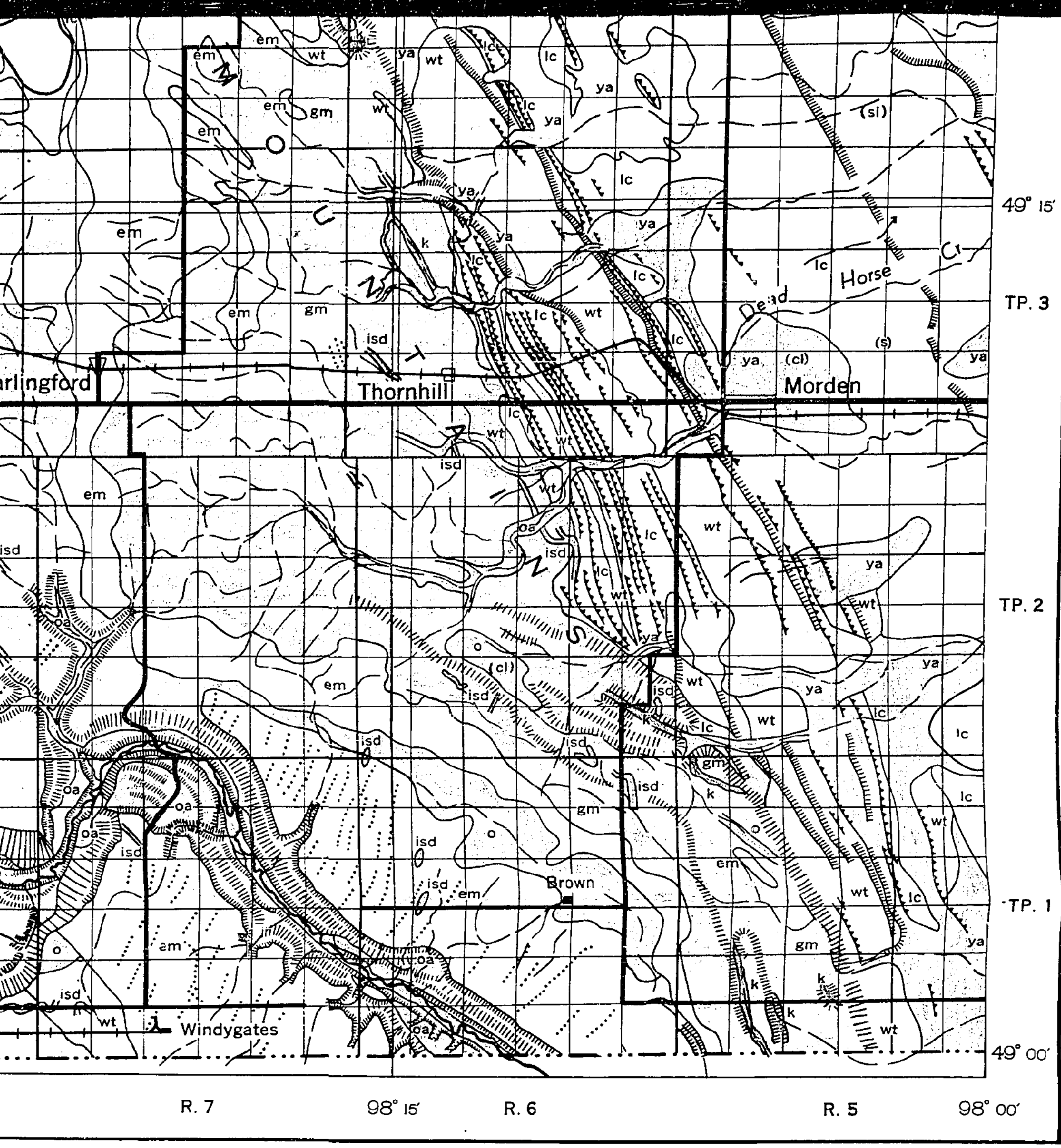
Miles

3 0 3 6 9

PLATE 3



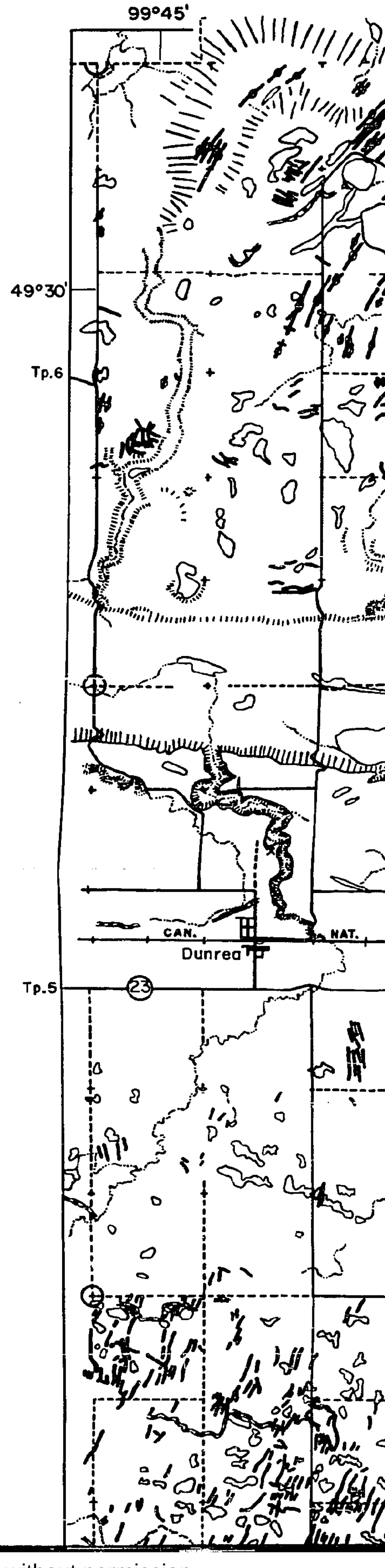
Main High
Road well
Railway . . . .
Internationa
Township b



LEGEND

Main Highway		*Section line*	
Road well travelled		*Intermittent stream*	
Railway		*Drainage ditch*	
International boundary		*Marsh*	
Township boundary		*Height in feet above mean sea-level*	*1321*

PLATE 4



SURFACE FEATURES

PELICAN LAKE AREA

MANITOBA

Scale of Miles

1 0 1 2 3 4

LEGEND

Main roads and highways .... (3)

Secondary roads ....

Railway ....

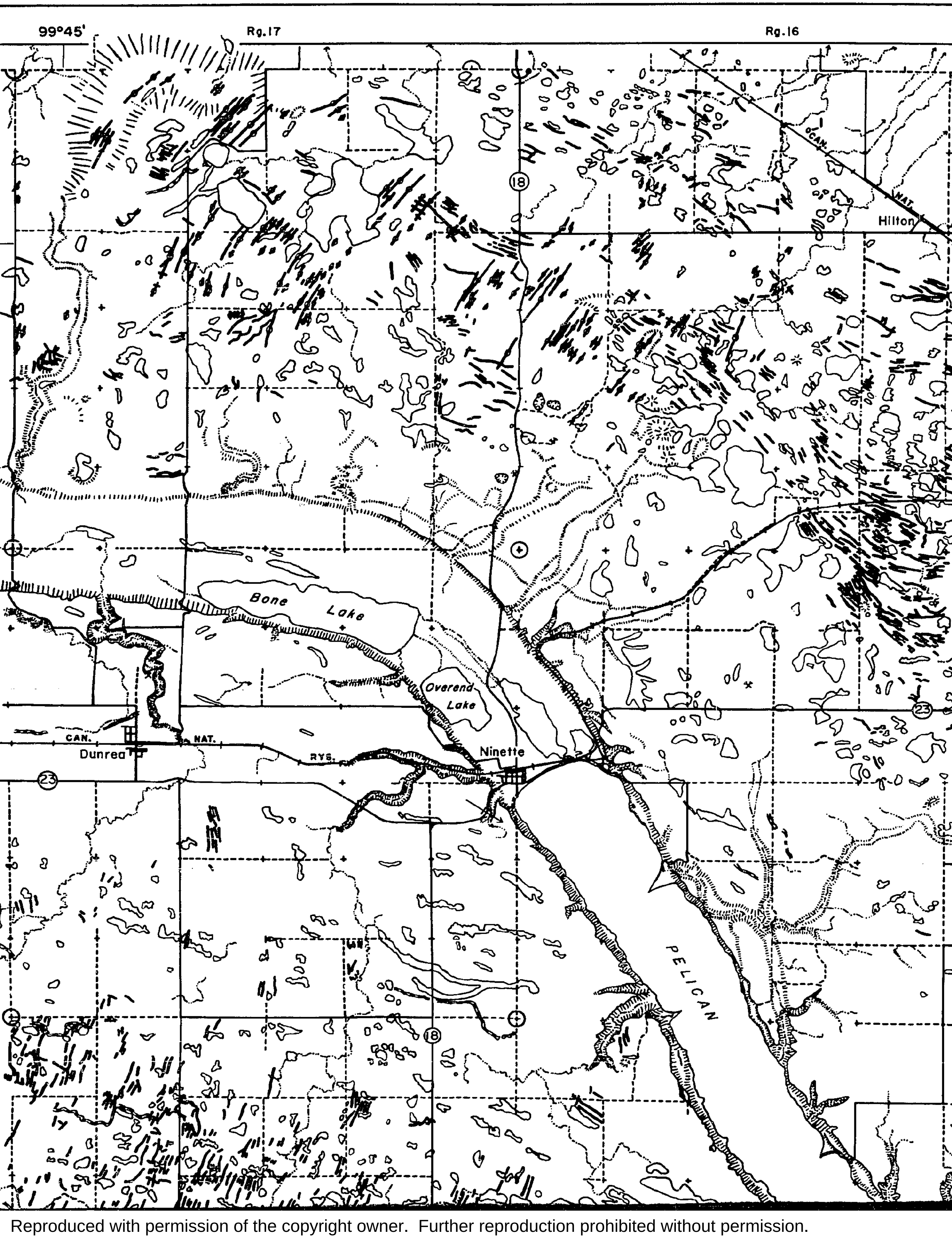
Township corners, section corners ....

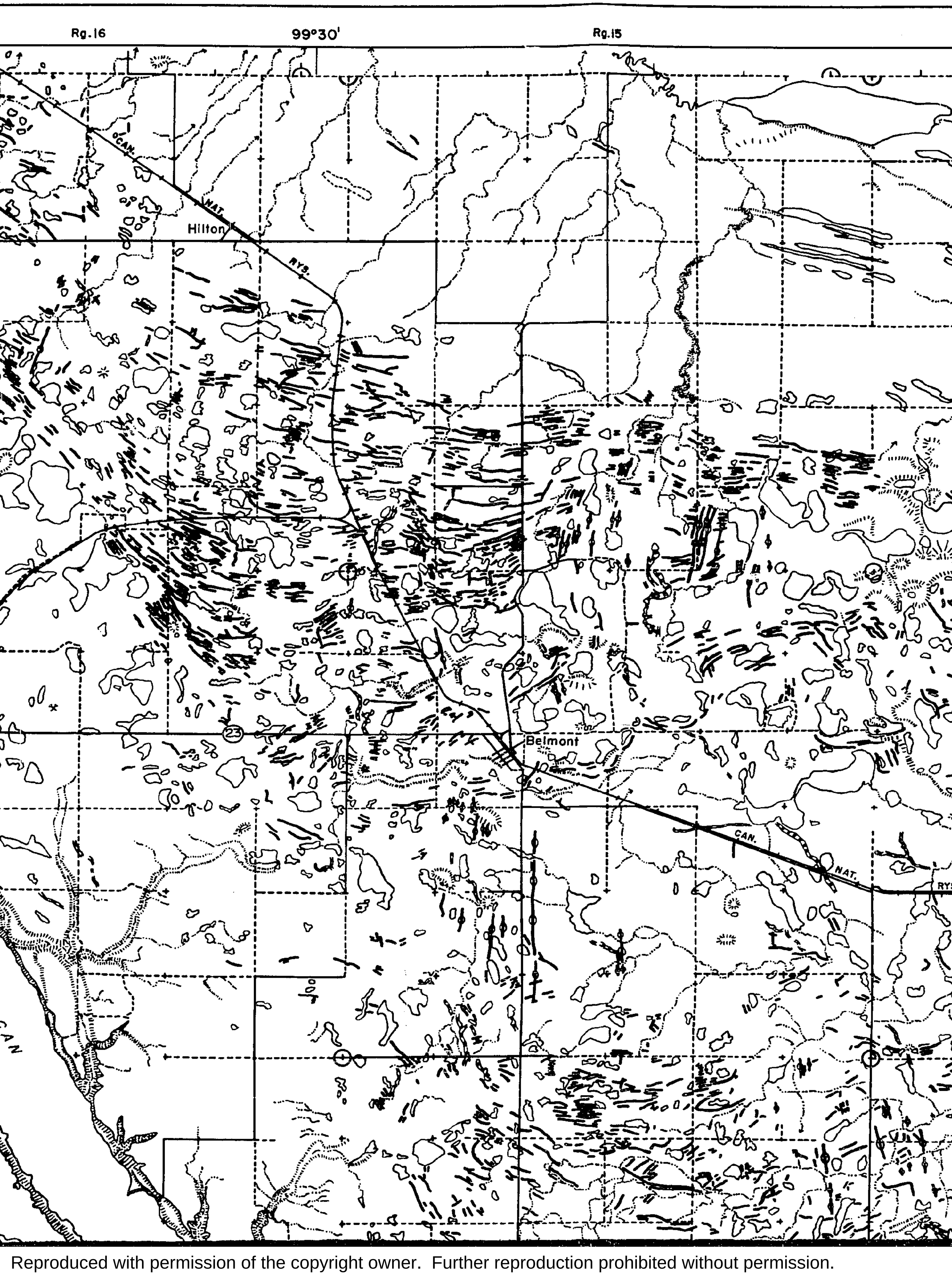
Stream: intermittent, perennial ....

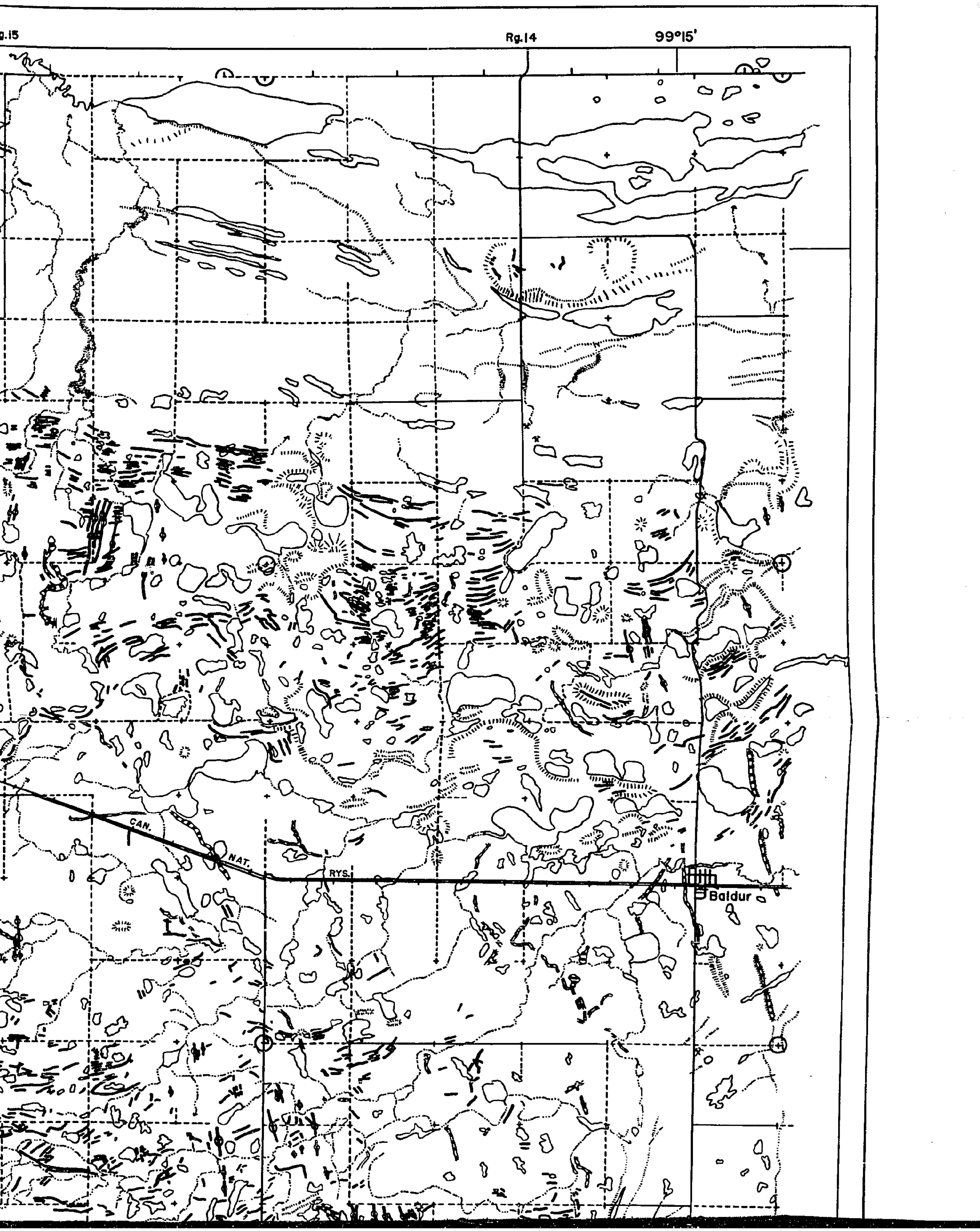
Depression: lake, intermittent pond, or marsh ....

Scarp, without and with sharp crest ....

Drift ridge, generally till


99°45'
Rg.17
Rg.16
Hilton
Bone Lake
Overend Lake
Ninette
Dunrea
CAN.
NAT.
RYS.
PELICAN
18
23


Rg.16
99°30'
Rg.15
Hilton
CAN.
NAT.
RYS.
23
Belmont
CAN.
NAT.
RYS.
CAN


g.15
Rg.14
99°15'
CAN.
NAT.
RYS.
Baldur

LEGEND

Main roads and highways

Secondary roads

Railway

Township corners, section corners

Stream: intermittent, perennial

Depression: lake, intermittent pond, or marsh

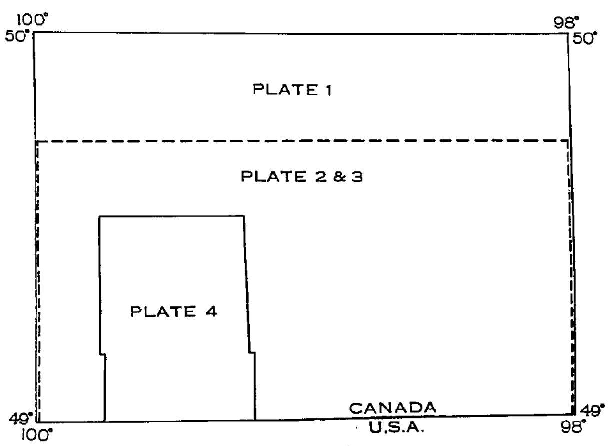
Scarp, without and with sharp crest

Drift ridge, generally till

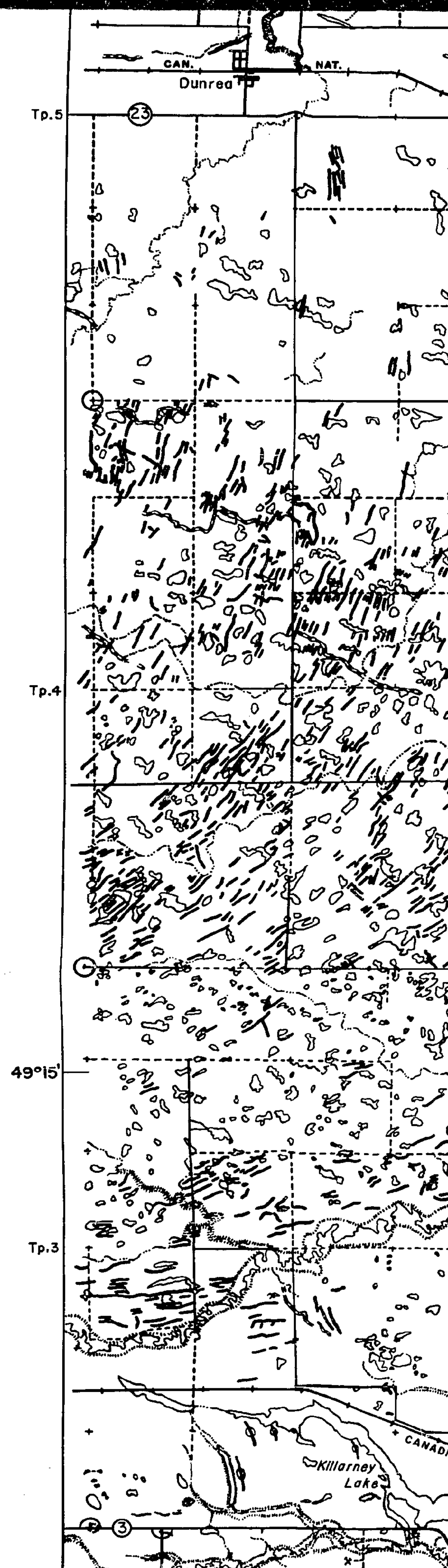
Glacially-streamlined ridge, generally with bedrock core

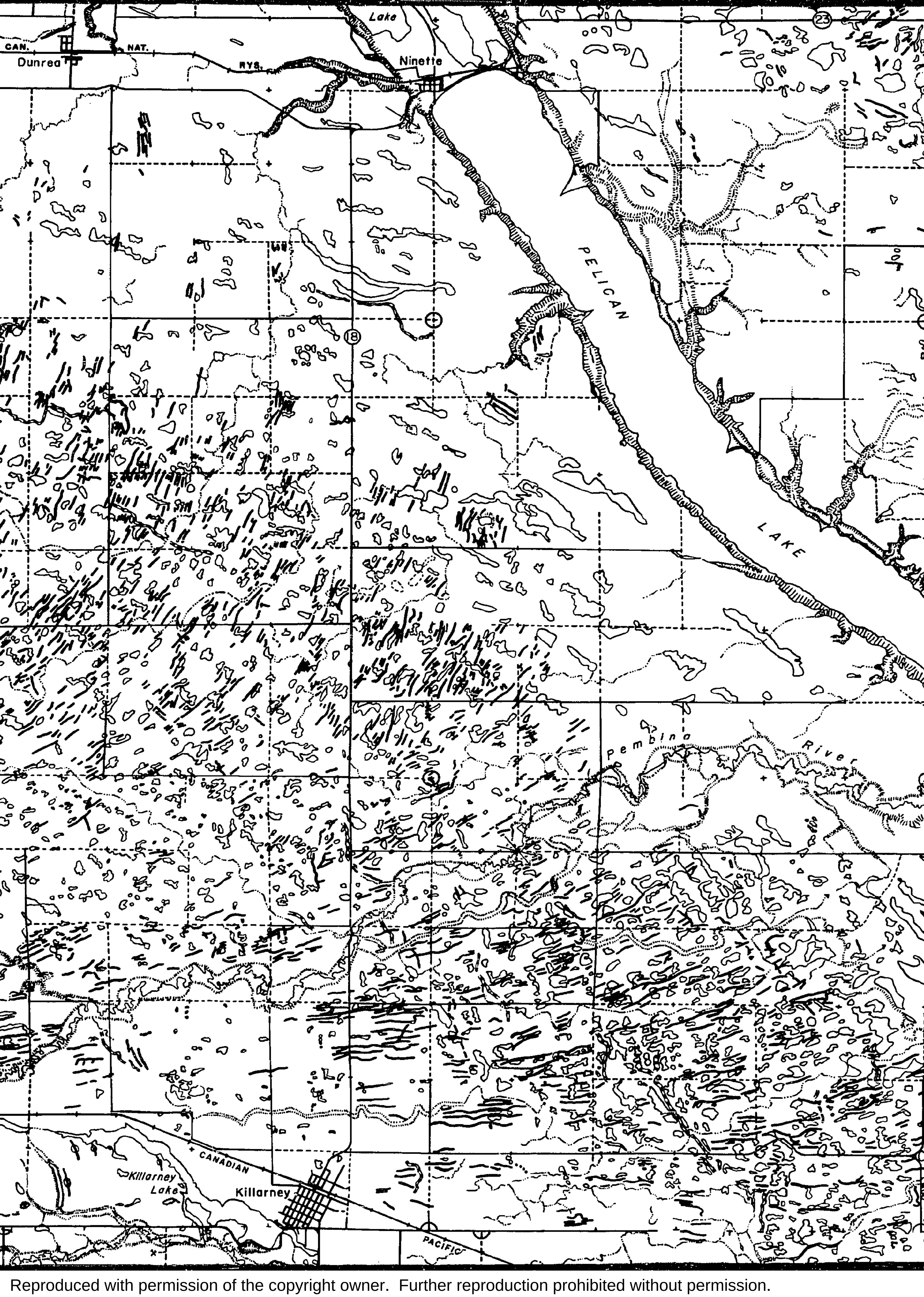
Esker

Direction of striae on striated boulder pavement

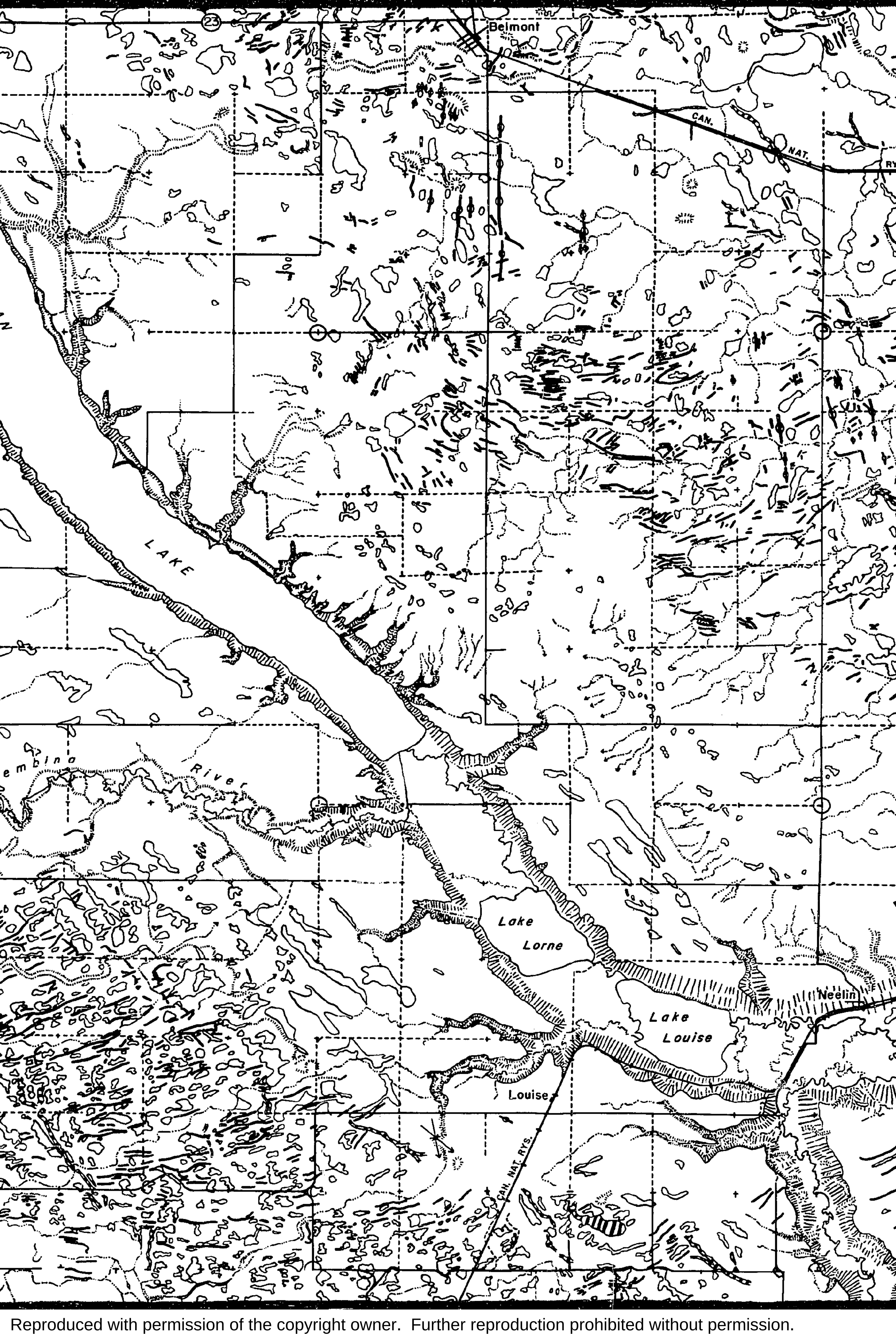


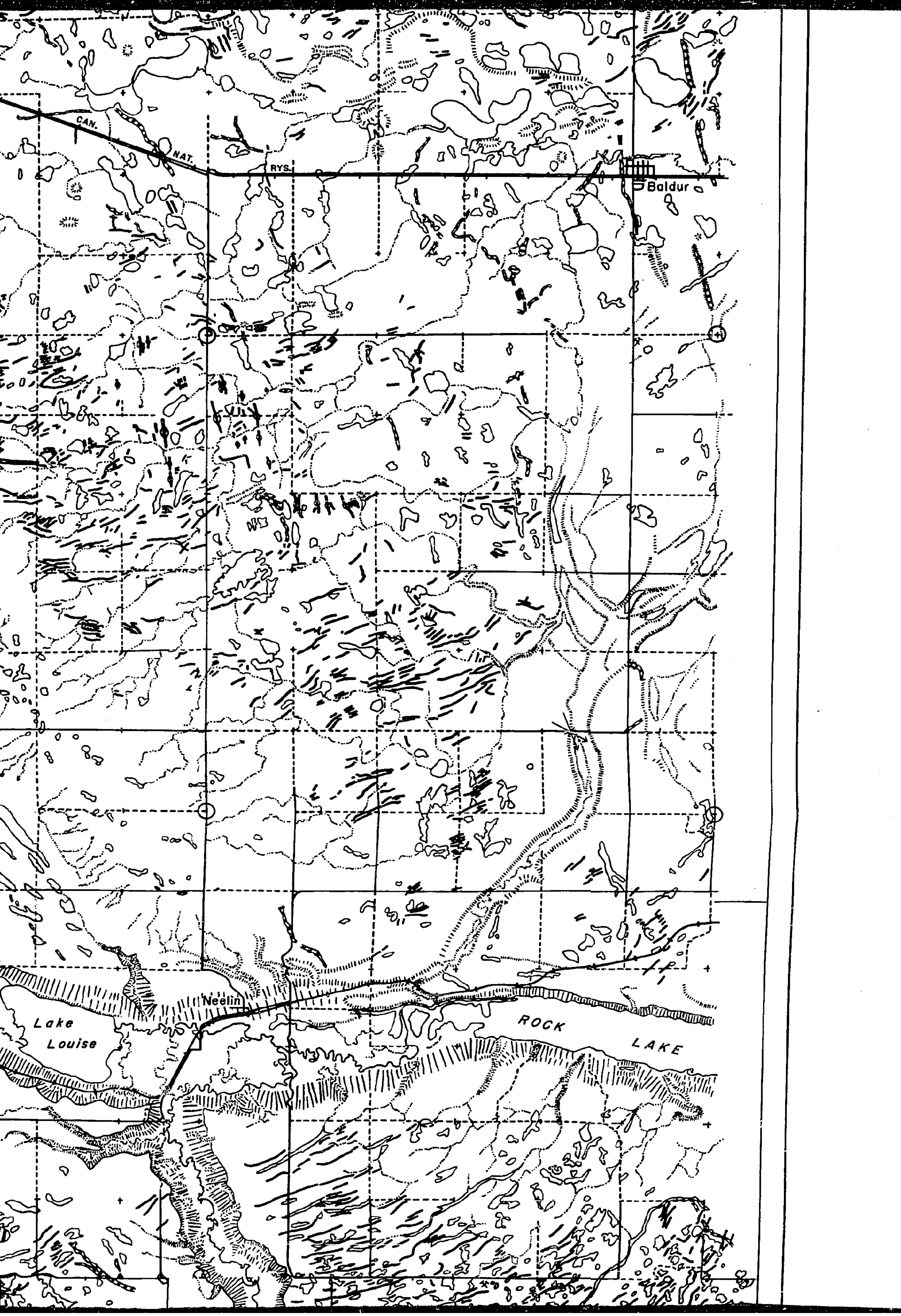
INDEX MAP





Lake
CAN.
NAT.
RYS.
Dunrea
Ninette
23
18
PELICAN
LAKE
Pembina
River
CANADIAN
Killarney Lake
Killarney
PACIFIC


23
Belmont
CAN.
NAT.
LAKE
embina
River
Lake
Lorne
Lake
Louise
Neelin
Louise
CAN. NAT. RYS.


CAN.
NAT.
RYS.
Baldur
Neelin
Lake
Louise
ROCK
LAKE

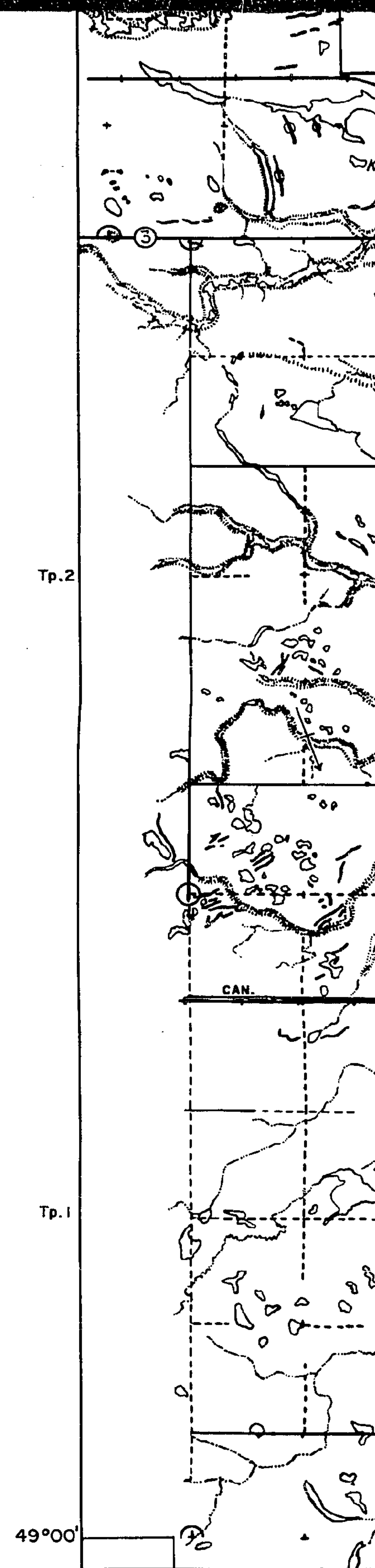
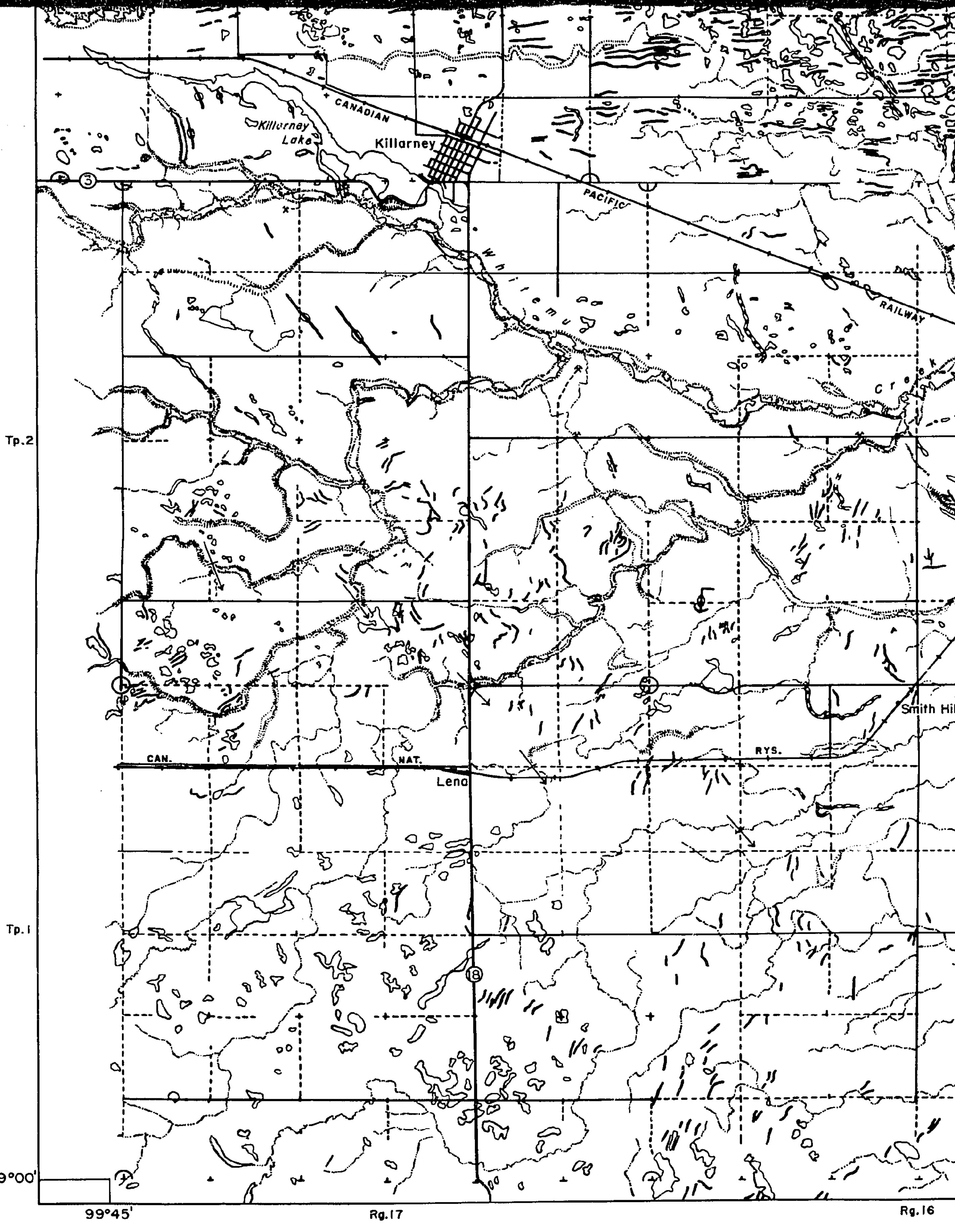
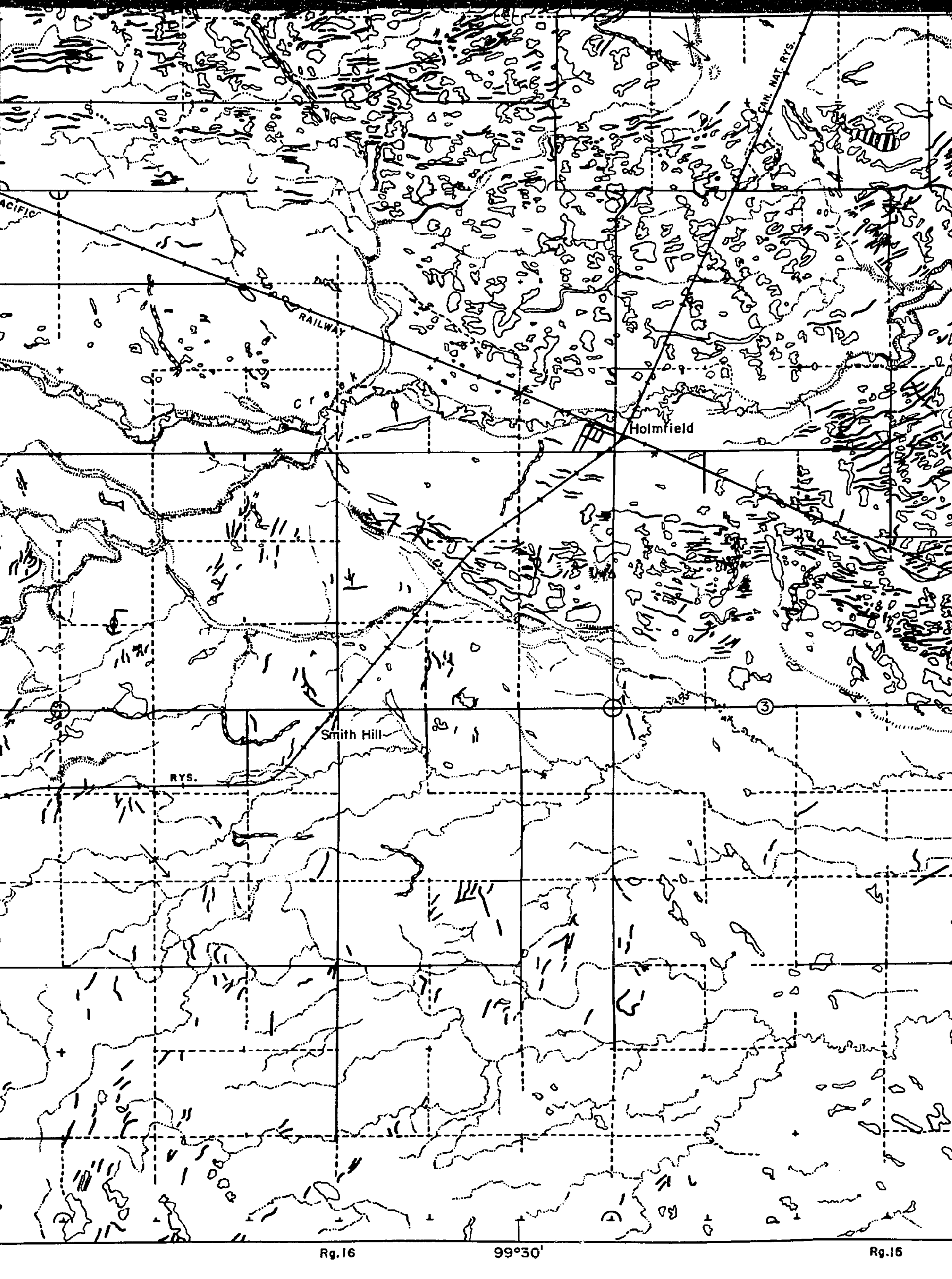


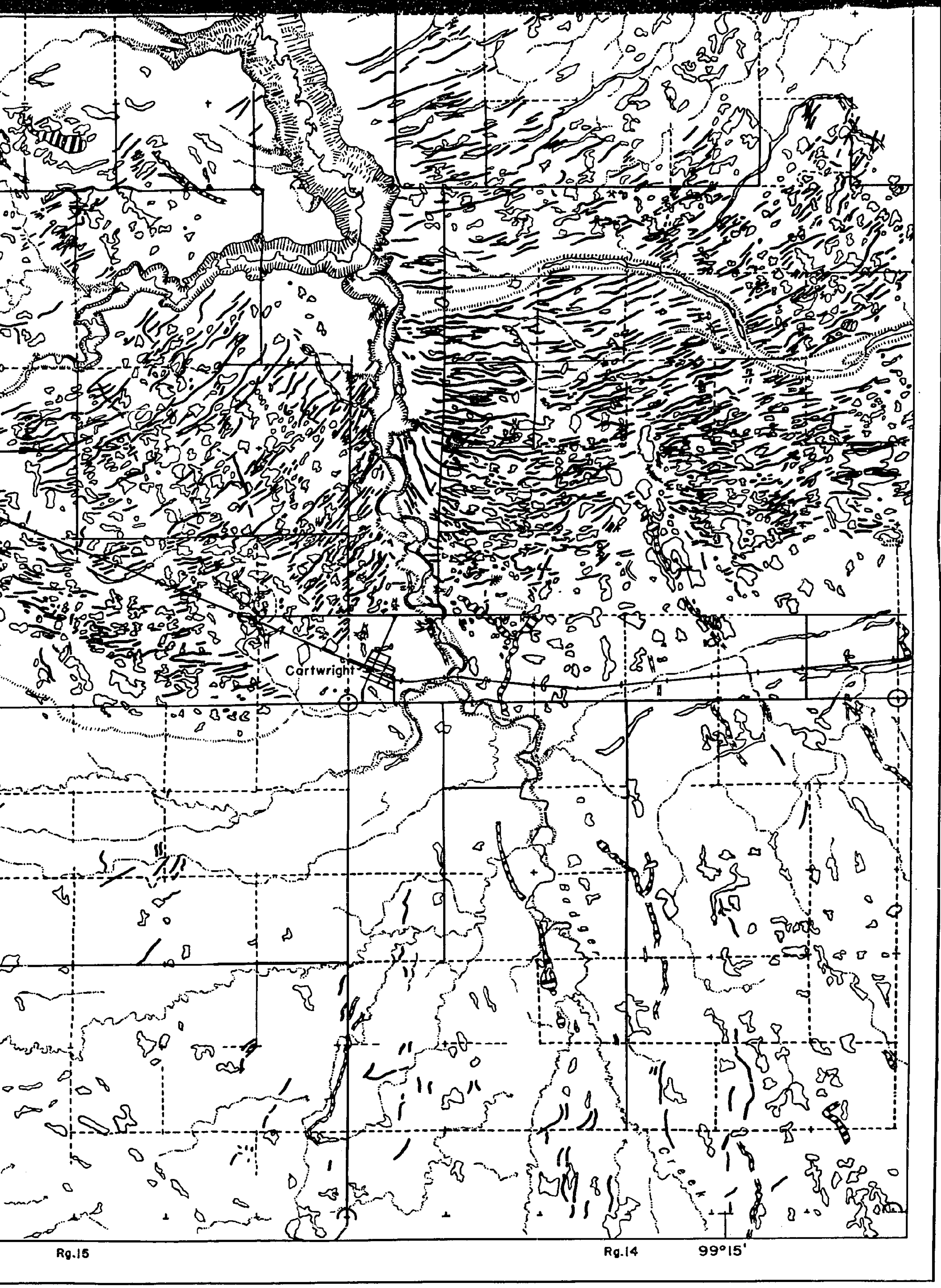
PLATE 4

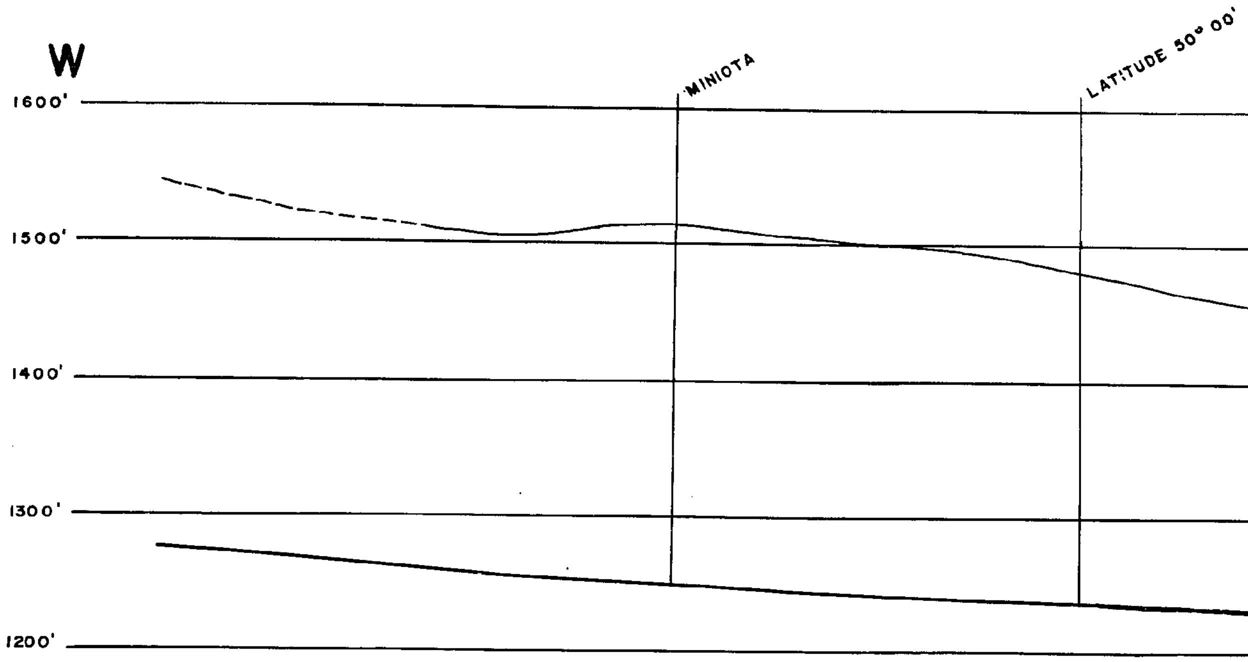


CANADIAN
PACIFIC
RAILWAY
Killarney
Lake
Killarney
3
Whitemud
Creek
Tp.2
Tp.1
CAN.
NAT.
RYS.
Lena
Smith Hil
18
9°00'
99°45'
Rg.17
Rg.16



CAN. NAT. RYS.
PACIFIC
RAILWAY
Creek
Holmfield
Smith Hill
RYS.
3
Rg.16
99°30'
Rg.15


Cartwright
Rg.15
Rg.14
99°15'
Creek



LONG PROFILES of ASSINIBOINE RIVER and RELATED SURFACES

HORIZONTAL SCALE 0 4 MILES 8 12

Valley bottom, terrace

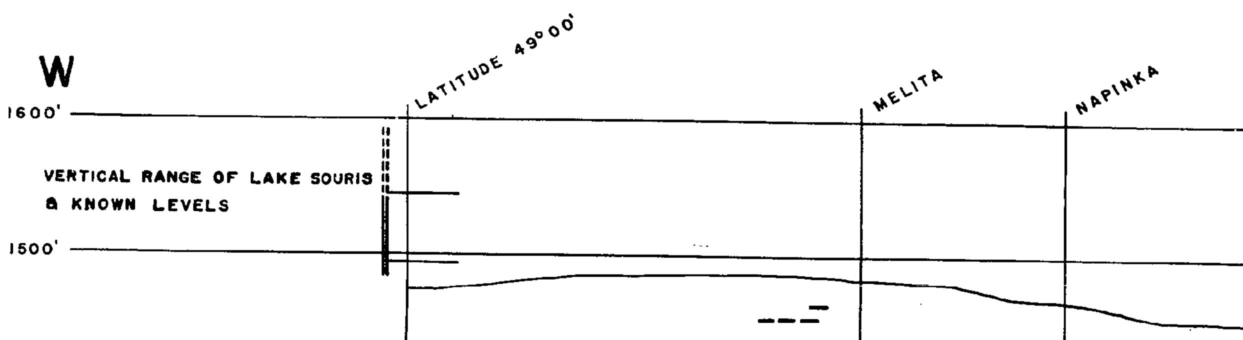
Abandoned channel (spillway)

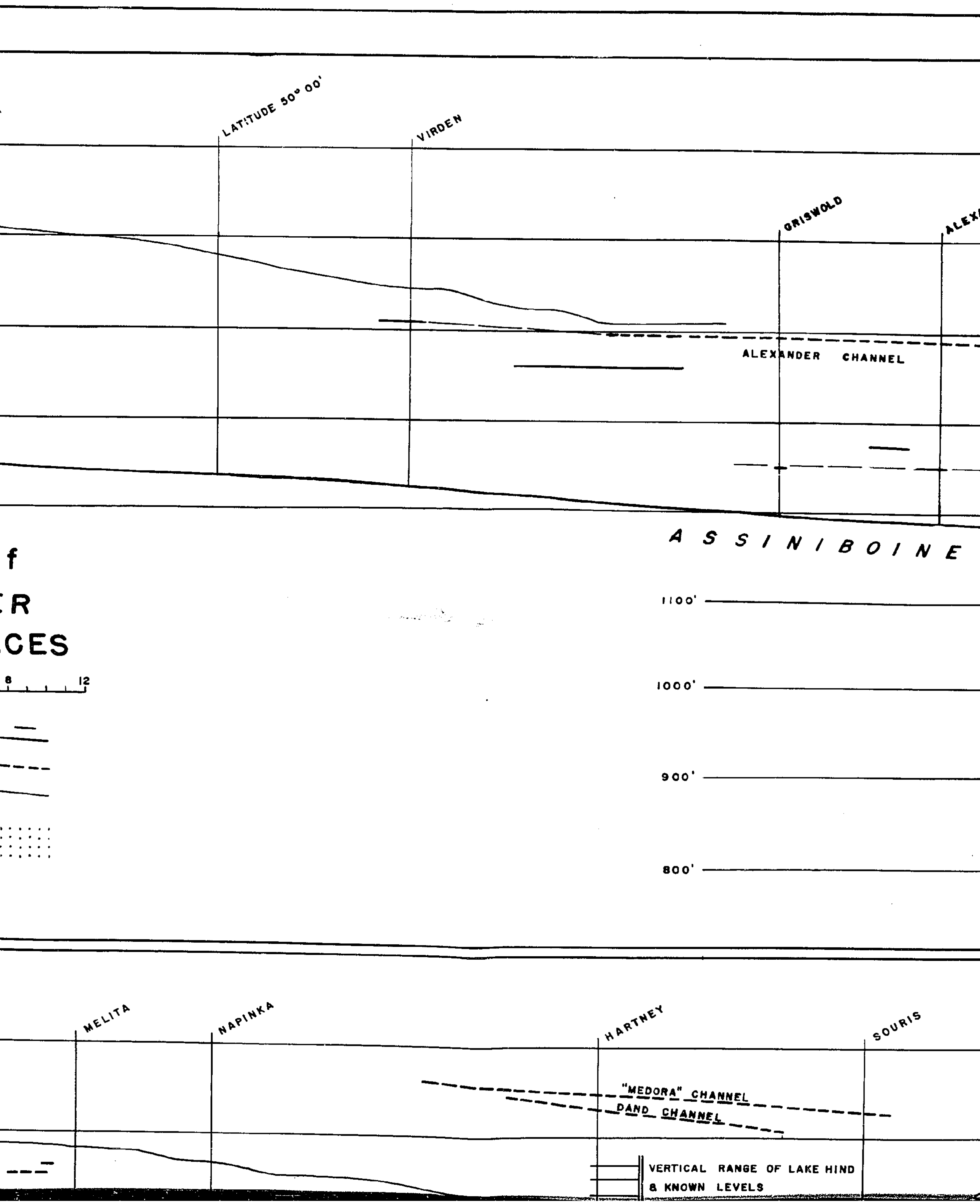
Upland surface near valley

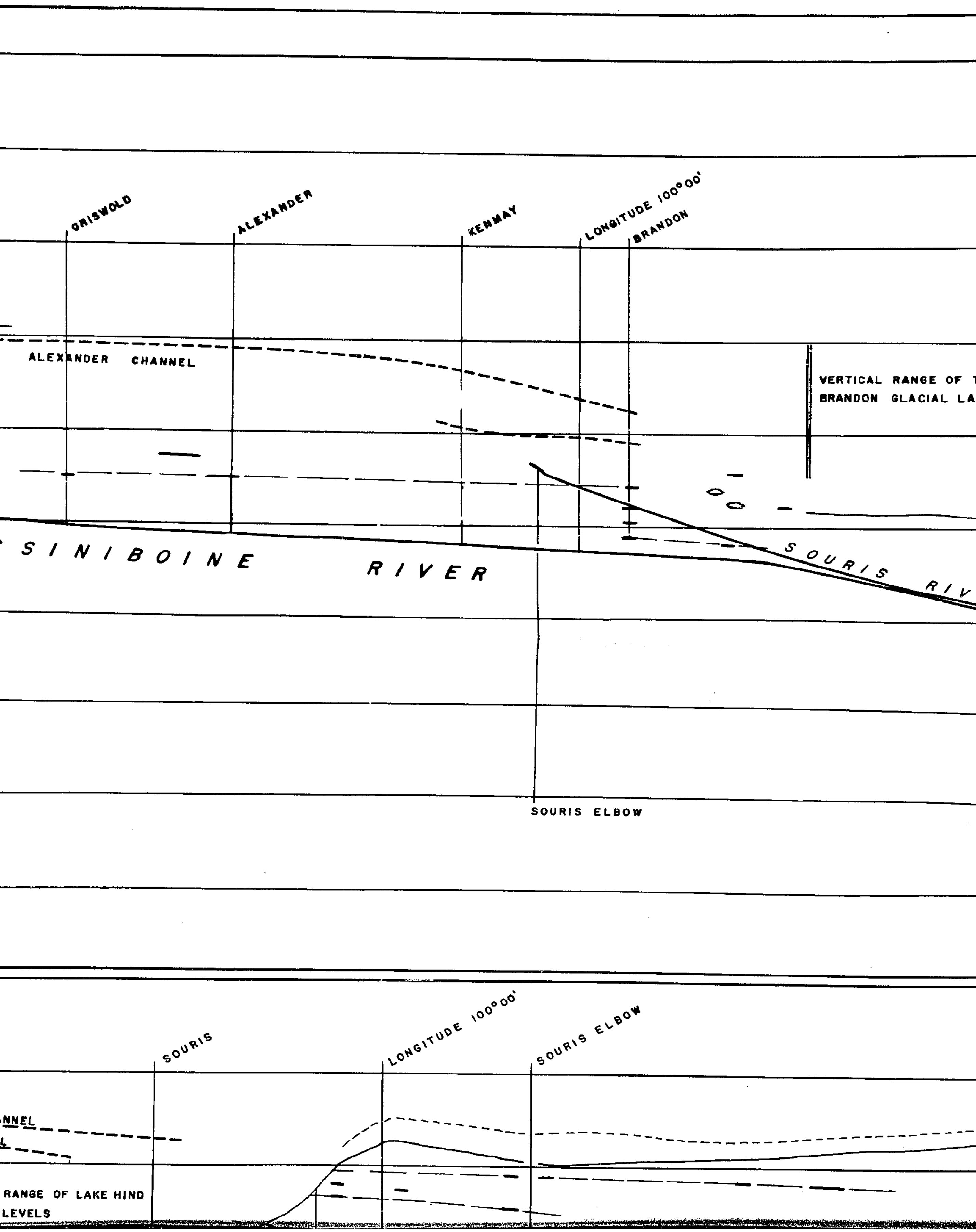
Lake Agassiz beach bar

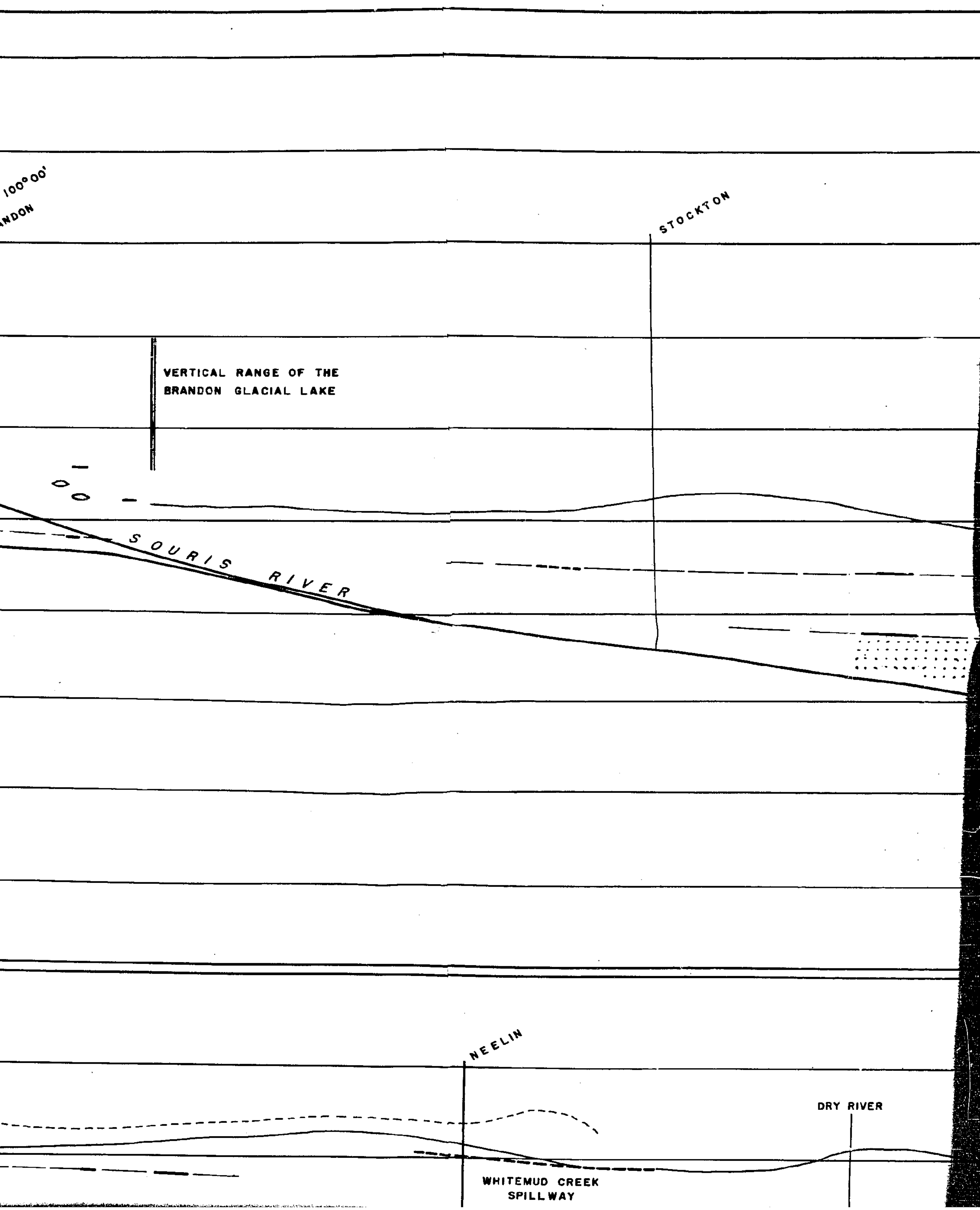
Alluvial fill

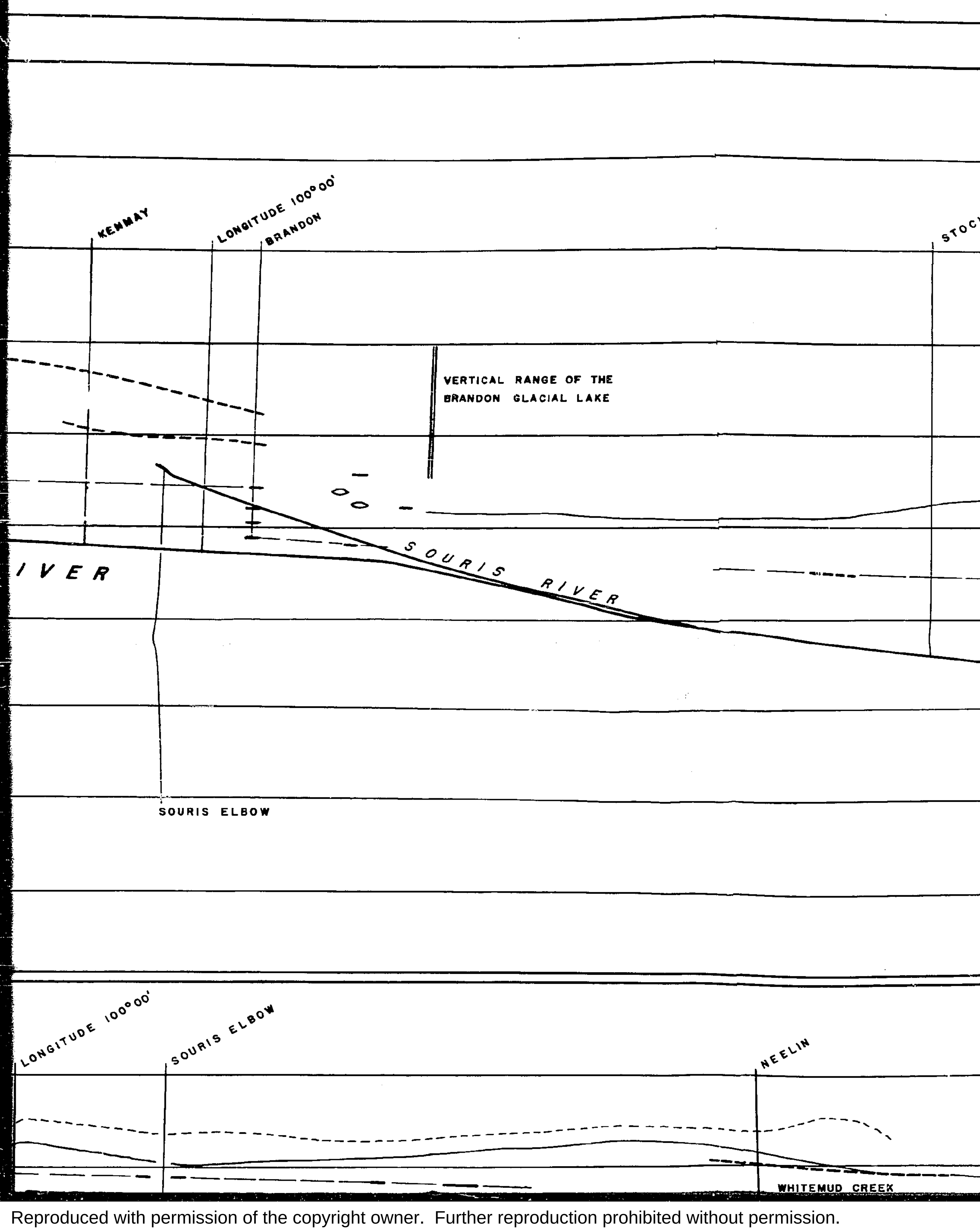
PLATE 5(a)

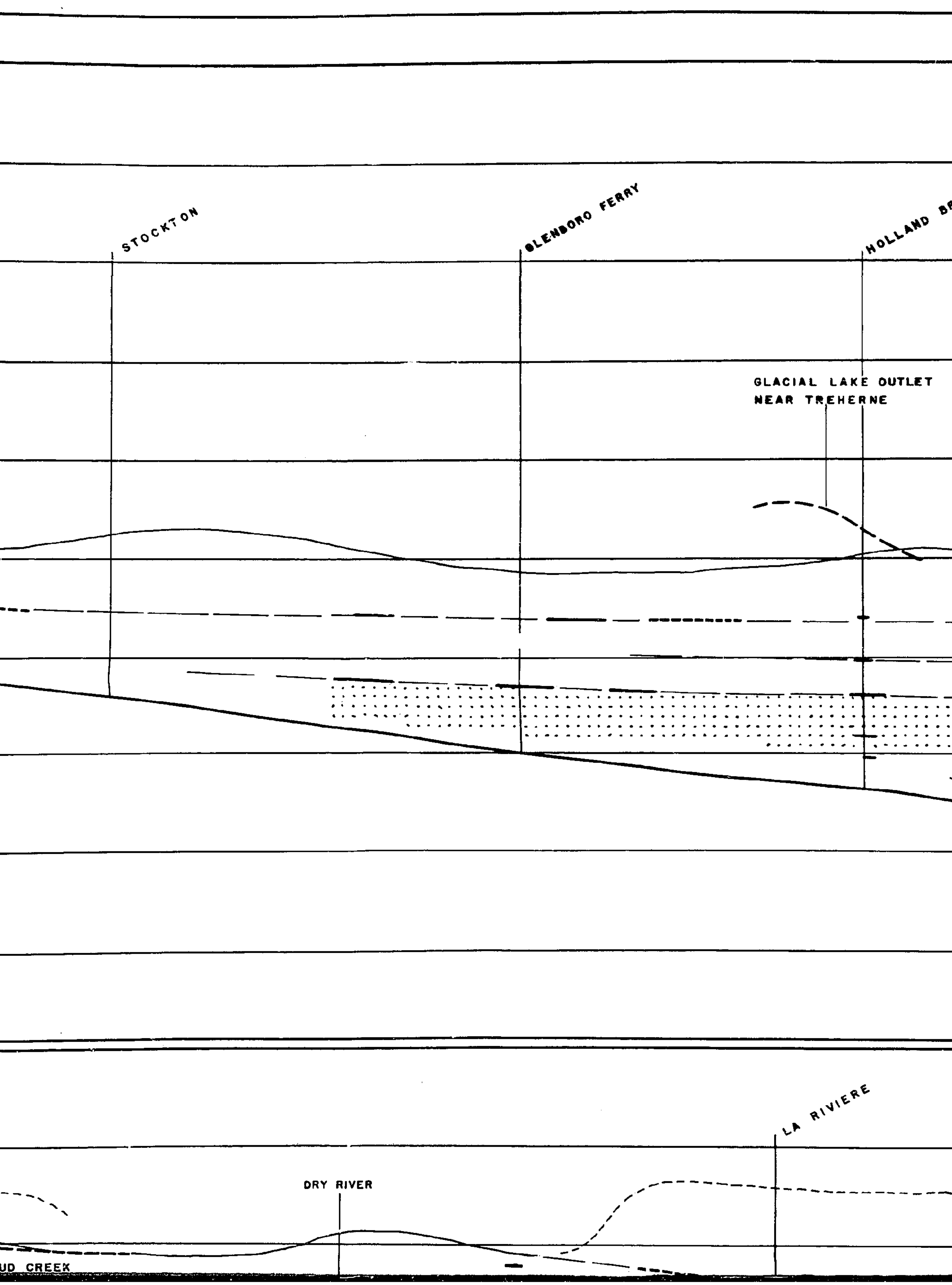


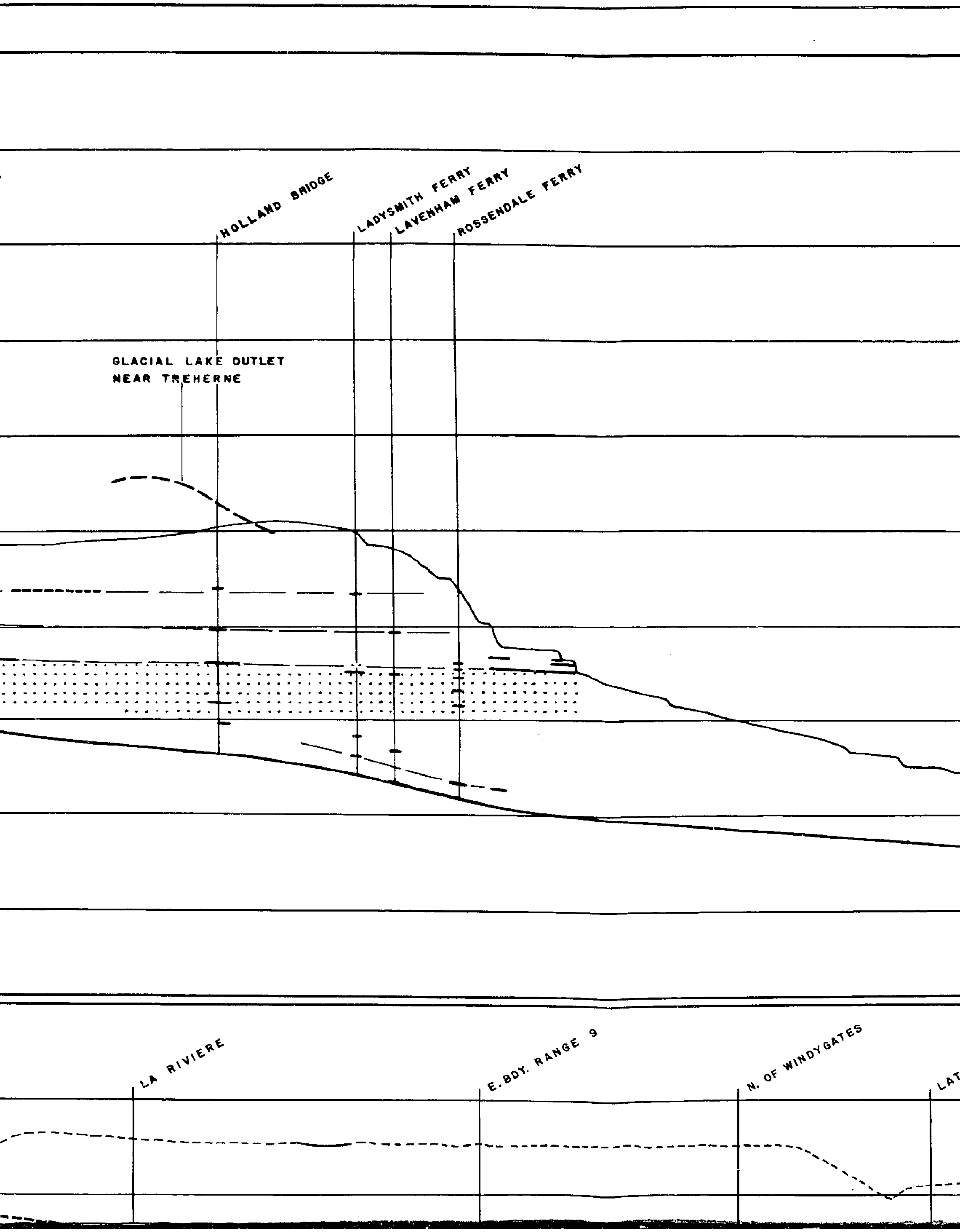

LATITUDE 50° 00'
VIRDEN
GRISWOLD
ALEXANDER CHANNEL
ASSINIBOINE
8
12
1100'
1000'
900'
800'
MELITA
NAPINKA
HARTNEY
SOURIS
"MEDORA" CHANNEL
DAND CHANNEL
VERTICAL RANGE OF LAKE HIND
& KNOWN LEVELS

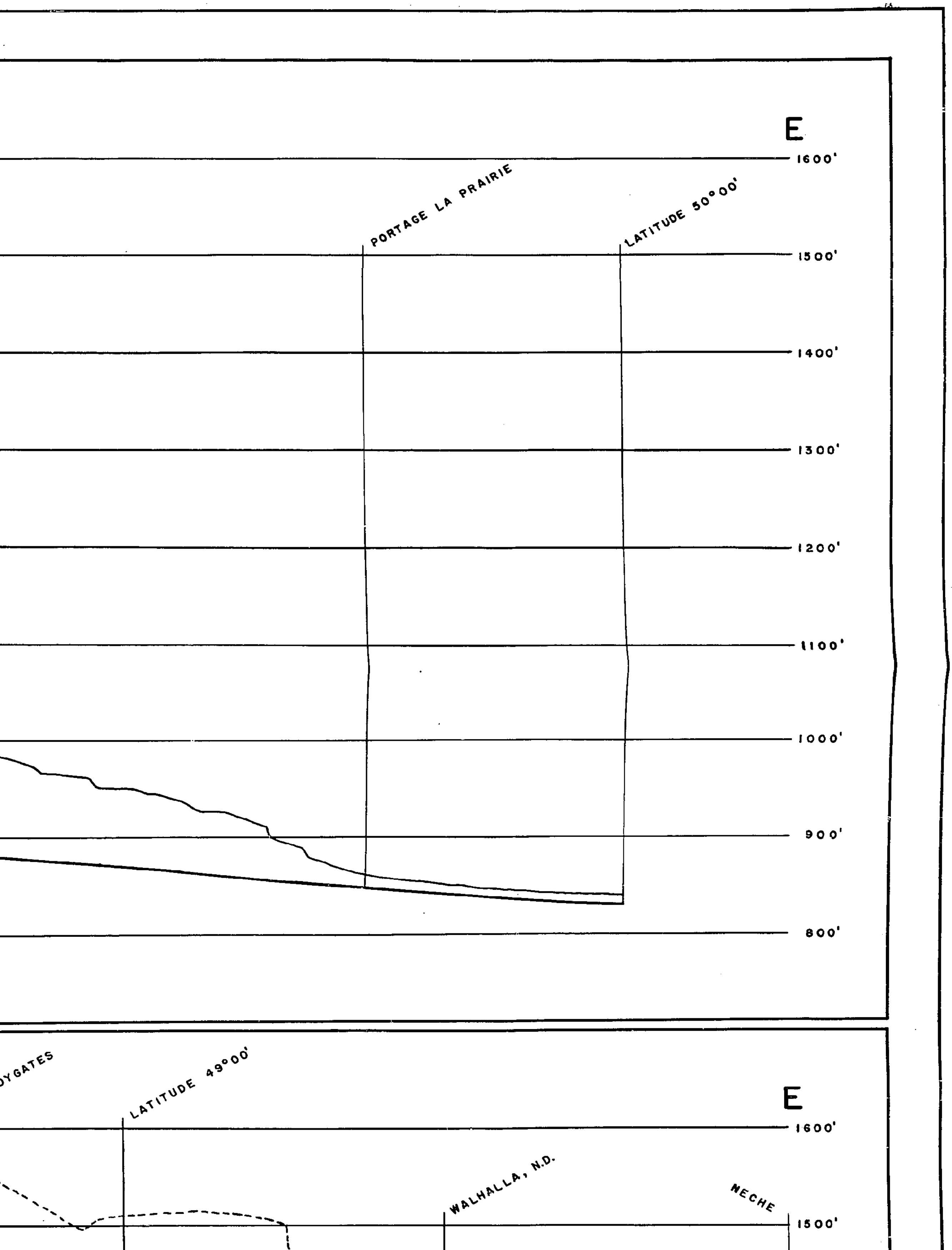

GRISWOLD
ALEXANDER
KEMMAY
LONGITUDE 100°00'
BRANDON
ALEXANDER CHANNEL
VERTICAL RANGE OF T
BRANDON GLACIAL LA
SINIBOINE
RIVER
SOURIS RIV
SOURIS ELBOW
SOURIS
LONGITUDE 100°00'
SOURIS ELBOW
NNEL
RANGE OF LAKE HIND
LEVELS


100°00'
STOCKTON
VERTICAL RANGE OF THE
BRANDON GLACIAL LAKE
SOURIS RIVER
NEELIN
DRY RIVER
WHITEMUD CREEK
SPILLWAY


KENMAY
LONGITUDE 100° 00'
BRANDON
STOC
VERTICAL RANGE OF THE
BRANDON GLACIAL LAKE
IVER
SOURIS RIVER
SOURIS ELBOW
LONGITUDE 100° 00'
SOURIS ELBOW
NEELIN
WHITEMUD CREEK


STOCKTON
GLENBORO FERRY
HOLLAND BR
GLACIAL LAKE OUTLET
NEAR TREHERNE
LA RIVIERE
DRY RIVER
UD CREEK


HOLLAND BRIDGE
LADYSMITH FERRY
LAVENHAM FERRY
ROSSENDALE FERRY
GLACIAL LAKE OUTLET
NEAR TREHERNE
LA RIVIERE
E. BDY. RANGE 9
N. OF WINDYGATES

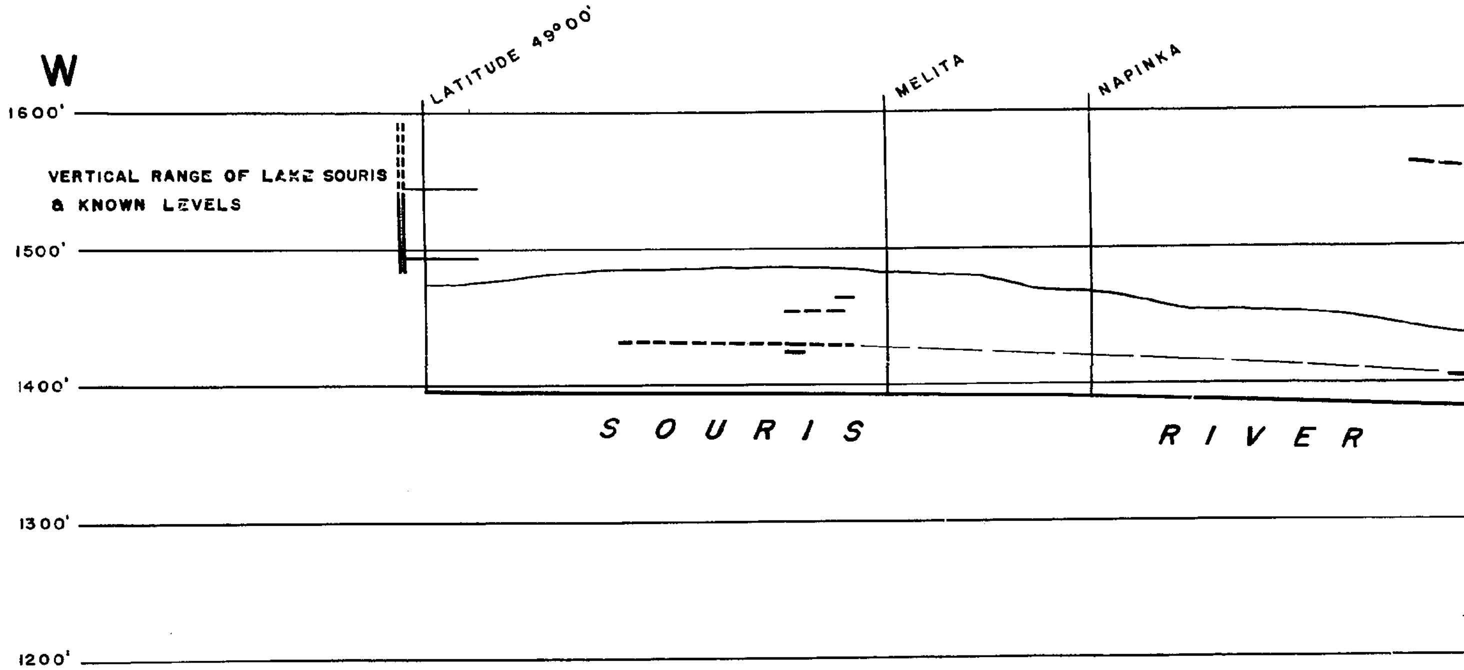


E
1600'
PORTAGE LA PRAIRIE
LATITUDE 50°00'
1500'
1400'
1300'
1200'
1100'
1000'
900'
800'
LATITUDE 49°00'
E
1600'
WALHALLA, N.D.
NECHE
1500'

Lake Agassiz beach bar

Alluvial fill

PLATE 5(a)



LONG PROFILES of SOURIS RIVER – PEMBINA TRENCH SYSTEM and RELATED SURFACES

HORIZONTAL SCALE 0 4 MILES 8 12

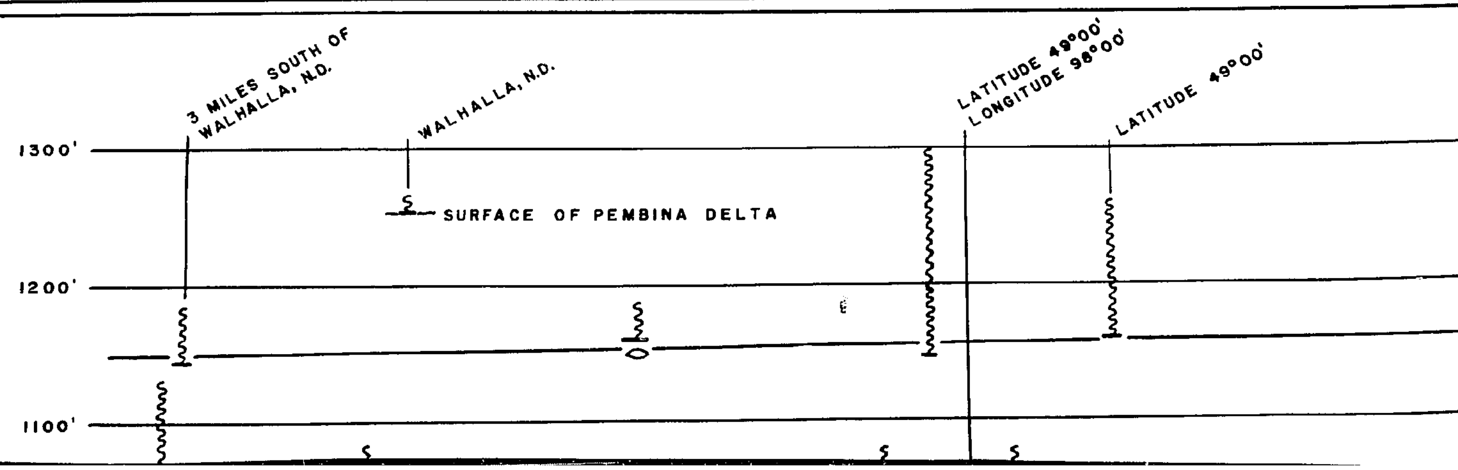
Valley bottom, terrace

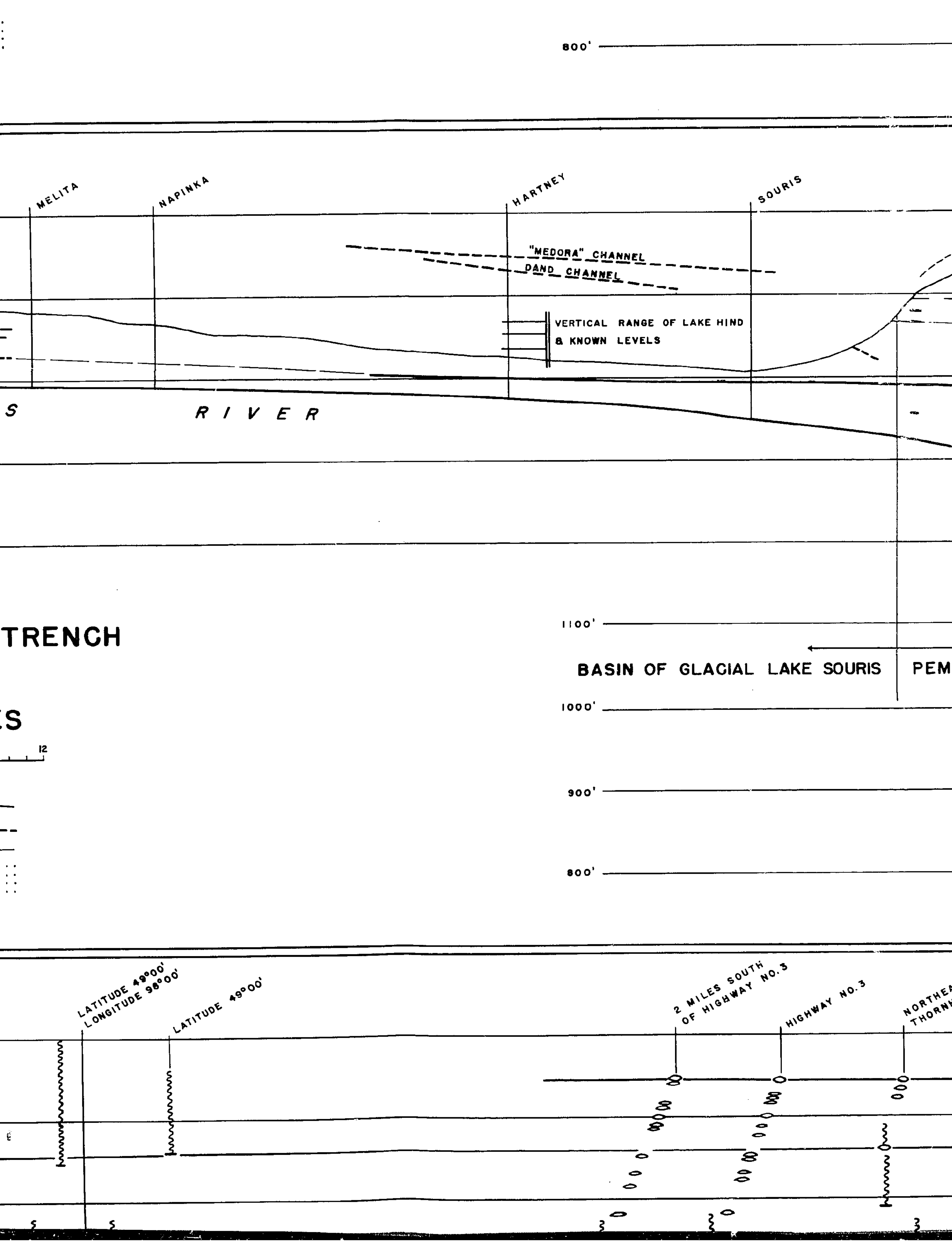
Abandoned channel

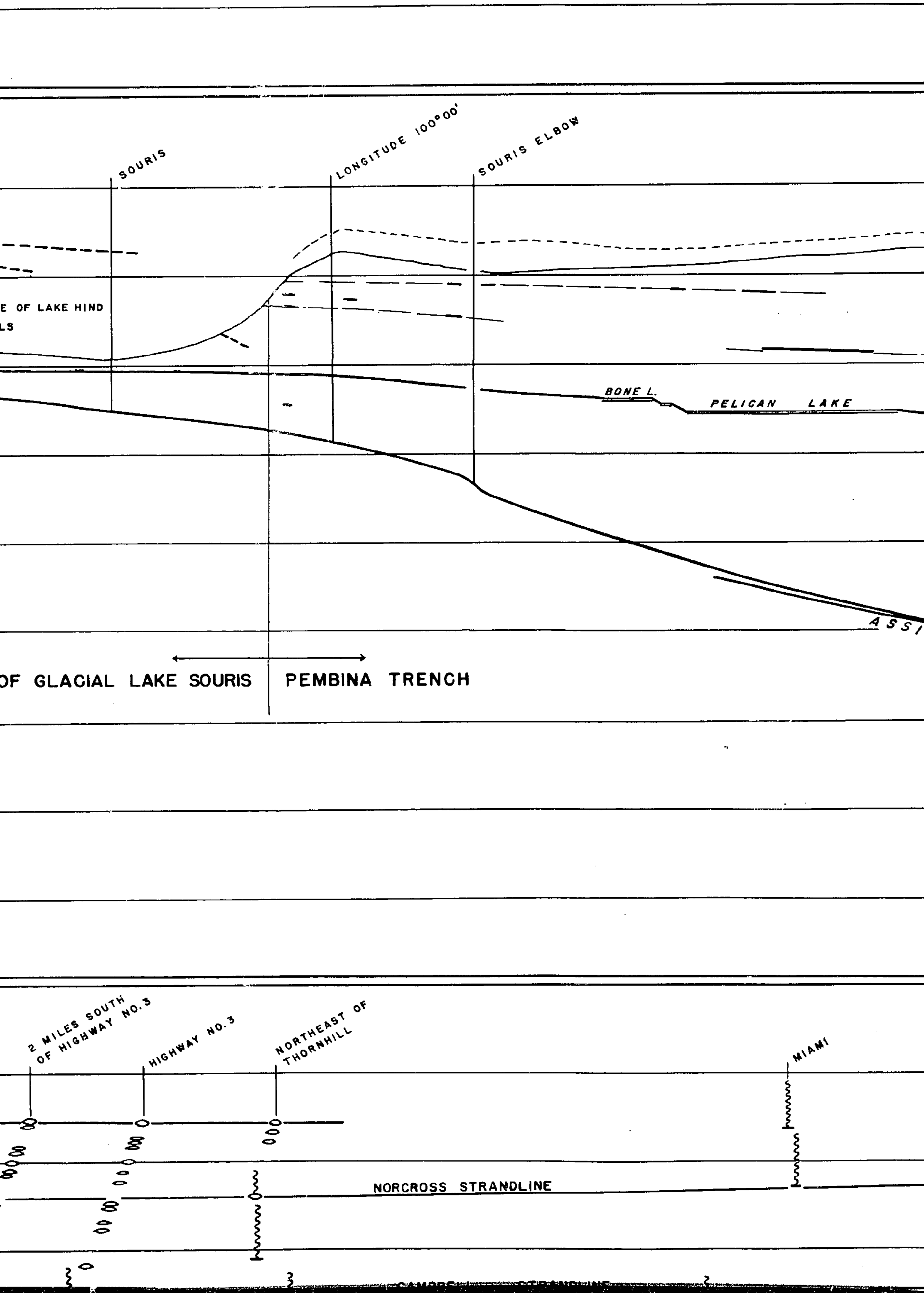
Upland surface near valley ,water-washed

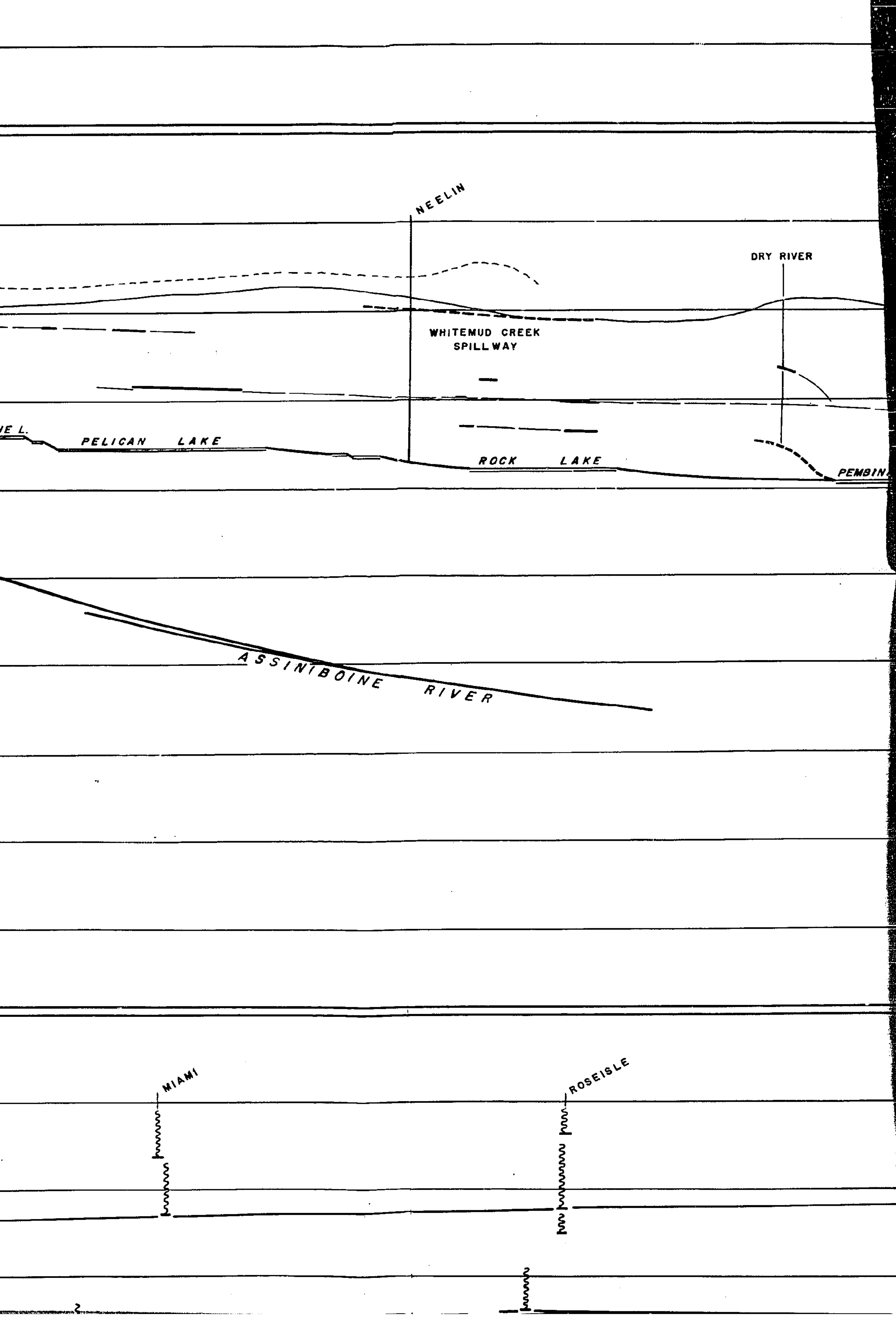
Alluvial fill

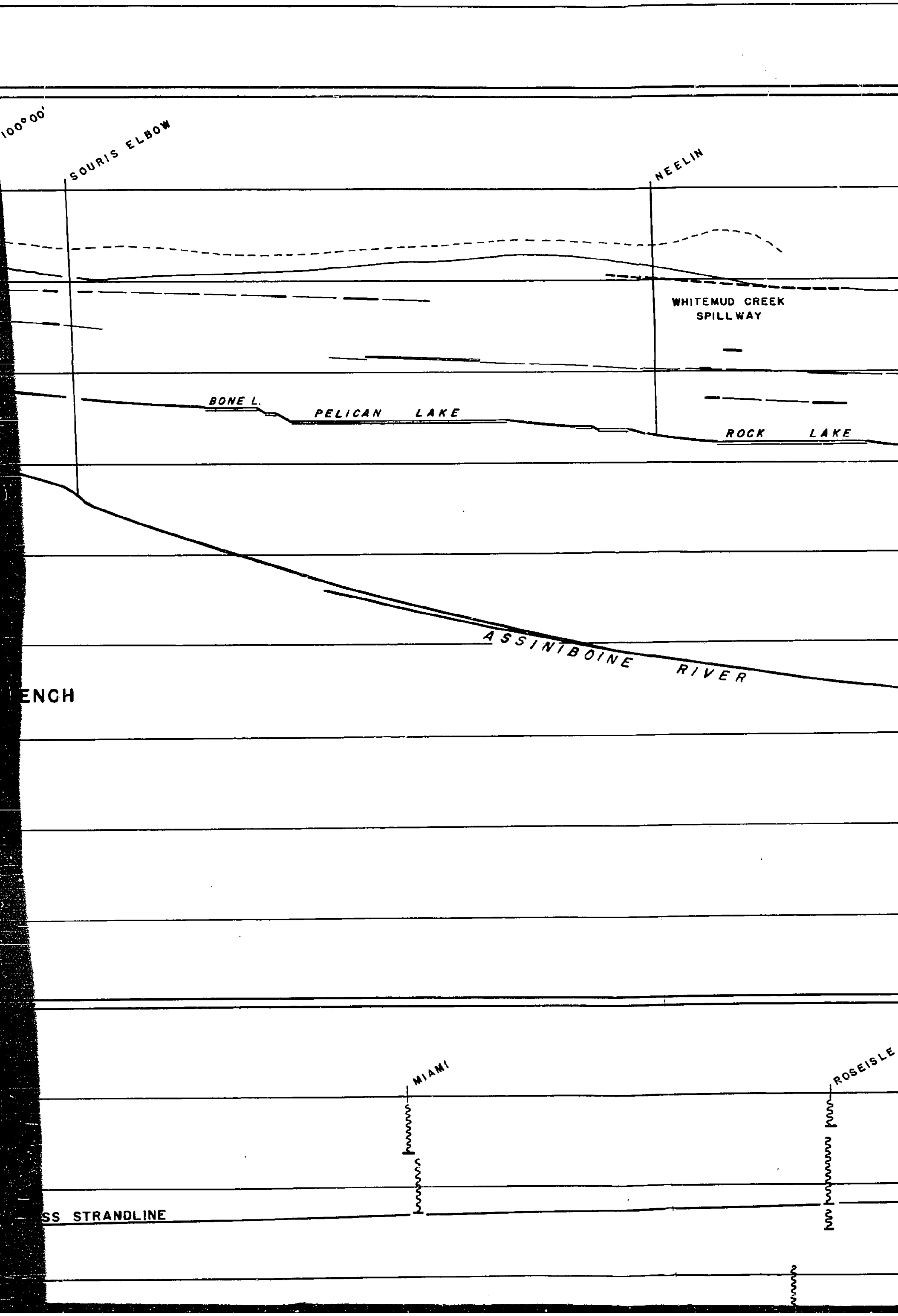
PLATE 5(b)

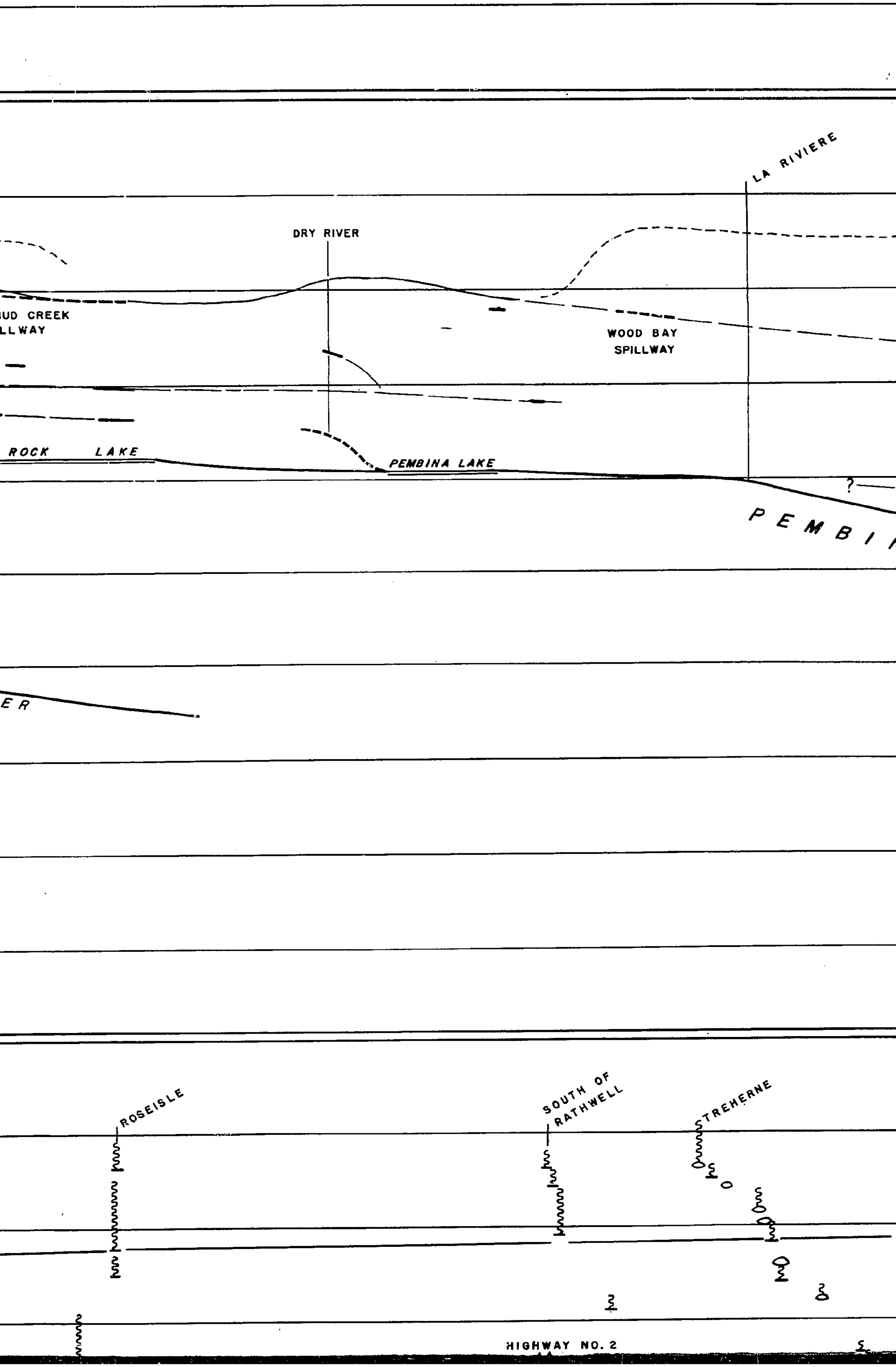


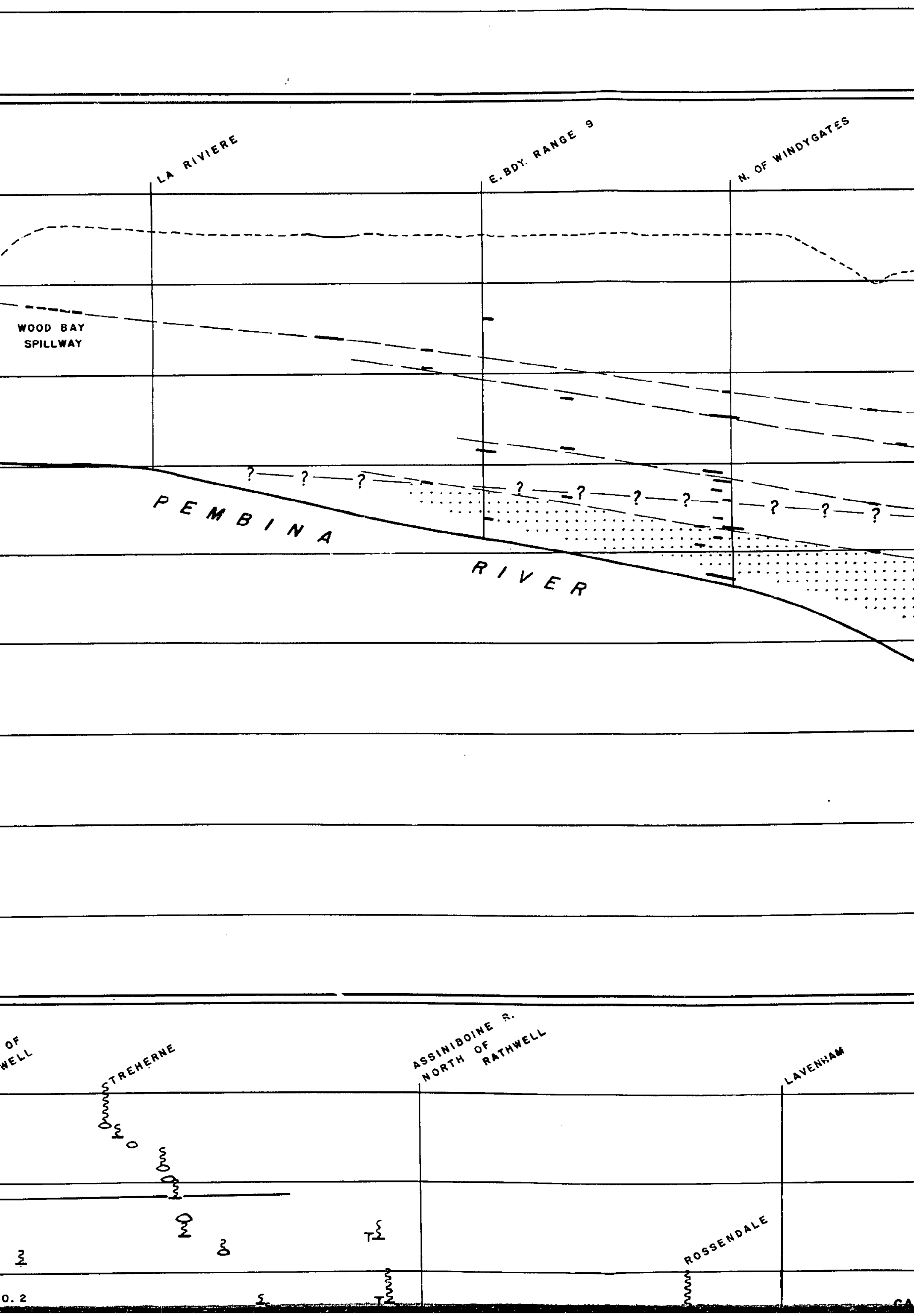

800'
MELITA
NAPINKA
HARTNEY
SOURIS
"MEDORA" CHANNEL
DAND CHANNEL
VERTICAL RANGE OF LAKE HIND & KNOWN LEVELS
S RIVER
TRENCH
1100'
BASIN OF GLACIAL LAKE SOURIS
PEMB
1000'
ES
12
900'
800'
LATITUDE 49°00' LONGITUDE 98°00'
LATITUDE 49°00'
2 MILES SOUTH OF HIGHWAY NO. 3
HIGHWAY NO. 3
NORTHEAS THORNHI


SOURIS
LONGITUDE 100°00'
SOURIS ELBOW
E OF LAKE HIND
LS
BONE L.
PELICAN LAKE
ASSI
OF GLACIAL LAKE SOURIS
PEMBINA TRENCH
2 MILES SOUTH OF HIGHWAY NO.3
HIGHWAY NO.3
NORTHEAST OF THORNHILL
MIAMI
NORCROSS STRANDLINE

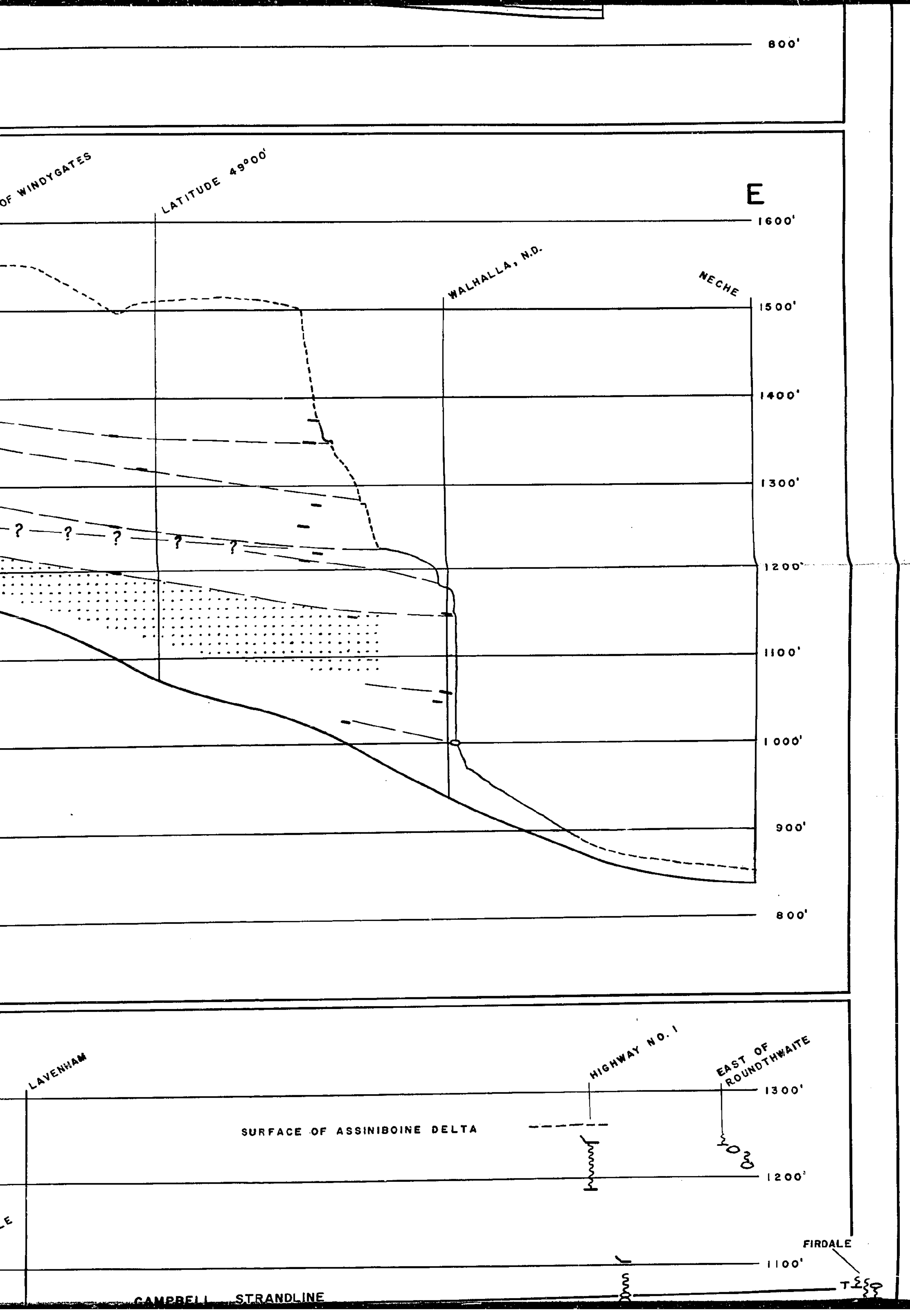

NEELIN
DRY RIVER
WHITEMUD CREEK
SPILLWAY
PELICAN LAKE
ROCK LAKE
ASSINIBOINE RIVER
MIAMI
ROSEISLE


100°00'
SOURIS ELBOW
NEELIN
WHITEMUD CREEK
SPILLWAY
BONE L.
PELICAN LAKE
ROCK LAKE
ASSINIBOINE RIVER
ENCH
MIAMI
ROSEISLE
SS STRANDLINE


LA RIVIERE
DRY RIVER
UD CREEK
LLWAY
WOOD BAY
SPILLWAY
ROCK LAKE
PEMBINA LAKE
PEMBI
ER
ROSEISLE
SOUTH OF
RATHWELL
TREHERNE
HIGHWAY NO. 2



LA RIVIERE
E. BDY. RANGE 9
N. OF WINDYGATES
WOOD BAY
SPILLWAY
PEMBINA
RIVER
OF
WELL
TREHERNE
ASSINIBOINE R.
NORTH OF RATHWELL
LAVENHAM
ROSSENDALE
O. 2


800'
OF WINDYGATES
LATITUDE 49°00'
E
1600'
WALHALLA, N.D.
NECHE
1500'
1400'
1300'
1200'
1100'
1000'
900'
800'
LAVENHAM
HIGHWAY NO. 1
EAST OF ROUNDTHWAITE
1300'
SURFACE OF ASSINIBOINE DELTA
1200'
FIRDALE
1100'
CAMPBELL STRANDLINE

HORIZONTAL SCALE

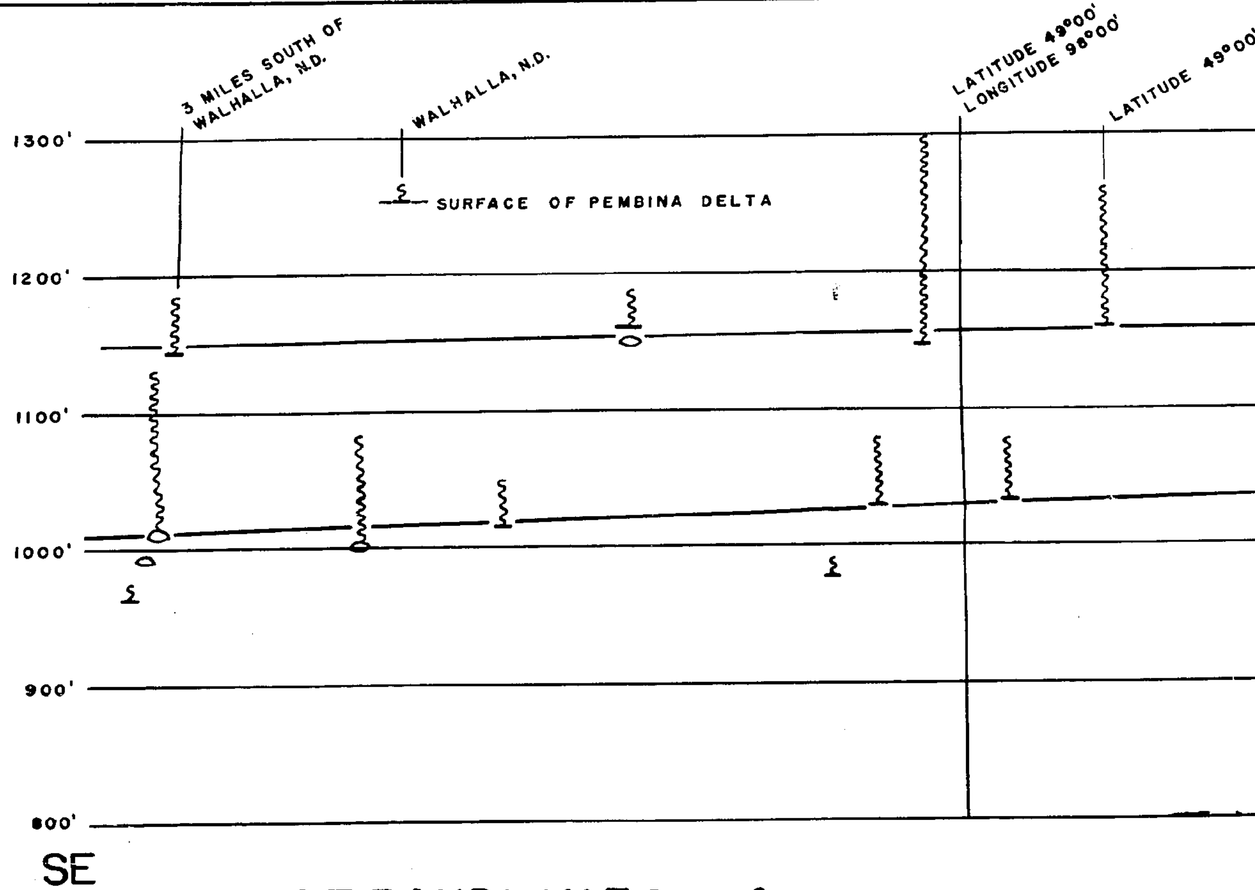
Valley bottom, terrace

Abandoned channel

Upland surface near valley , water-washed

Alluvial fill

PLATE 5(b)



STRANDLINES of GLACIAL LAKE AGASSIZ

PROJECTED ON VERTICAL PLANE SE-NW

0 2 4 MILES 6 8 10

Strandline scarp

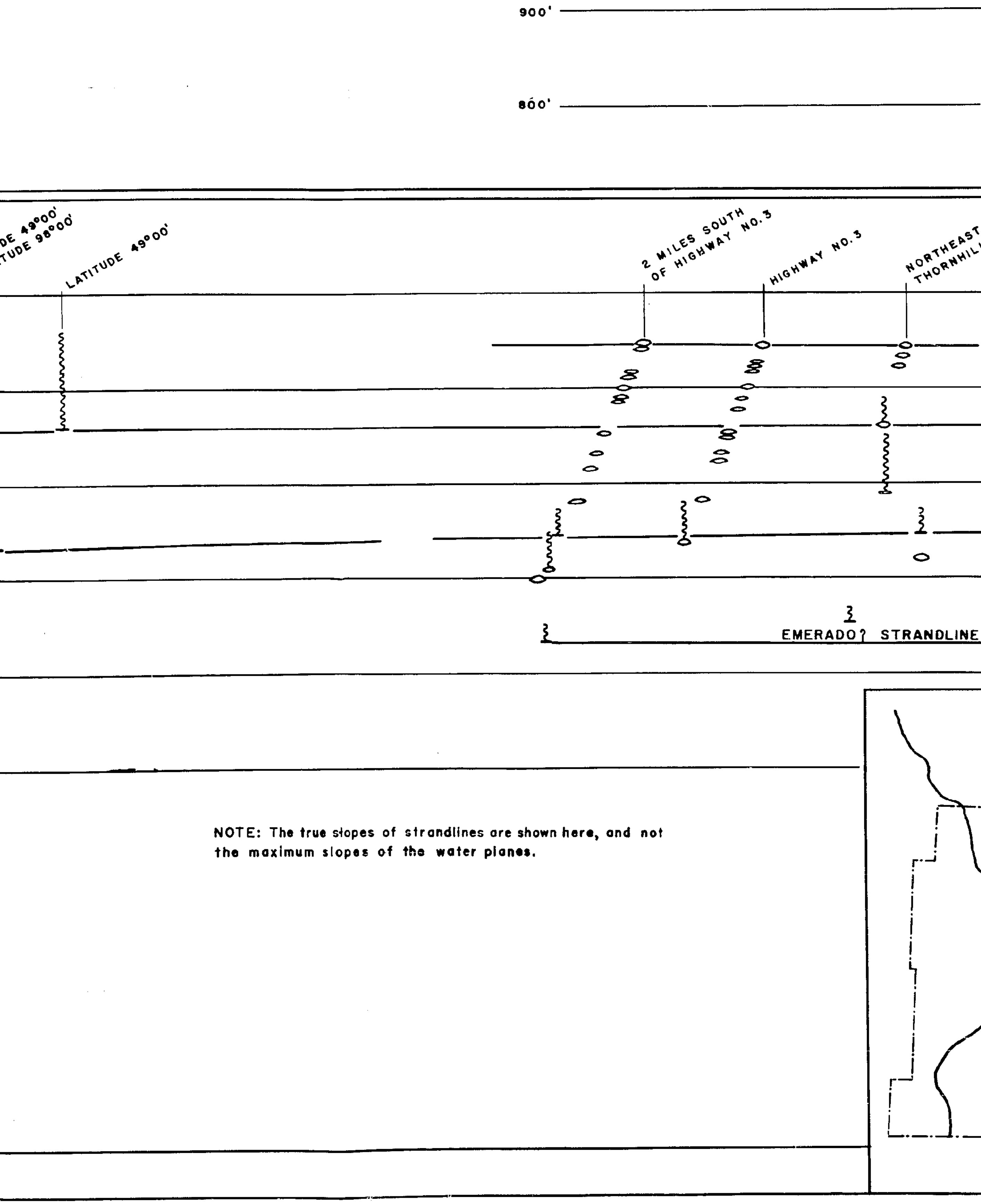
Beach bar

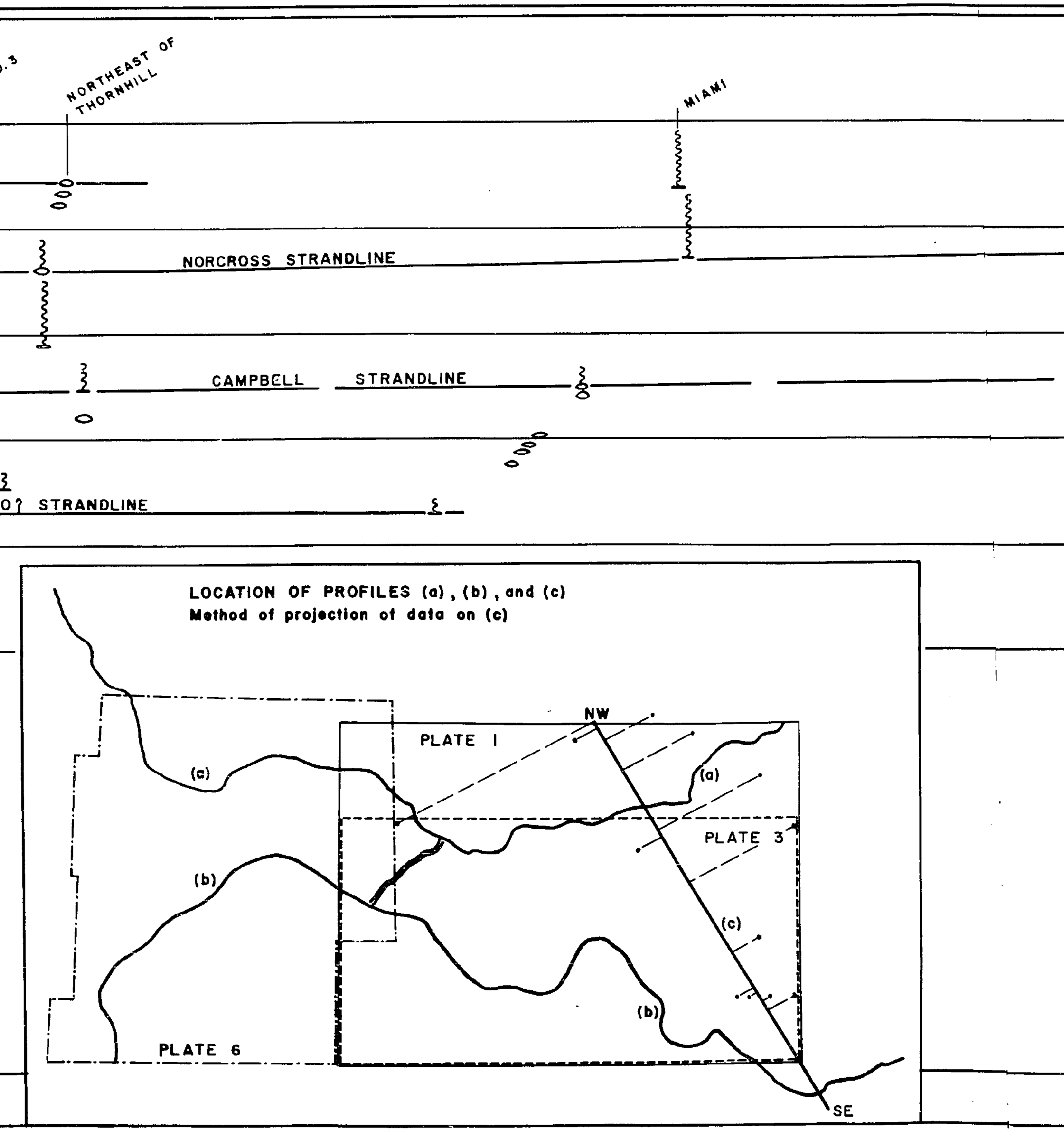
Sand dunes

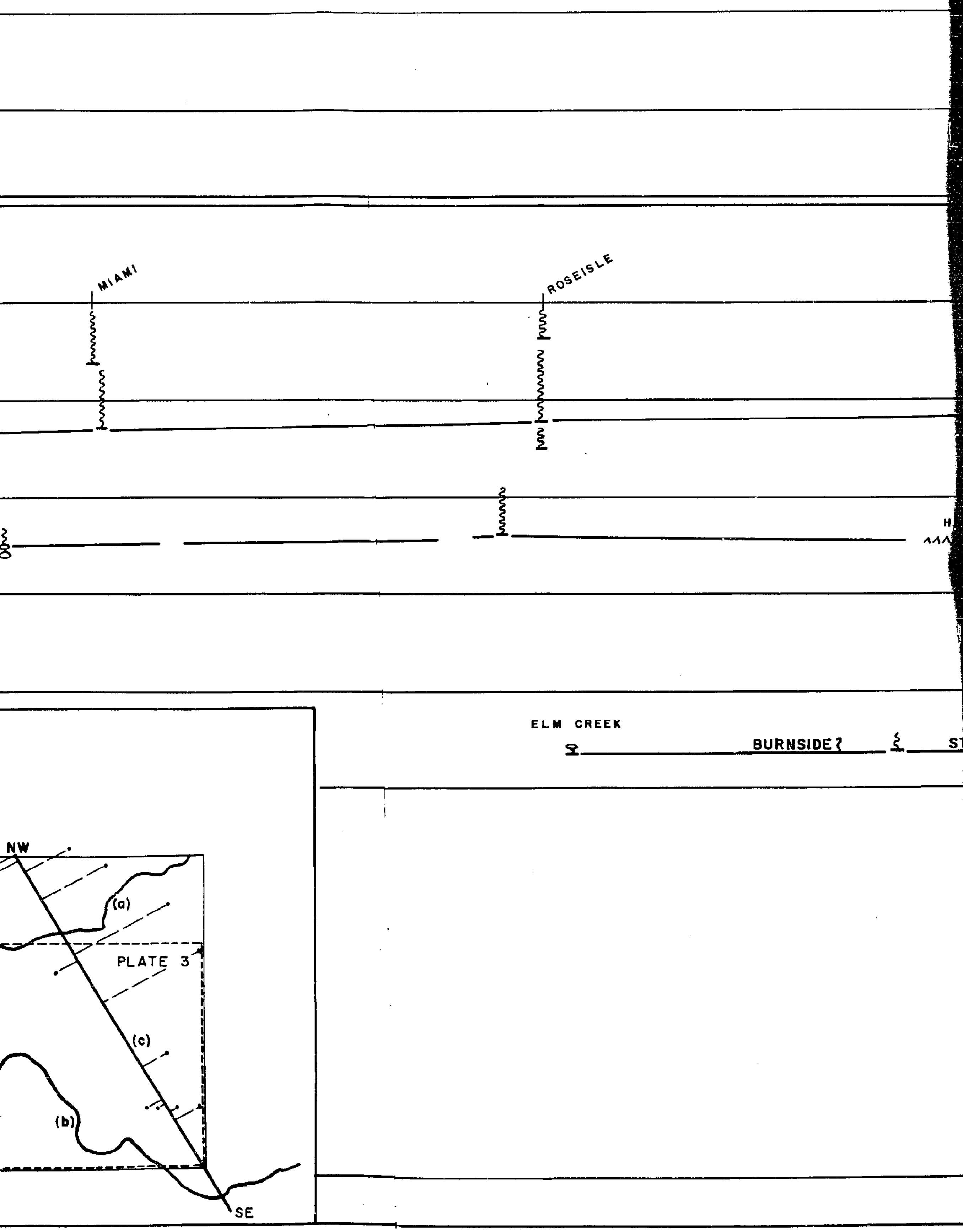
Paired stream terraces & scarp above

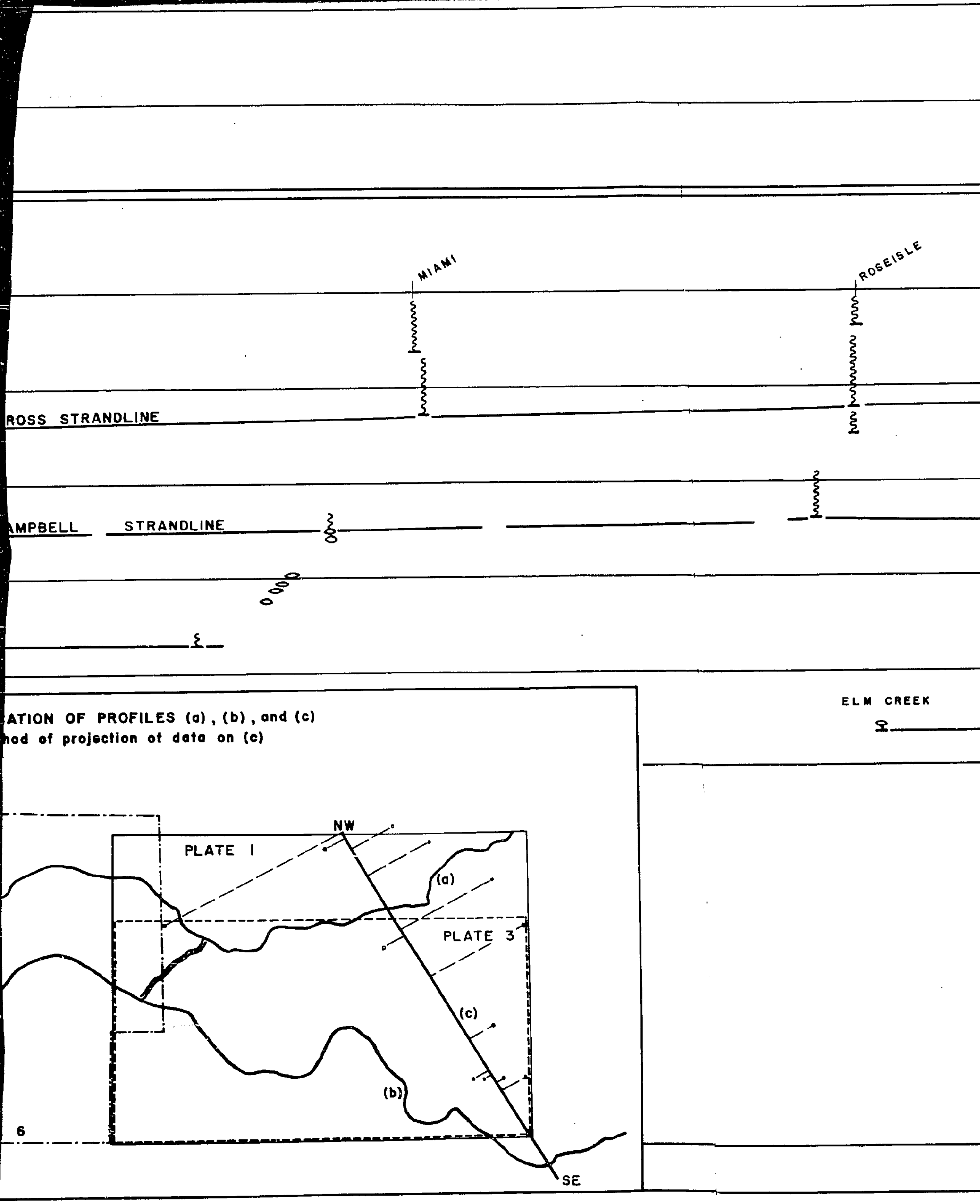
Well-developed strandline

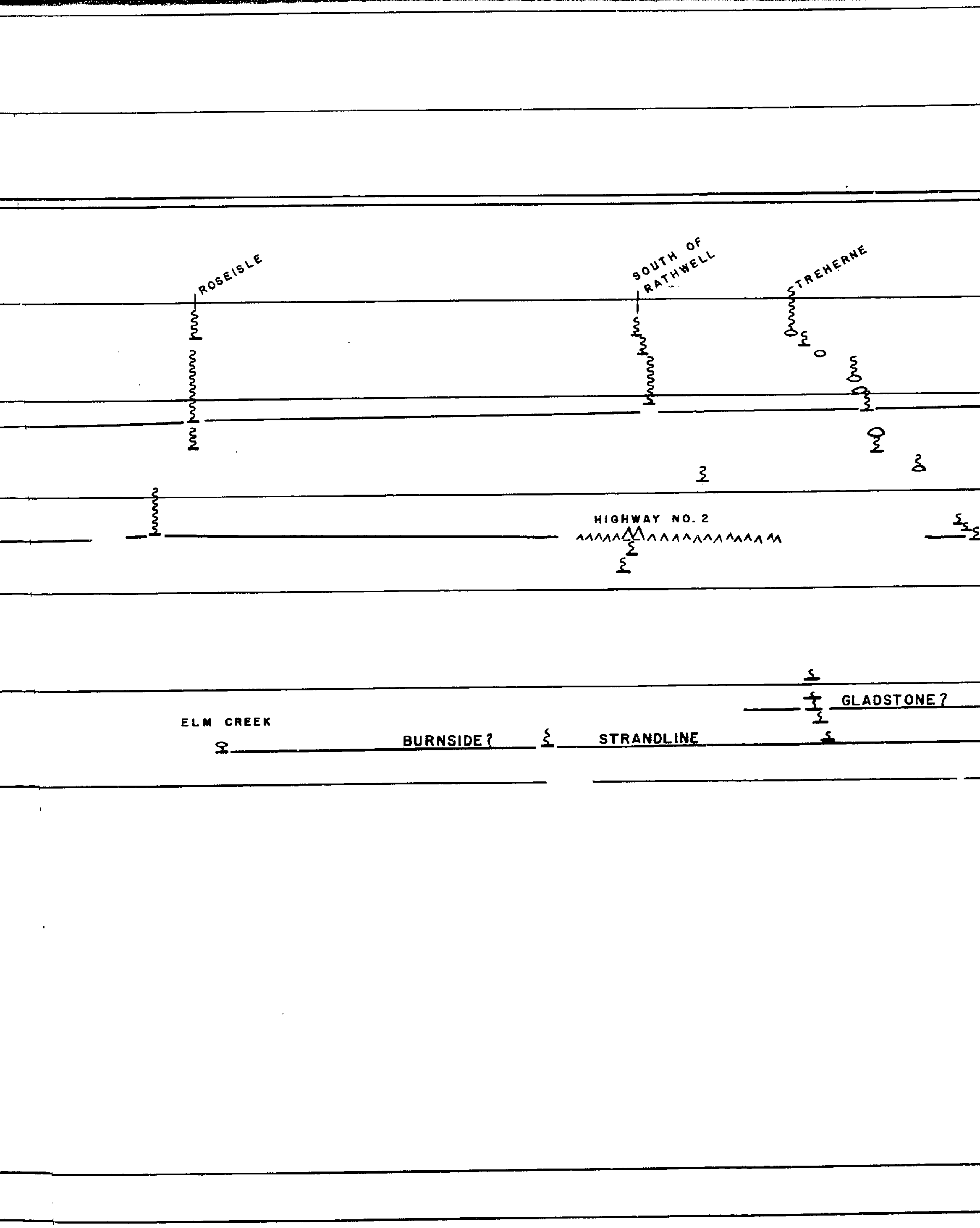
PLATE 5(c)


900'
800'
LATITUDE 49°00'
2 MILES SOUTH OF HIGHWAY NO.3
HIGHWAY NO.3
EMERADO? STRANDLINE
NOTE: The true slopes of strandlines are shown here, and not the maximum slopes of the water planes.

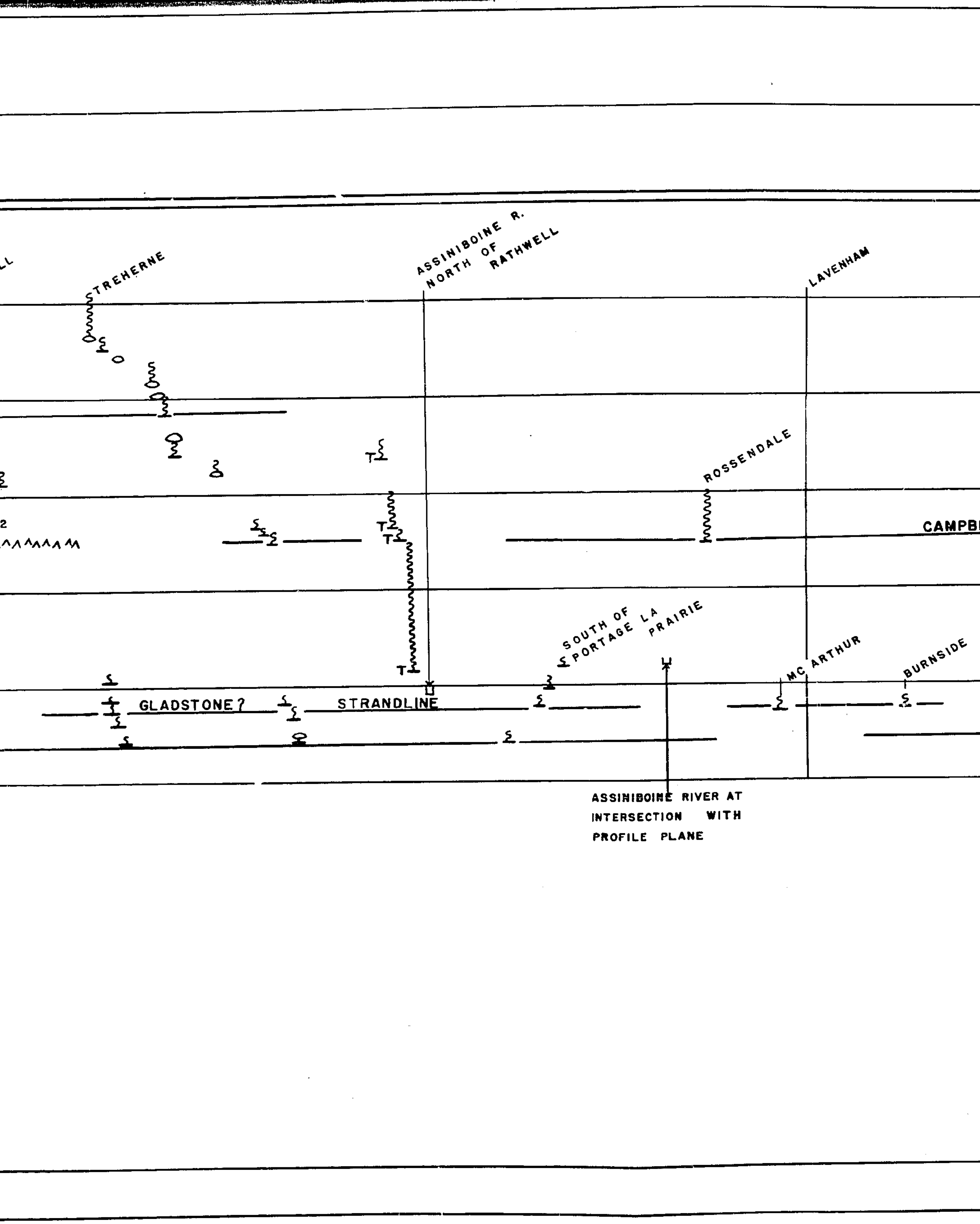

NORTHEAST OF THORNHILL
MIAMI
NORCROSS STRANDLINE
CAMPBELL STRANDLINE
STRANDLINE
LOCATION OF PROFILES (a), (b), and (c)
Method of projection of data on (c)
PLATE 1
PLATE 3
PLATE 6
NW
SE
(a)
(b)
(c)

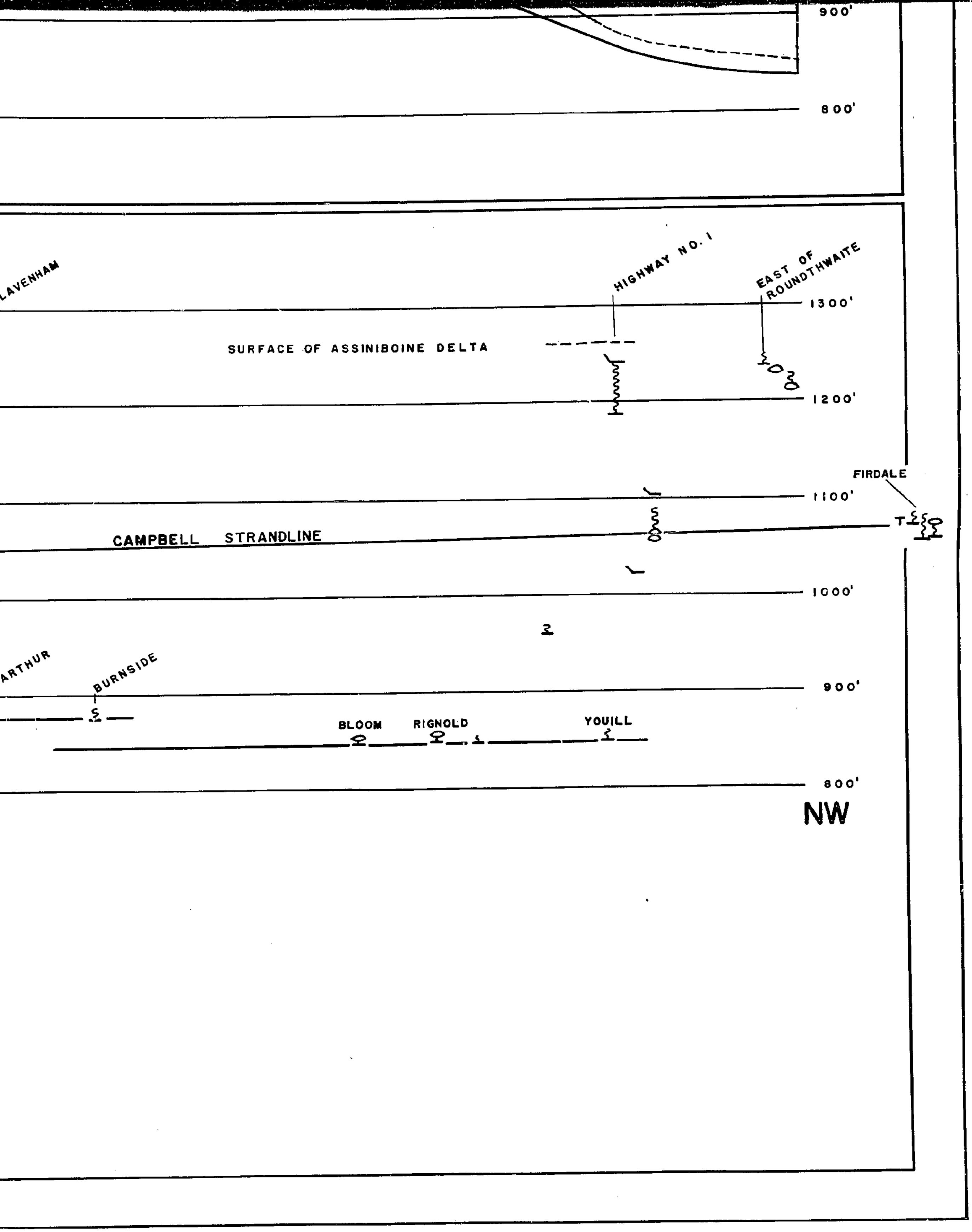

MIAMI
ROSEISLE
ELM CREEK
BURNSIDE ?
NW
(a)
PLATE 3
(c)
(b)
SE


MIAMI
ROSEISLE
ROSS STRANDLINE
AMPBELL STRANDLINE
ELM CREEK
ATION OF PROFILES (a), (b), and (c)
hod of projection of data on (c)
NW
PLATE I
PLATE 3
(a)
(b)
(c)
6
SE

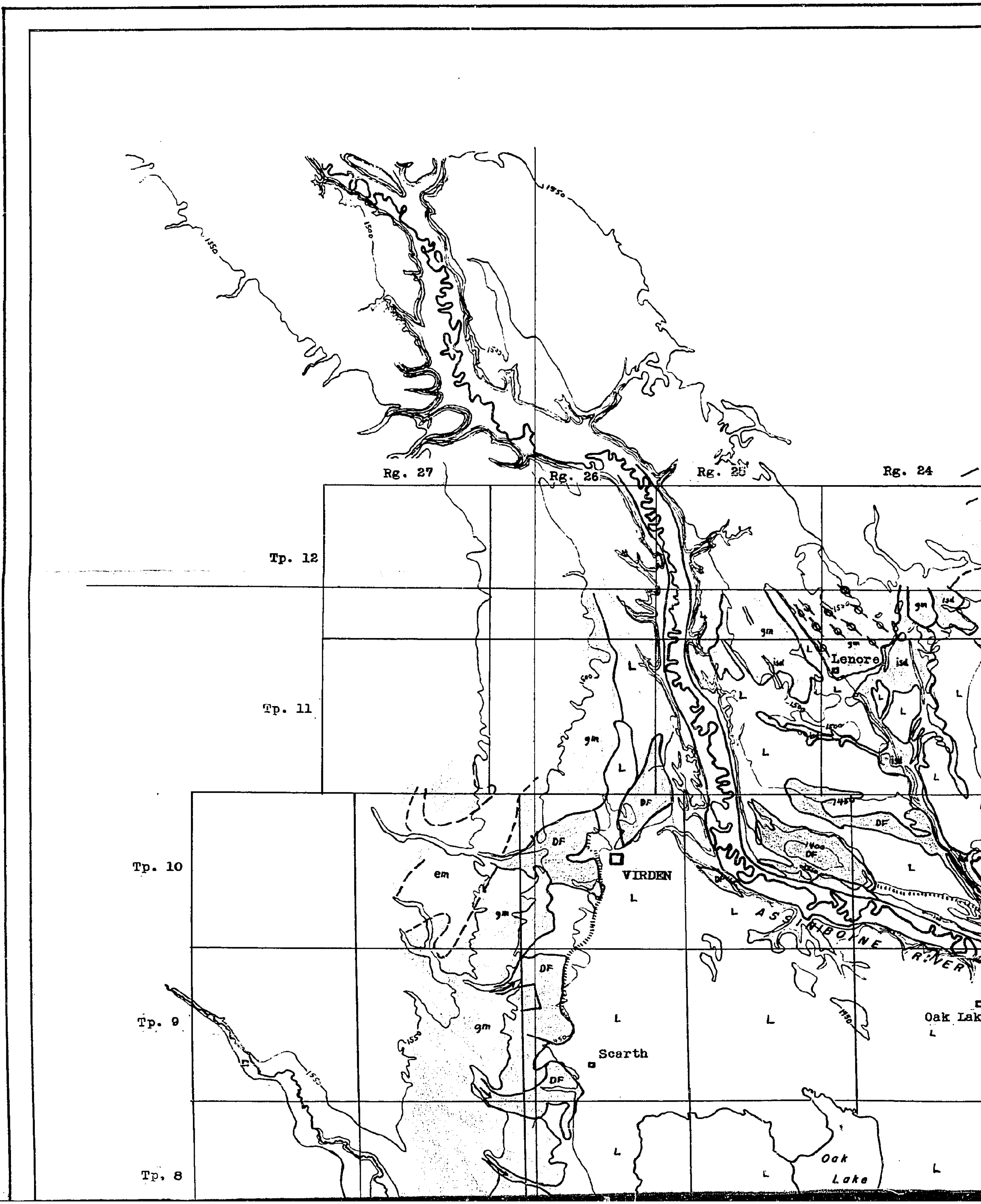


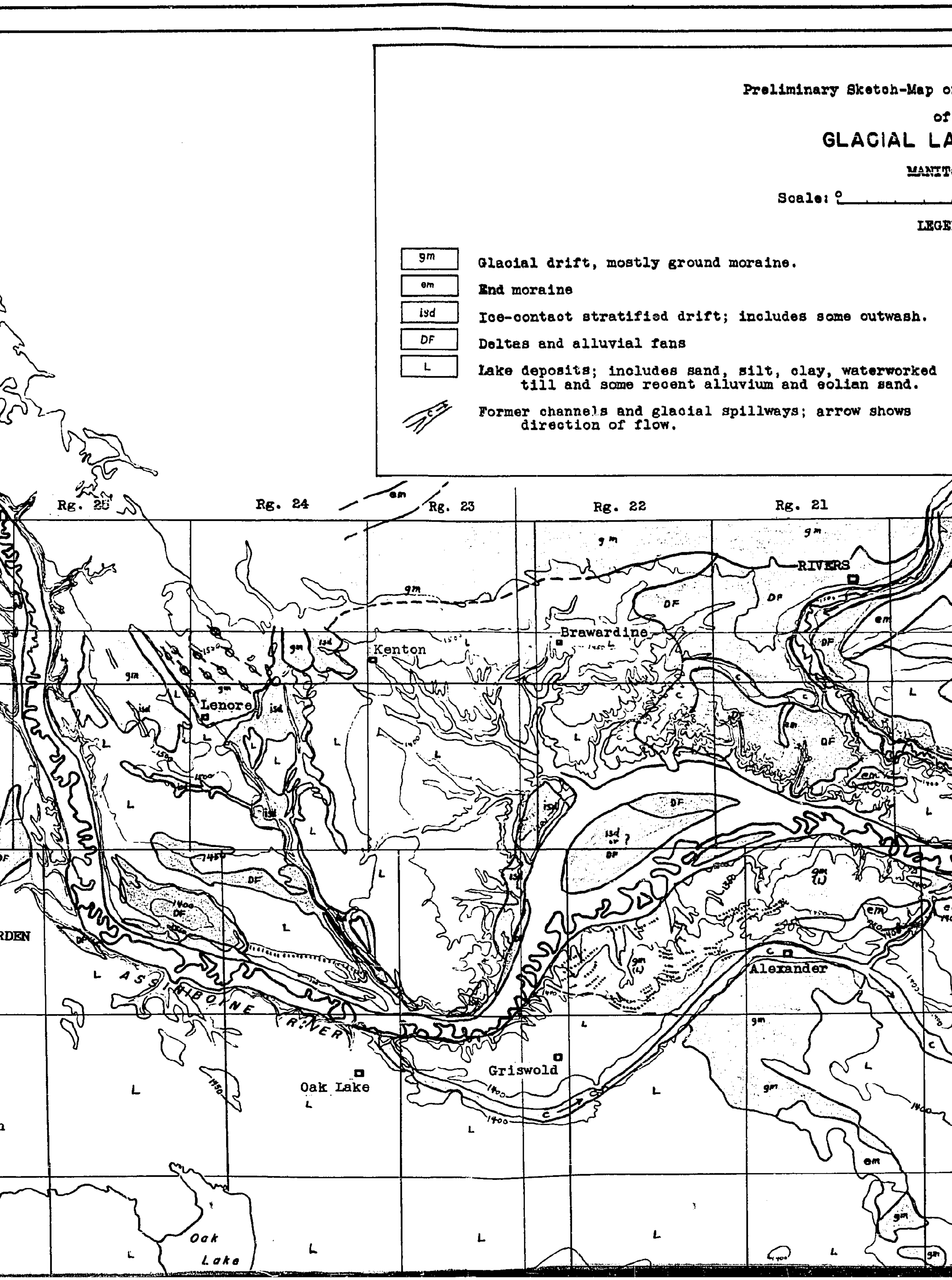
ROSEISLE
SOUTH OF RATHWELL
TREHERNE
HIGHWAY NO. 2
GLADSTONE ?
ELM CREEK
BURNSIDE ?
STRANDLINE


TREHERNE
ASSINIBOINE R. NORTH OF RATHWELL
LAVENHAM
ROSSENDALE
SOUTH OF PORTAGE LA PRAIRIE
MC ARTHUR
BURNSIDE
GLADSTONE ?
STRANDLINE
ASSINIBOINE RIVER AT INTERSECTION WITH PROFILE PLANE



900'
800'
LAVENHAM
HIGHWAY NO. 1
EAST OF ROUNDTHWAITE
1300'
SURFACE OF ASSINIBOINE DELTA
1200'
FIRDALE
1100'
CAMPBELL STRANDLINE
1000'
ARTHUR
BURNSIDE
900'
BLOOM
RIGNOLD
YOUILL
800'
NW


Rg. 27
Rg. 26
Rg. 25
Rg. 24
Tp. 12
Tp. 11
Tp. 10
Tp. 9
Tp. 8
Lenore
VIRDEN
Scarth
Oak Lak
ASSINIBOINE RIVER
Oak Lake
1550
1500
DF
gm
isd
em
L


Preliminary Sketch-Map o
of
GLACIAL LA
Scale:
gm Glacial drift, mostly ground moraine.
em End moraine
isd Ice-contact stratified drift; includes some outwash.
DF Deltas and alluvial fans
L Lake deposits; includes sand, silt, clay, waterworked till and some recent alluvium and eolian sand.
Former channels and glacial spillways; arrow shows direction of flow.
Rg. 25
Rg. 24
Rg. 23
Rg. 22
Rg. 21
RIVERS
Brawardine
Kenton
Lenore
Alexander
Griswold
Oak Lake
ASSINIBOINE RIVER
Oak Lake
RDEN

eliminary Sketch-Map of the Surficial Geology

of

GLACIAL LAKE SOURIS

MANITOBA

PLATE 6

Scale: 0 miles 10

LEGEND

ine.

ludes some outwash.

t, clay, waterworked
m and eolian sand.

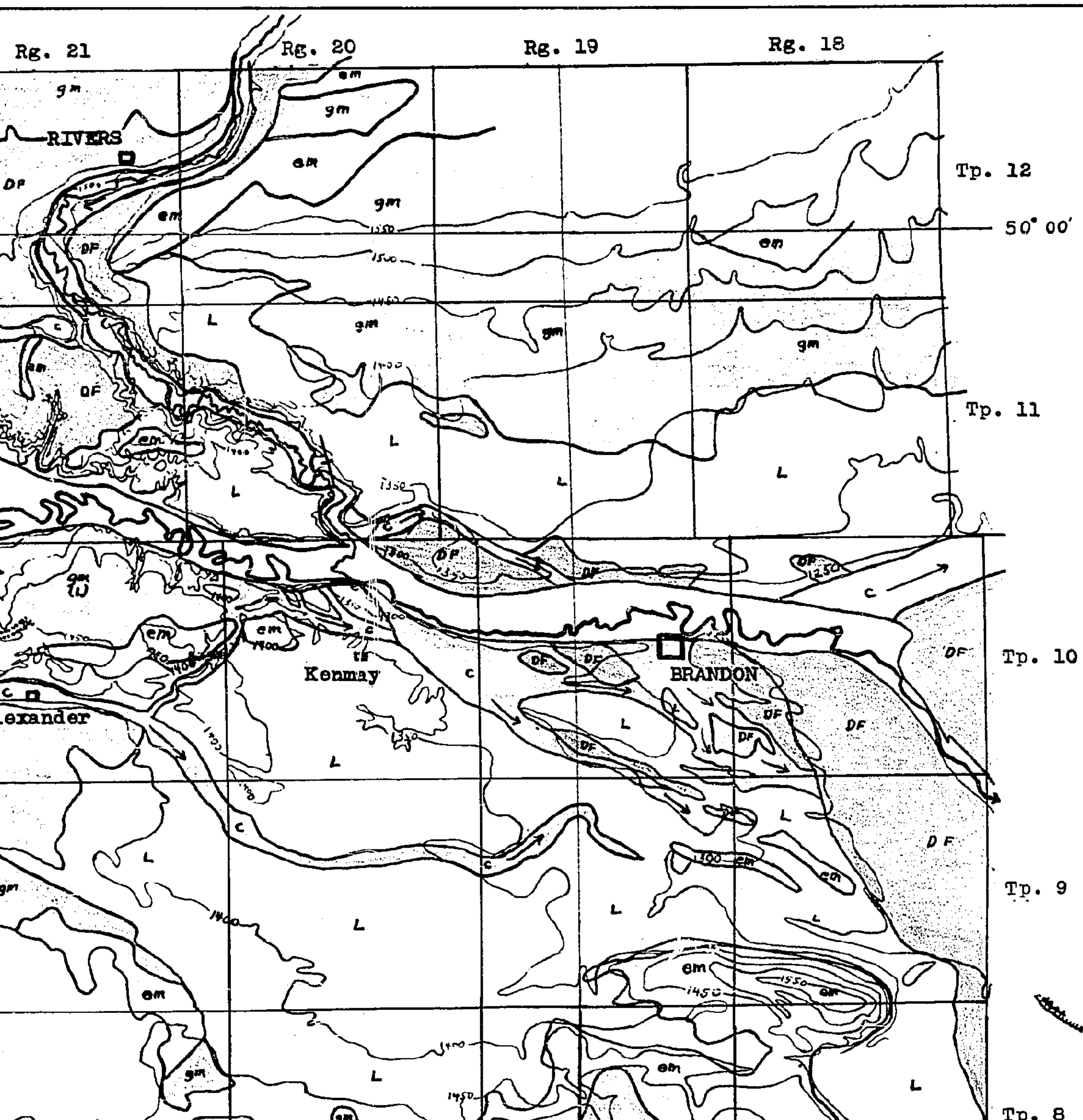
ways; arrow shows

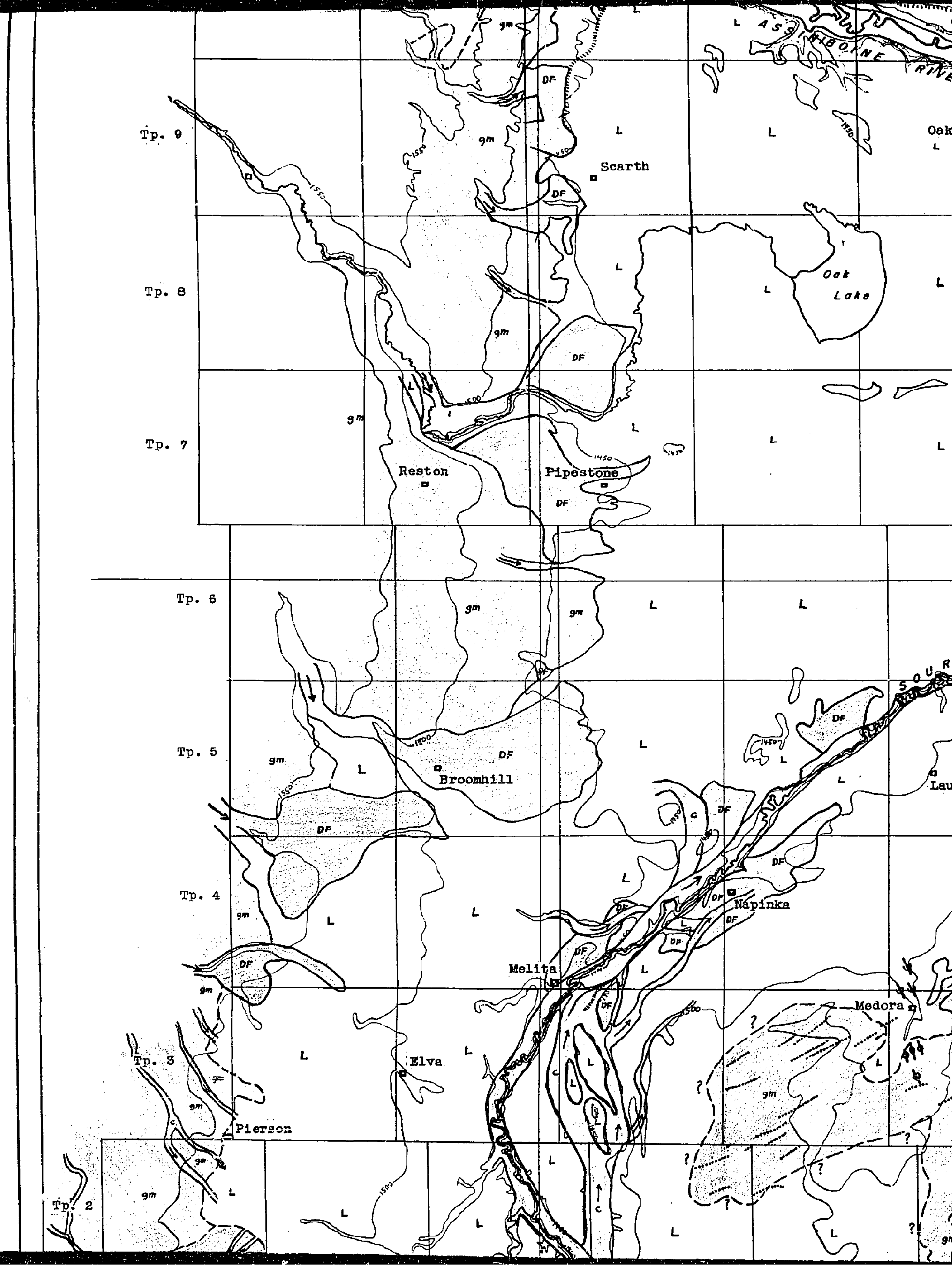
Trends of minor moraines.

Directions of drumlins, glacial grooves, striae on boulder pavements, direction of preferred pebble orientation in till.

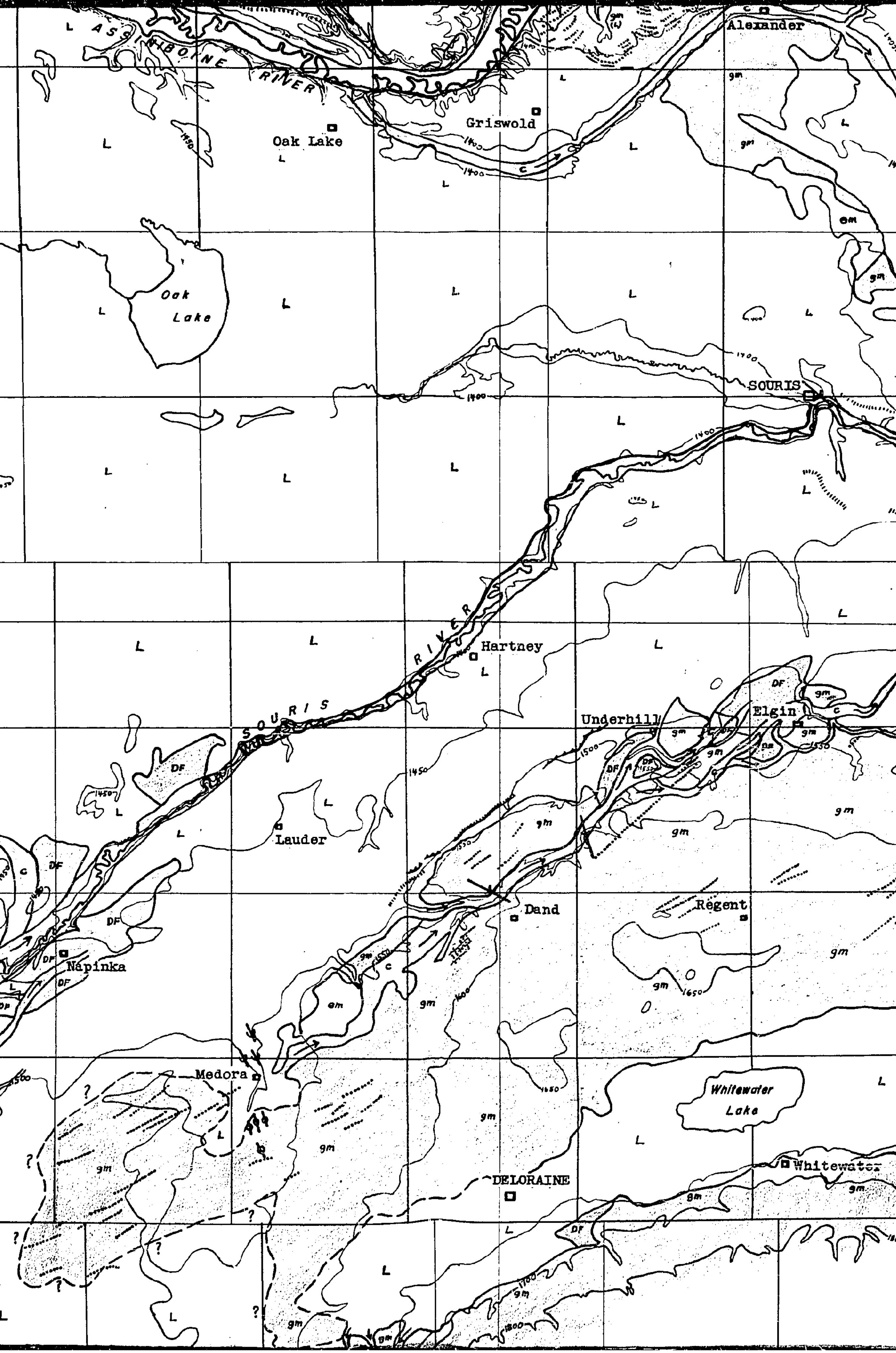
Strandlines: bars, scarps.

Contours are from Sectional Maps No. 21, 22, 71, 72, National Topographic Series (1 inch to 3 miles), some contours omitted. Geology based on field work by J.A. Elson, 1953.

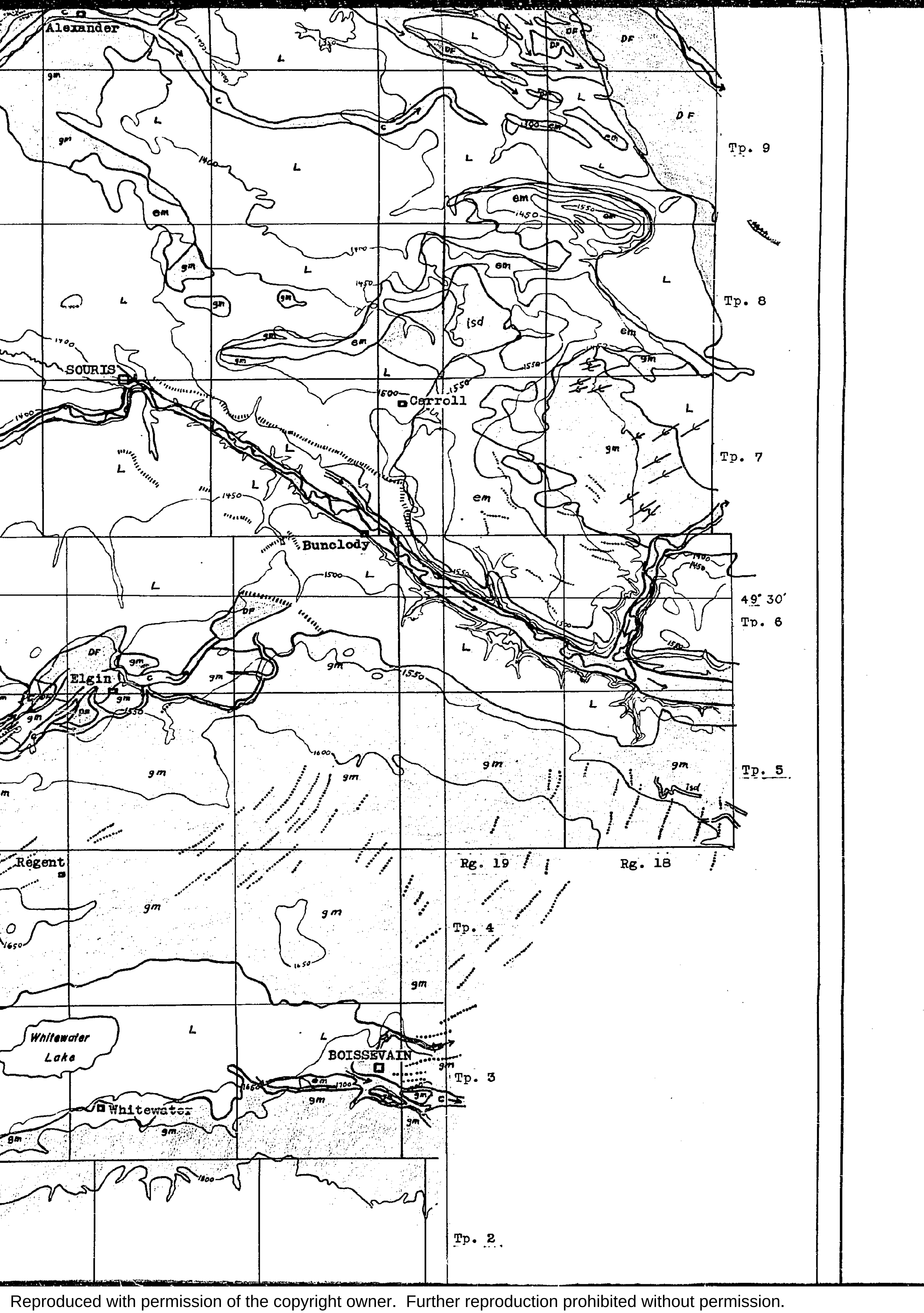




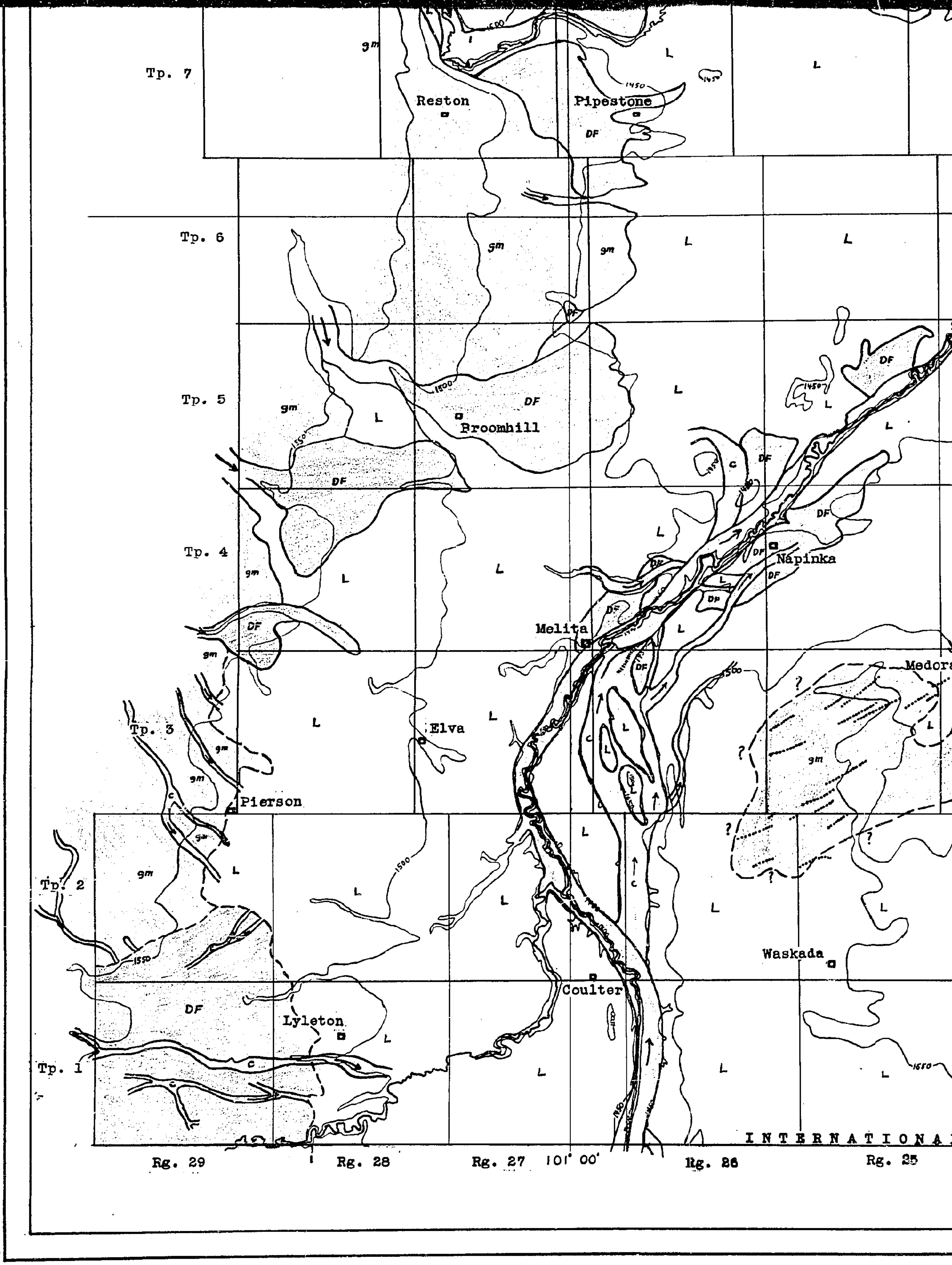
Tp. 9
Tp. 8
Tp. 7
Tp. 6
Tp. 5
Tp. 4
Tp. 3
Tp. 2
Scarth
Oak Lake
Reston
Pipestone
Broomhill
Napinka
Melita
Medora
Elva
Pierson
gm
DF
L

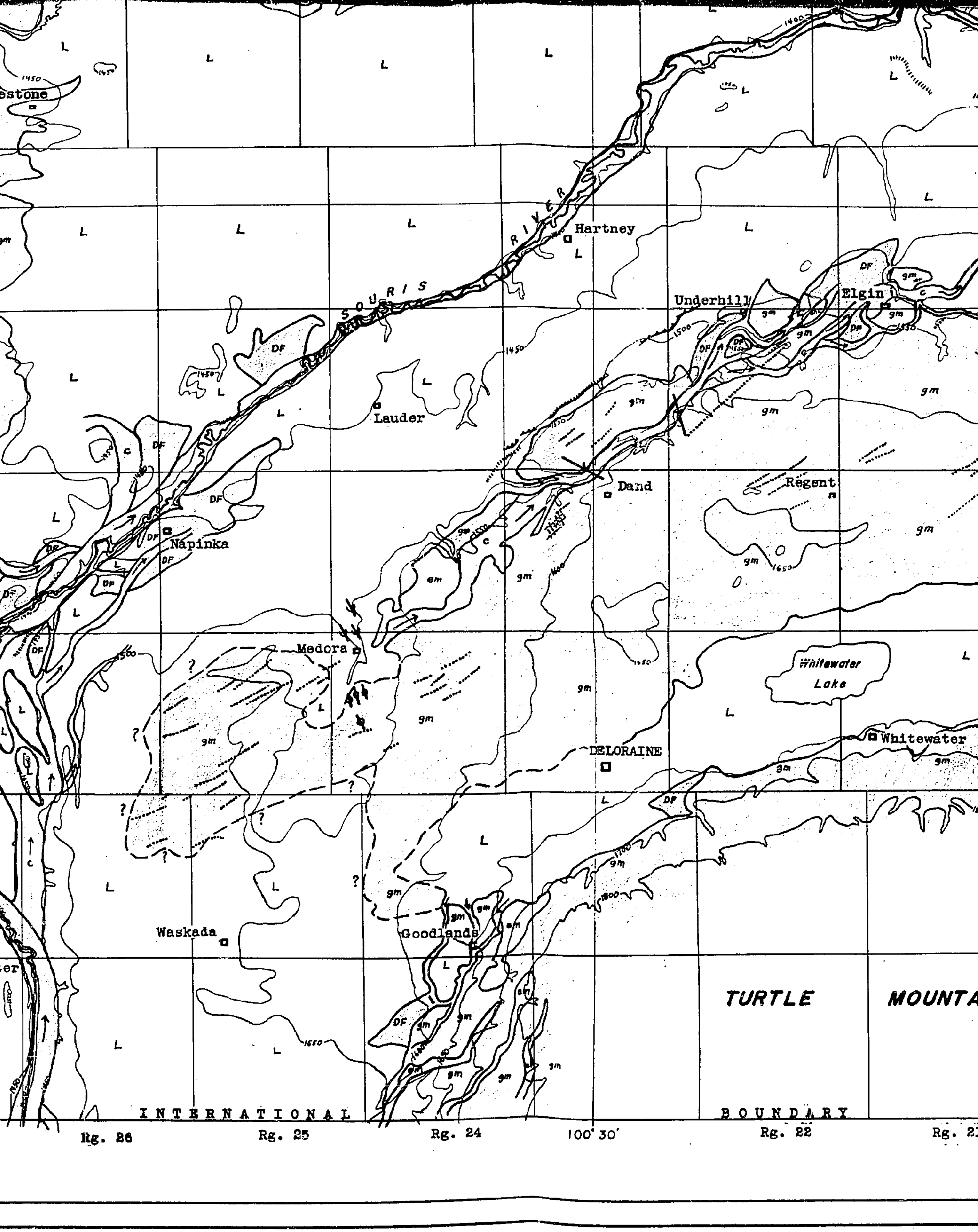


ASSINIBOINE RIVER
Alexander
Griswold
Oak Lake
Oak Lake
SOURIS
SOURIS RIVER
Hartney
Underhill
Elgin
Lauder
Dand
Regent
Napinka
Medora
Whitewater Lake
Whitewater
DELORAINE



Alexander
Tp. 9
Tp. 8
SOURIS
Carroll
Tp. 7
Bunclody
49° 30′
Tp. 6
Elgin
Tp. 5
Regent
Rg. 19
Rg. 18
Tp. 4
Whitewater Lake
BOISSEVAIN
Tp. 3
Whitewater
Tp. 2


Tp. 7
Reston
Pipestone
Tp. 6
Tp. 5
Broomhill
Tp. 4
Melita
Napinka
Tp. 3
Elva
Pierson
Tp. 2
Waskada
Coulter
Lyleton
Tp. 1
Rg. 29
Rg. 28
Rg. 27
101° 00'
Rg. 26
Rg. 25



SOURIS RIVER
Hartney
Underhill
Elgin
Lauder
Napinka
Dand
Regent
Medora
Whitewater Lake
Whitewater
DELORAINE
Waskada
Goodlands
TURTLE
MOUNTA
INTERNATIONAL
BOUNDARY
Rg. 26
Rg. 25
Rg. 24
100° 30′
Rg. 22

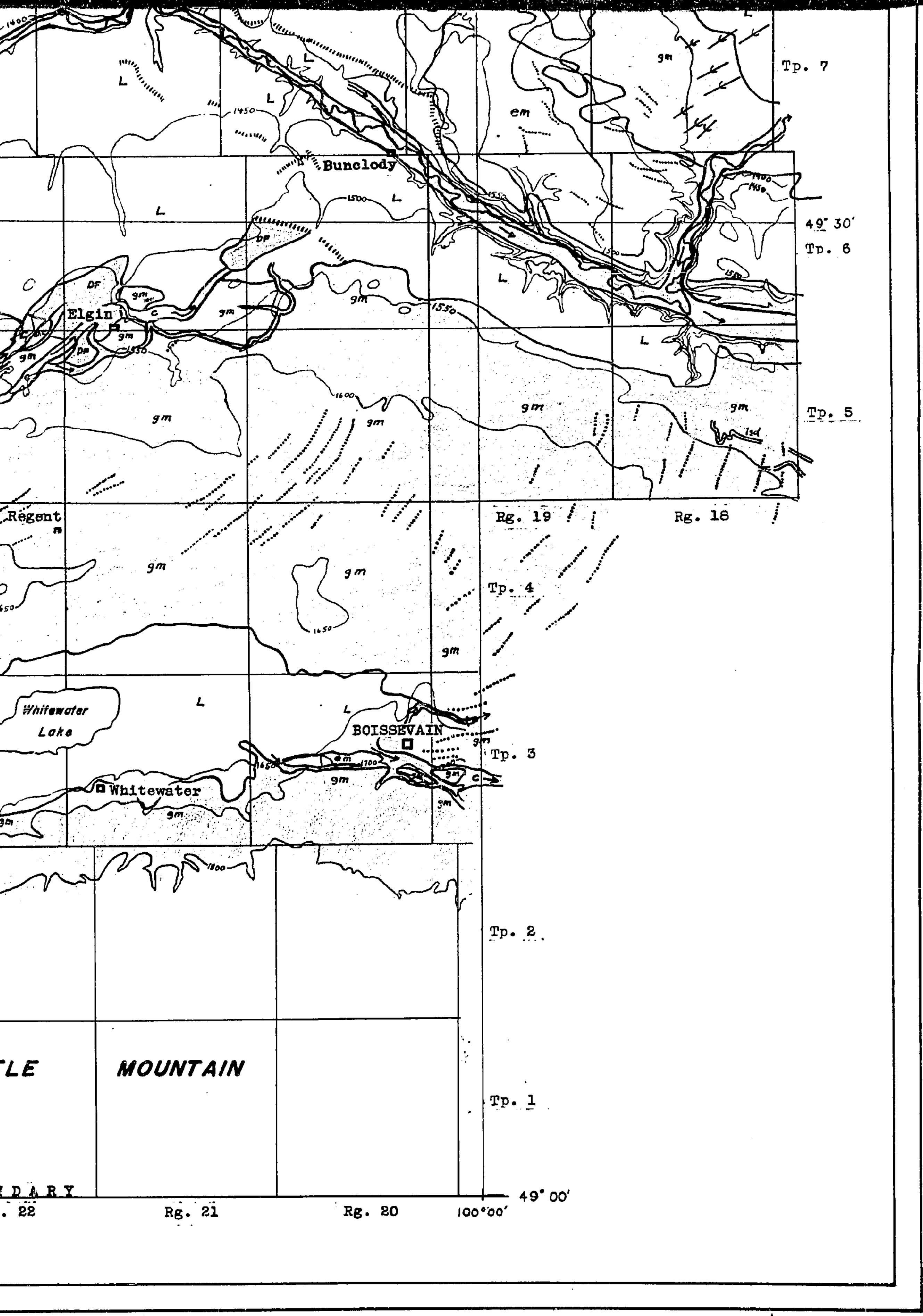

Tp. 7
Bunclody
49° 30'
Tp. 6
Elgin
Tp. 5
Regent
Rg. 19
Rg. 18
Tp. 4
Whitewater
Lake
BOISSEVAIN
Tp. 3
Whitewater
Tp. 2
MOUNTAIN
Tp. 1
49° 00'
Rg. 21
Rg. 20
100°00'
1450
1500
1550
1600
1650
1700
1800
L
gm
em
c

PLATE 7

PLEISTOCENE HISTORY OF THE TIGER HILLS REGION

AND ADJACENT AREAS

LEGEND

GLACIER MARGIN: STATIONARY, ADVANCING, RETREATING

DIRECTION OF GLACIER FLOW

STAGNANT ICE

END MORAINE (ACTIVE DEPOSITION)

SPILLWAY, CHANNEL: ACTIVE, ABANDONED, ASSUMED

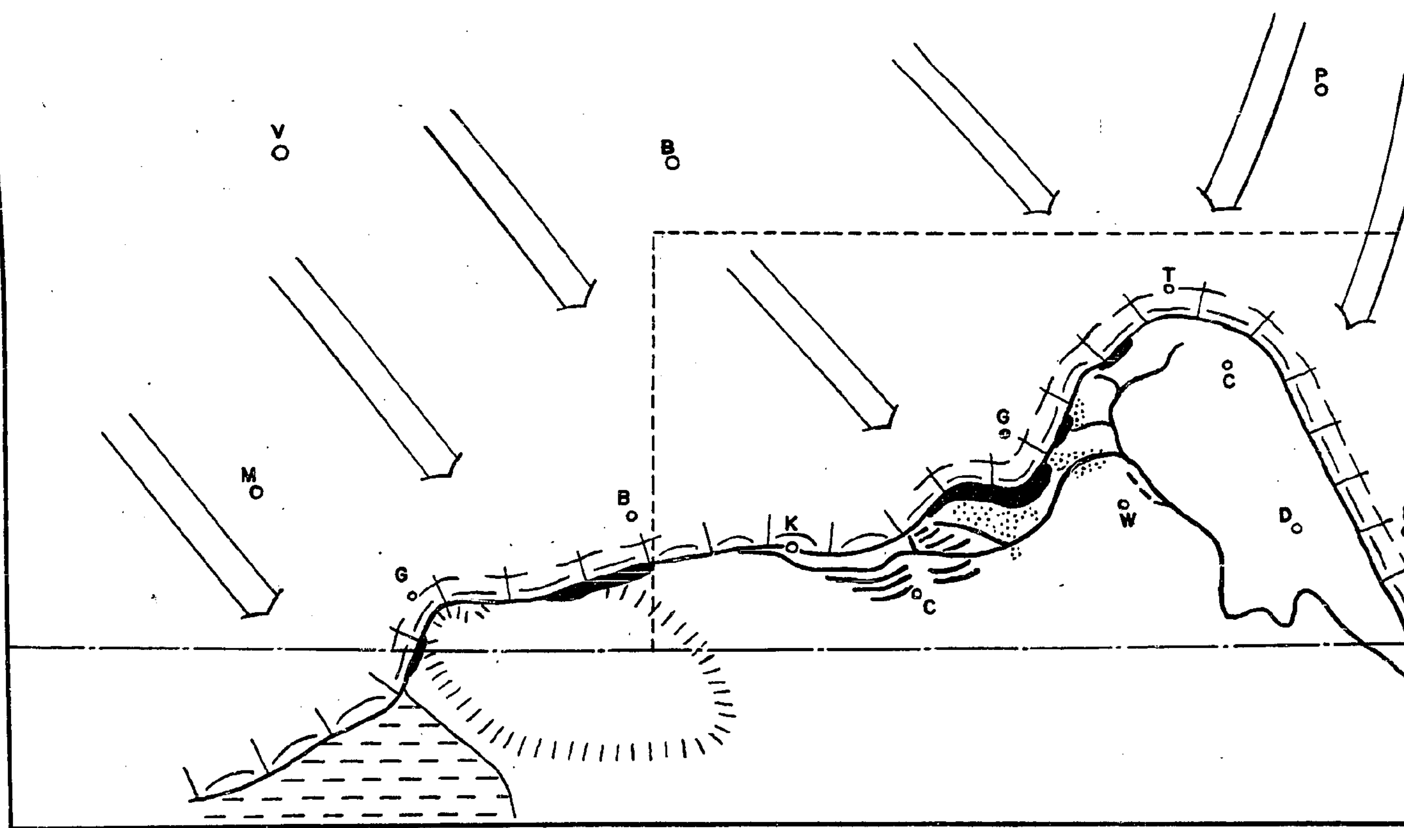
LAKE

DELTA, OUTWASH (ACTIVE DEPOSITION)

ALLUVIUM (ACTIVE DEPOSITION)

ESCARPMENT

C. WHITEMUD SPILLWAY PHASE

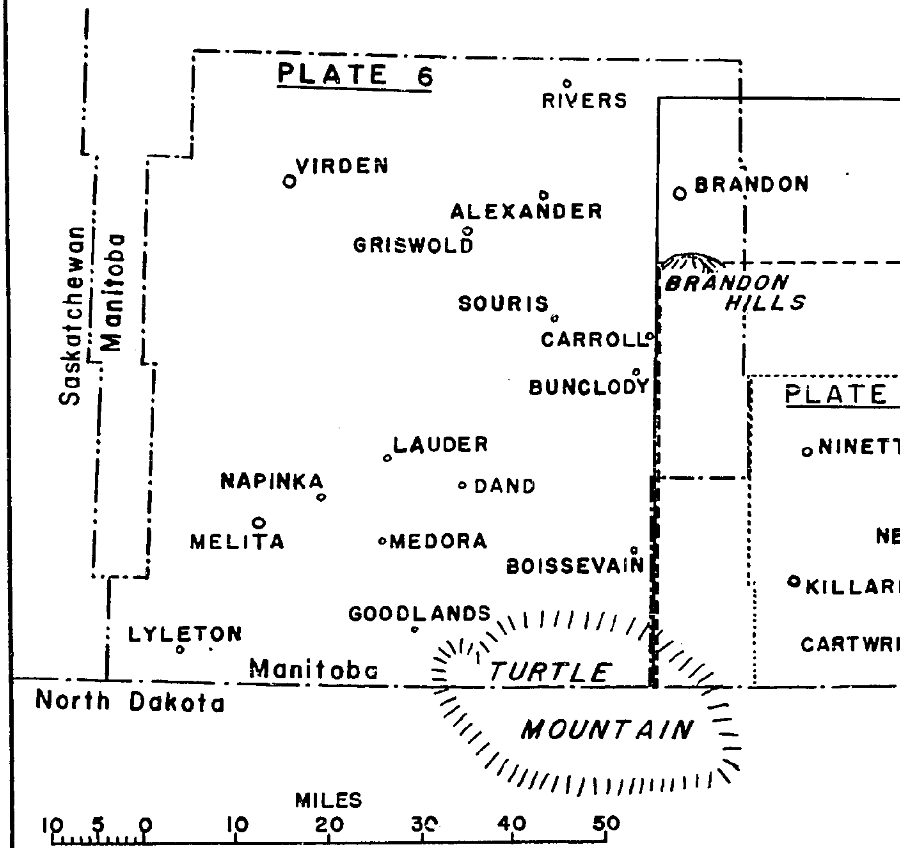


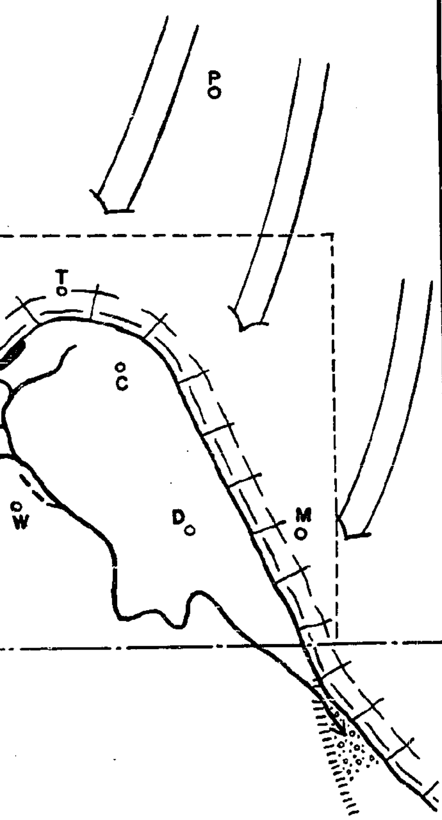
THE

TREATING

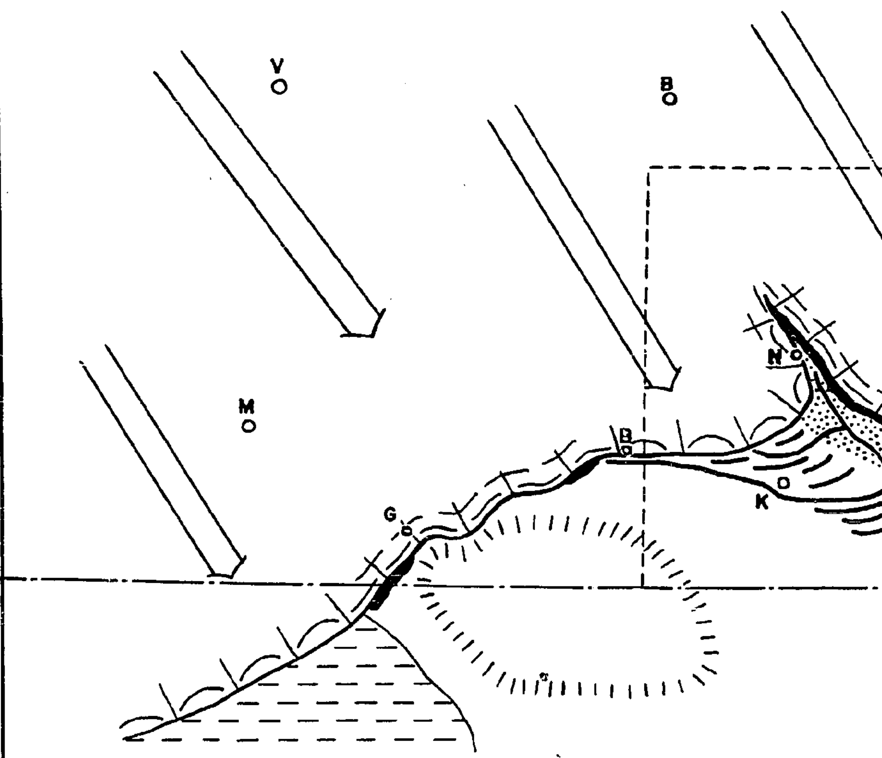
ASSUMED

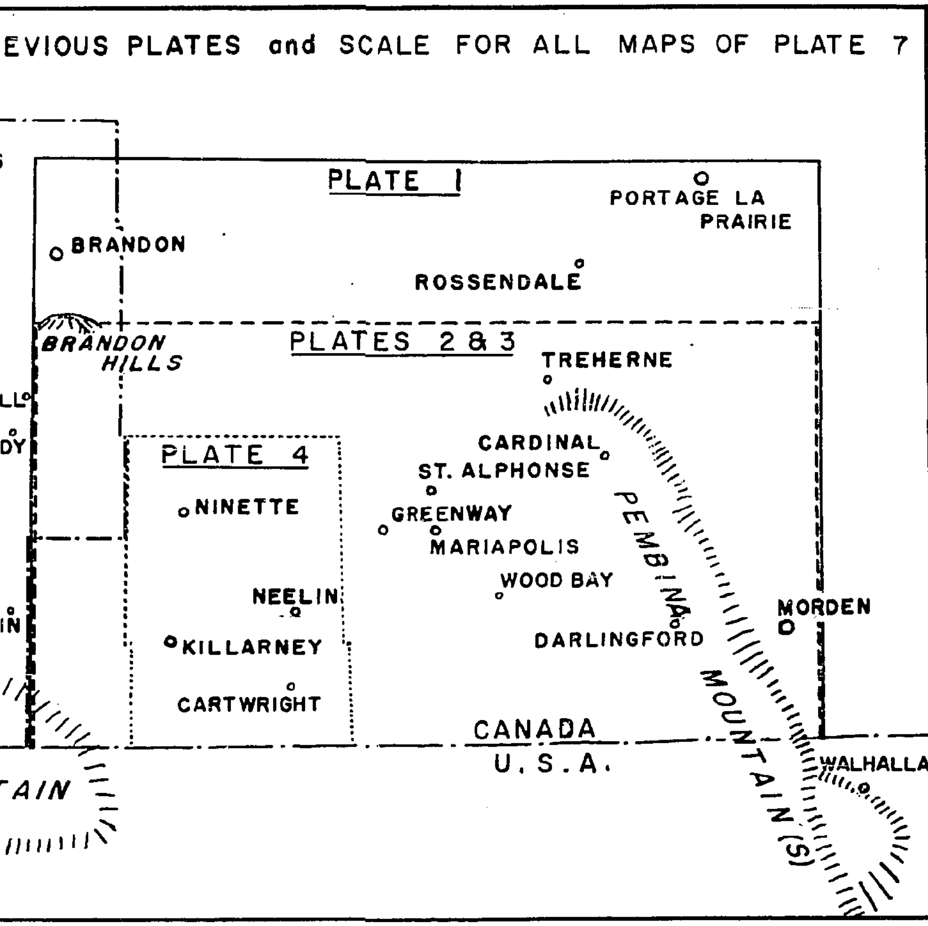
INDEX MAP WITH LOCATIONS OF PREVIOUS PLATES

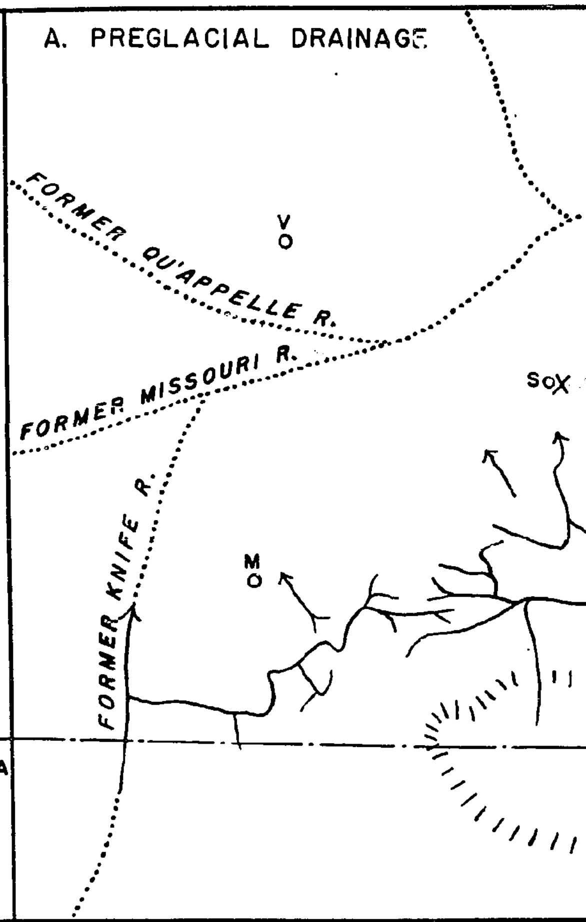


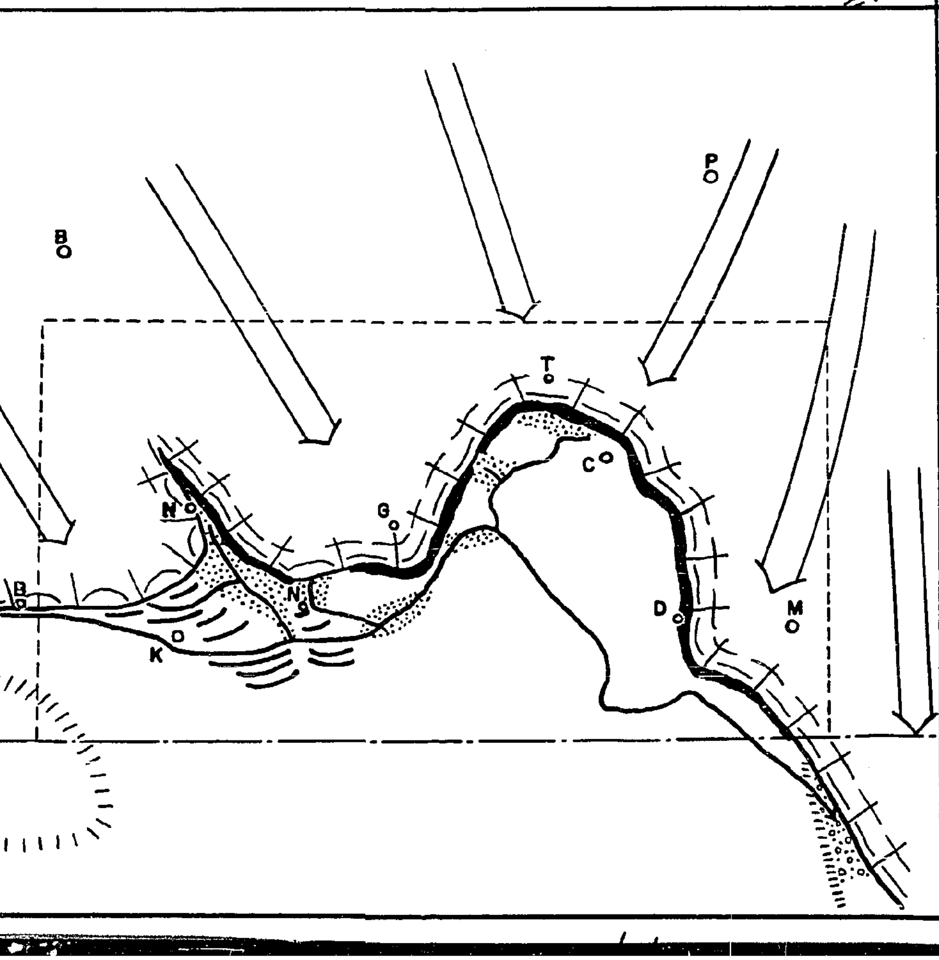


D. UPPER PEMBINA RIVER PHASE




EVIOUS PLATES and SCALE FOR ALL MAPS OF PLATE 7
PLATE 1
PORTAGE LA PRAIRIE
BRANDON
ROSSENDALE
BRANDON HILLS
PLATES 2 & 3
TREHERNE
PLATE 4
CARDINAL
ST. ALPHONSE
NINETTE
GREENWAY
MARIAPOLIS
PEMBINA MOUNTAIN(S)
WOOD BAY
NEELIN
MORDEN
KILLARNEY
DARLINGFORD
CARTWRIGHT
CANADA
U.S.A.
WALHALLA
TAIN


A. PREGLACIAL DRAINAGE
FORMER QU'APPELLE R.
V
FORMER MISSOURI R.
SOX
FORMER KNIFE R.
M


P
B
T
C
N
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B
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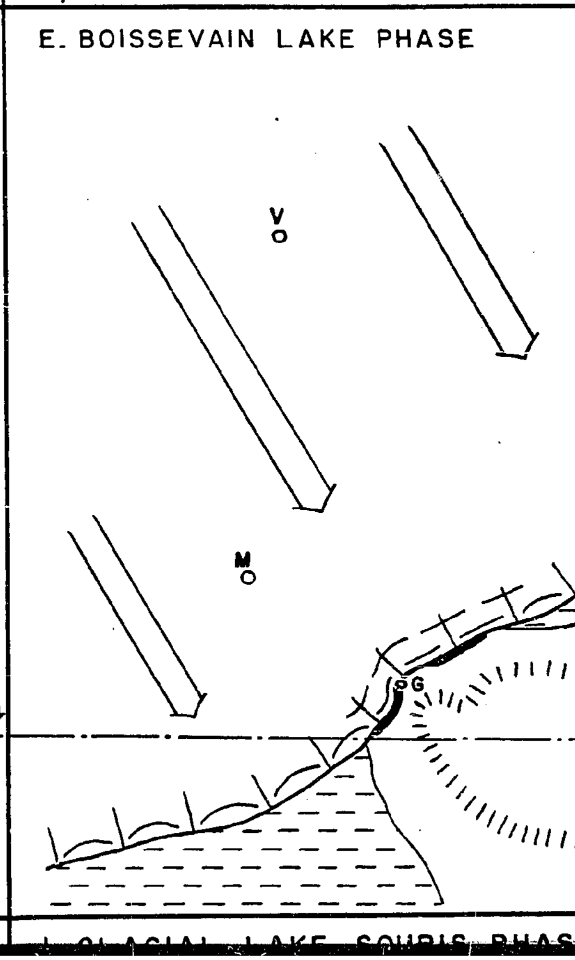
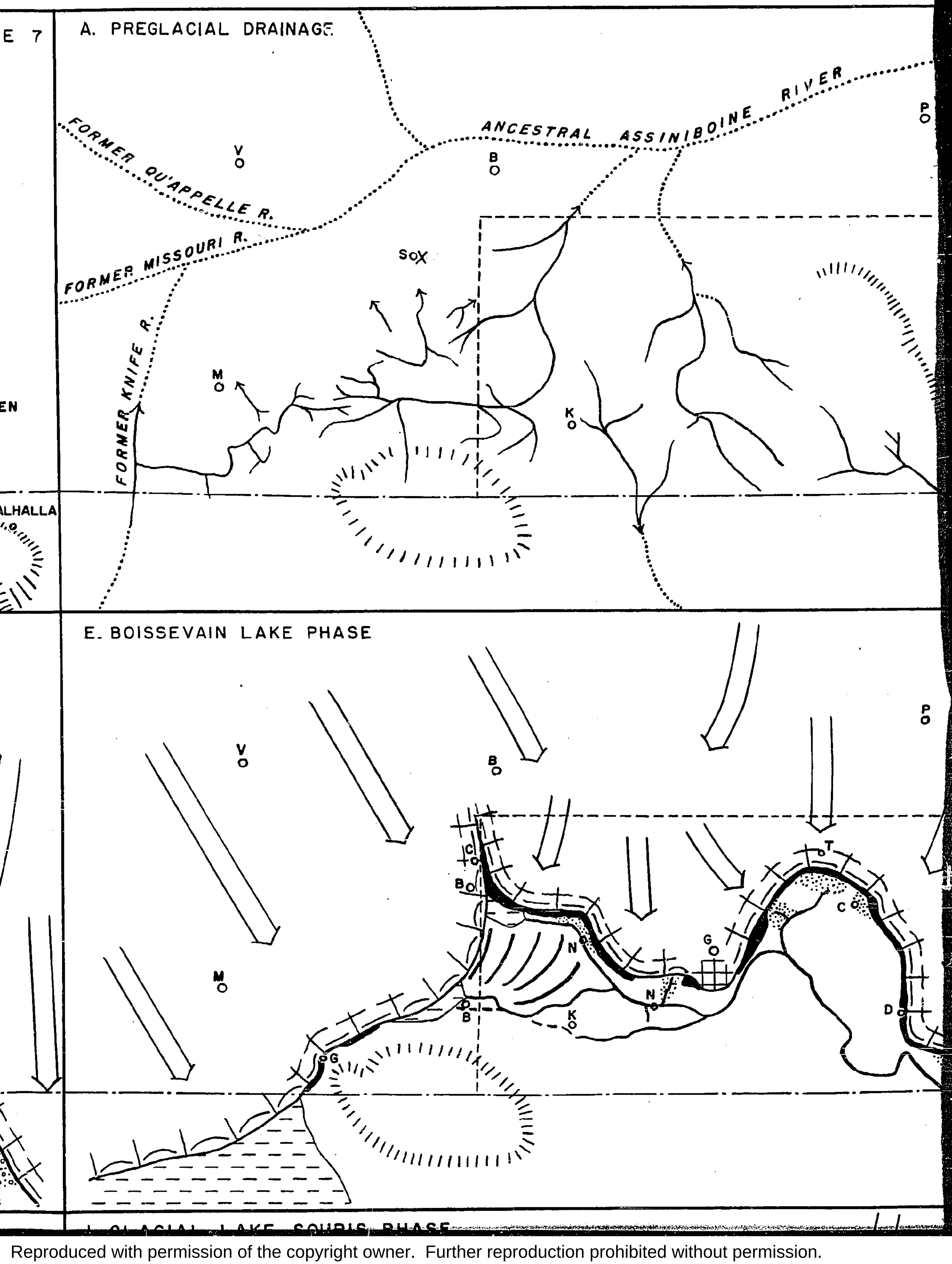
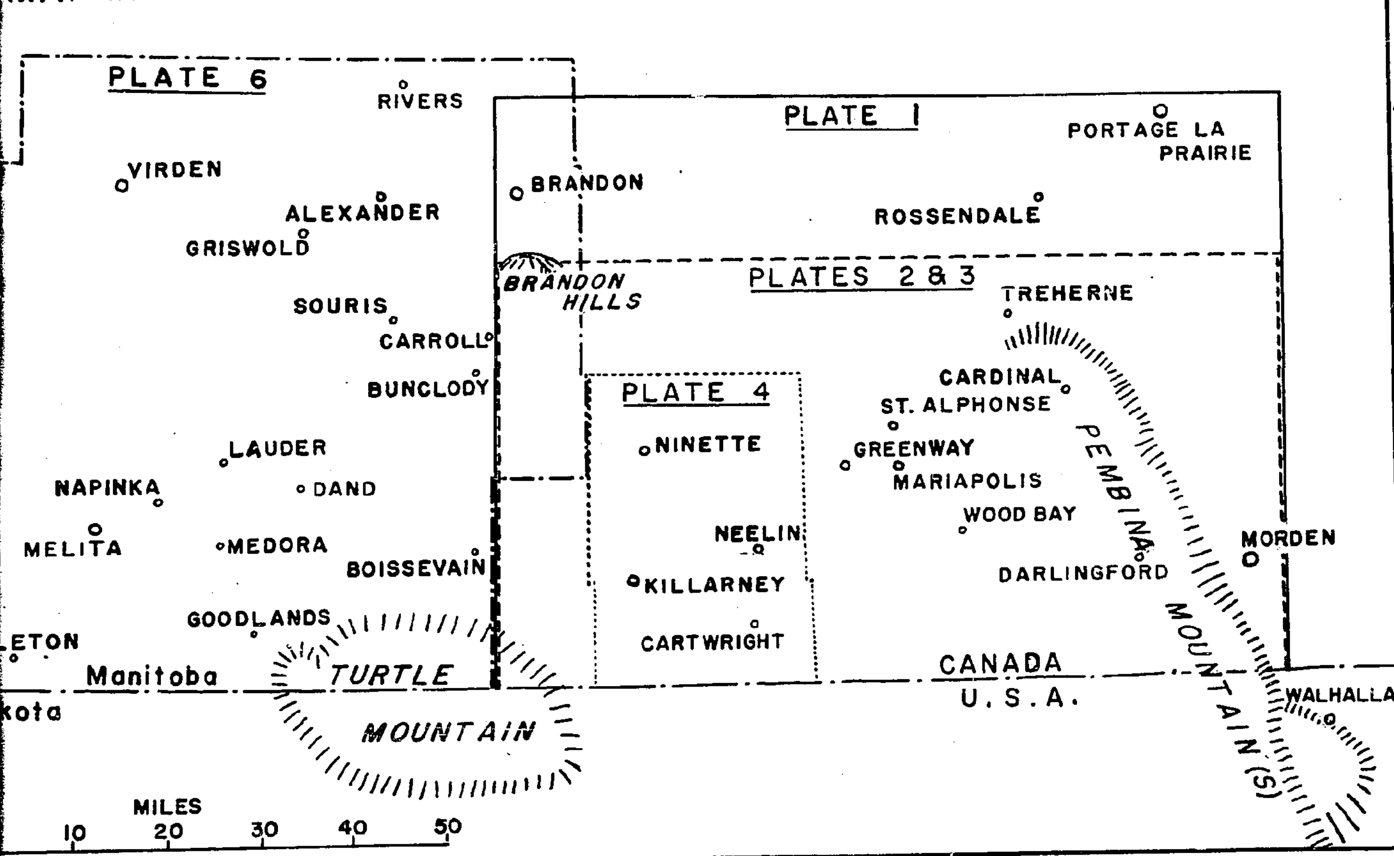
M
K

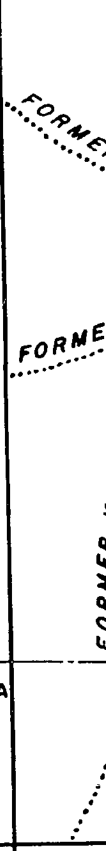

E. BOISSEVAIN LAKE PHASE
V
M
G


E 7
A. PREGLACIAL DRAINAGE
FORMER QU'APPELLE R.
ANCESTRAL ASSINIBOINE RIVER
FORMER MISSOURI R.
FORMER KNIFE R.
EN
ALHALLA
E. BOISSEVAIN LAKE PHASE

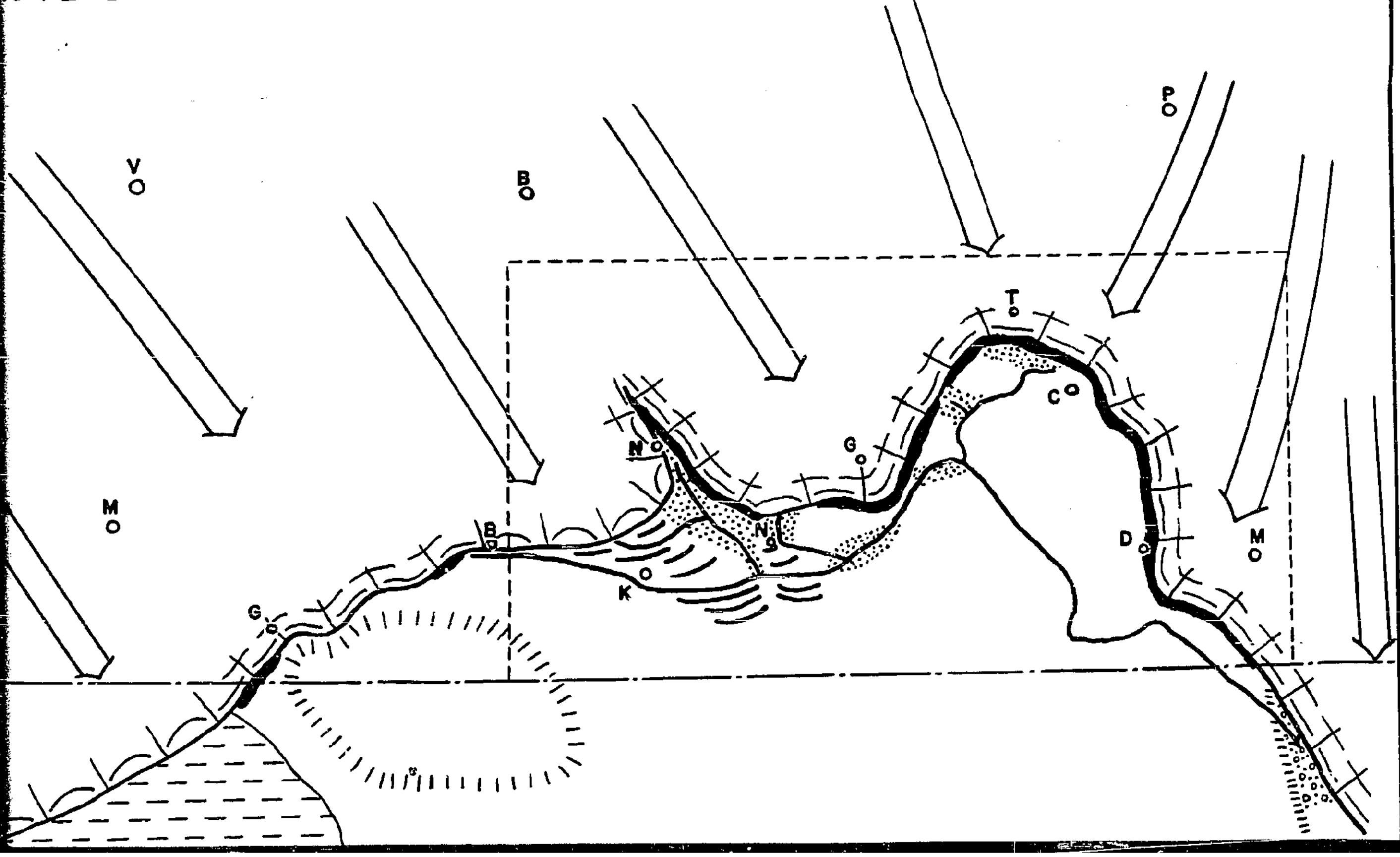
MAP WITH LOCATIONS OF PREVIOUS PLATES and SCALE FOR ALL MAPS OF PLATE 7



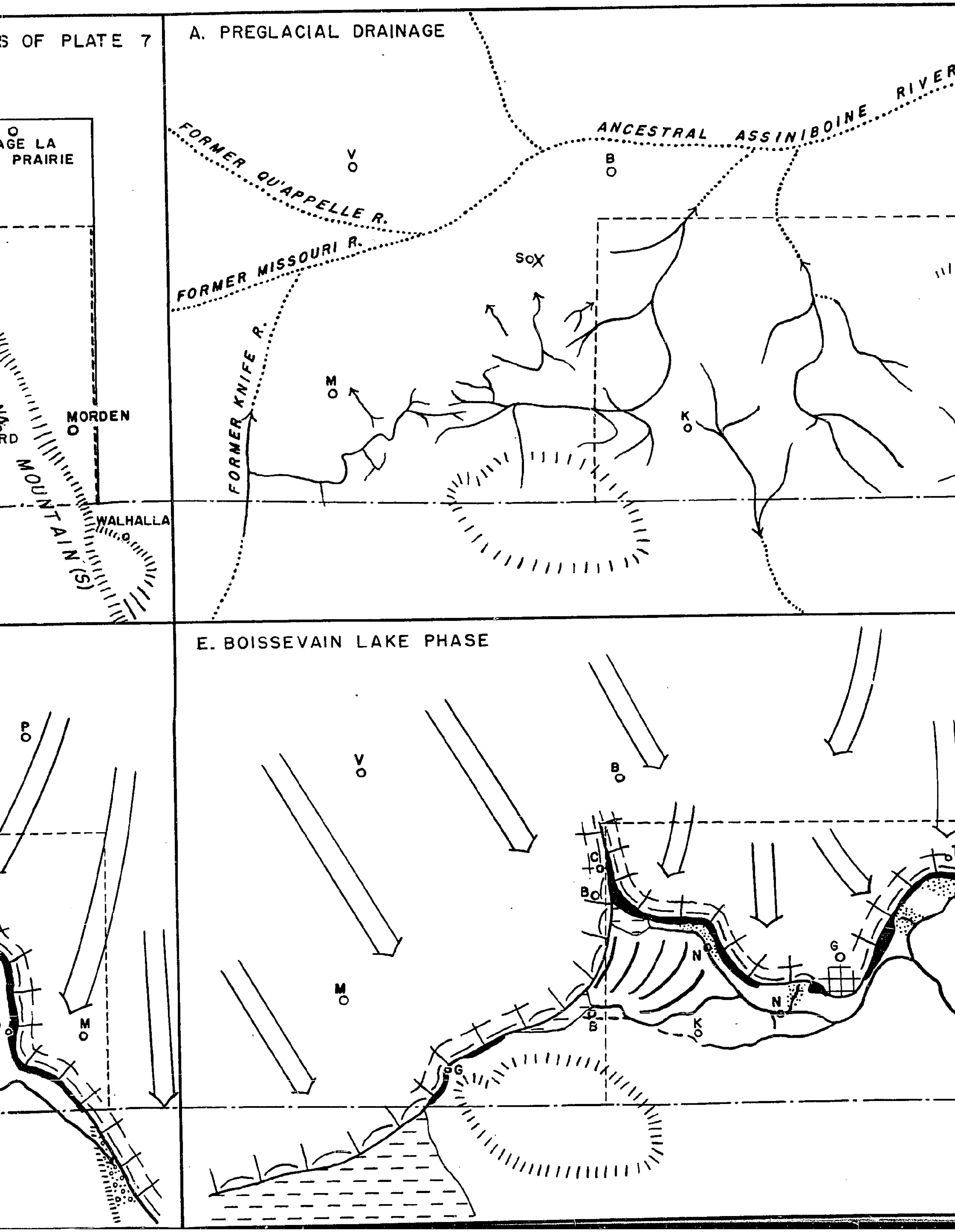
A. P

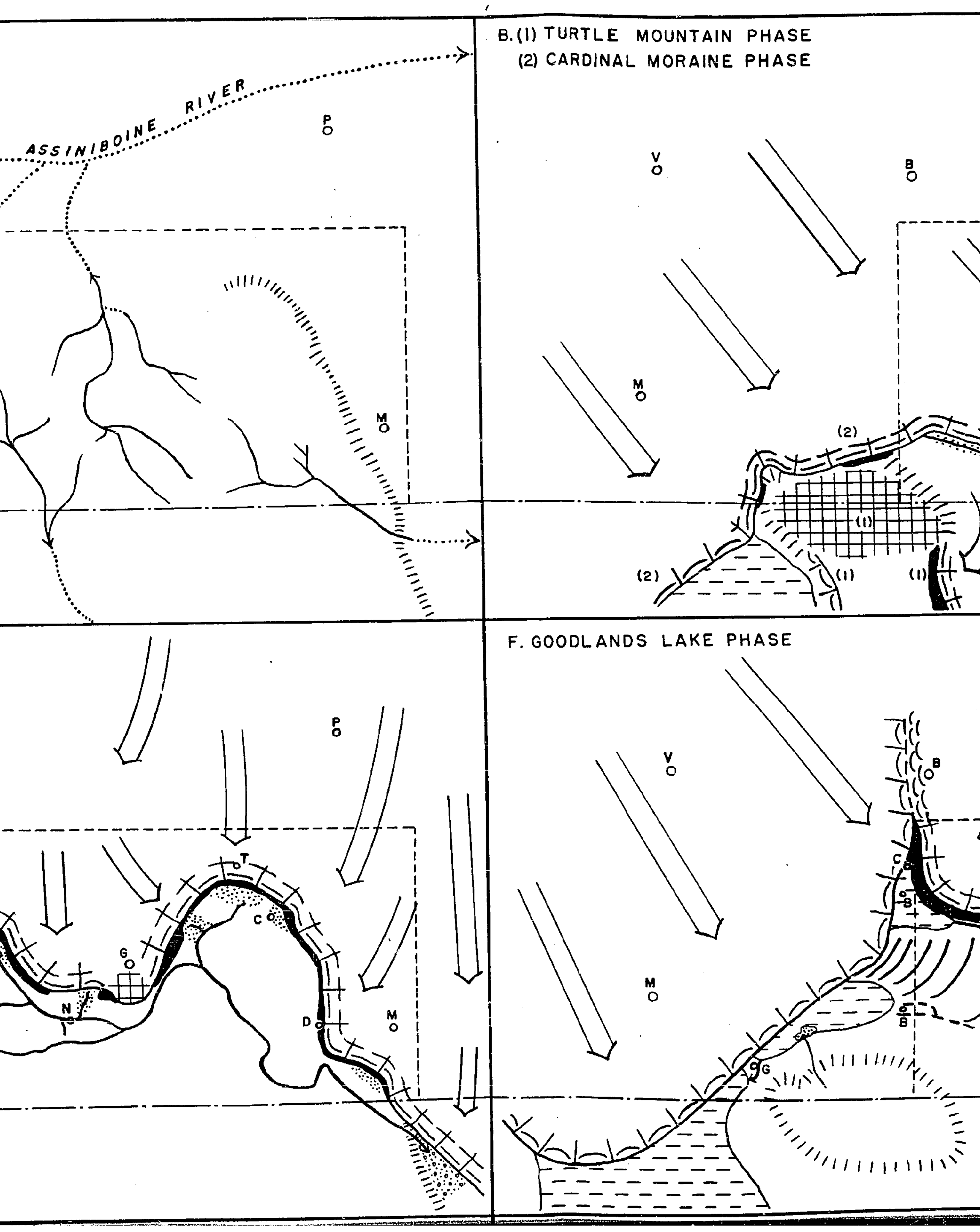


R PEMBINA RIVER PHASE

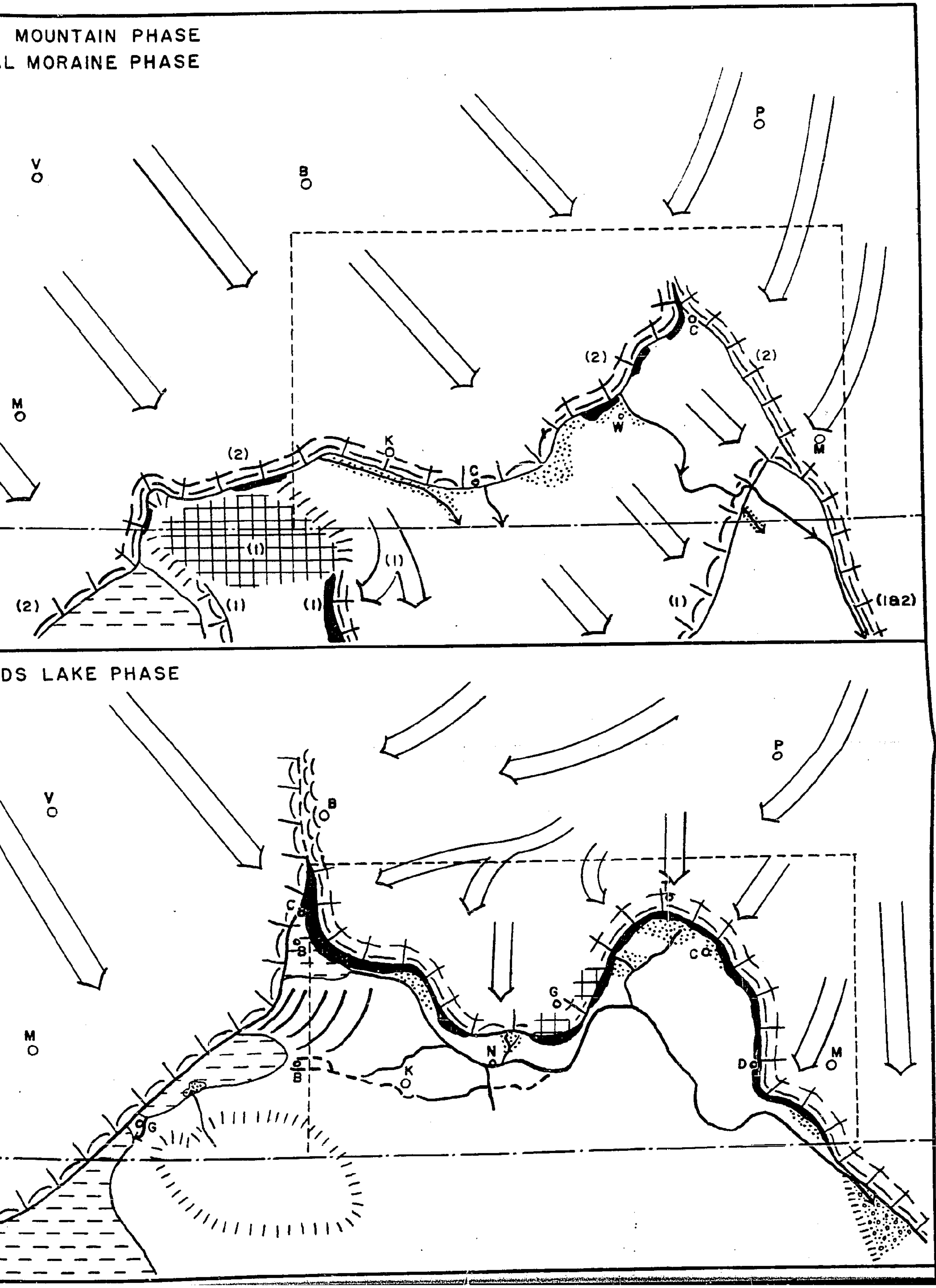


E. B


S OF PLATE 7
AGE LA PRAIRIE
MORDEN
MOUNTAIN (S)
WALHALLA
A. PREGLACIAL DRAINAGE
FORMER QU'APPELLE R.
FORMER MISSOURI R.
FORMER KNIFE R.
ANCESTRAL ASSINIBOINE RIVER
V
B
S
M
K
E. BOISSEVAIN LAKE PHASE
P
M
V
B
C
B
N
G
N
K
B
G



B. (1) TURTLE MOUNTAIN PHASE
(2) CARDINAL MORAINE PHASE
F. GOODLANDS LAKE PHASE
ASSINIBOINE RIVER


MOUNTAIN PHASE
L MORAINE PHASE
DS LAKE PHASE
V
B
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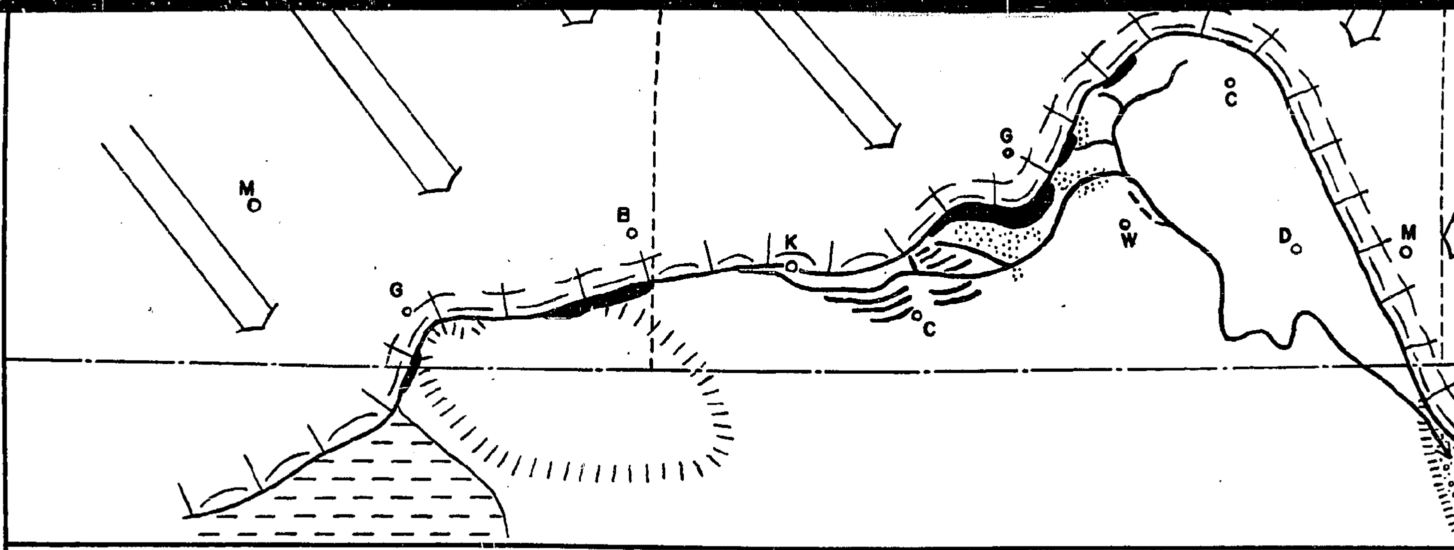
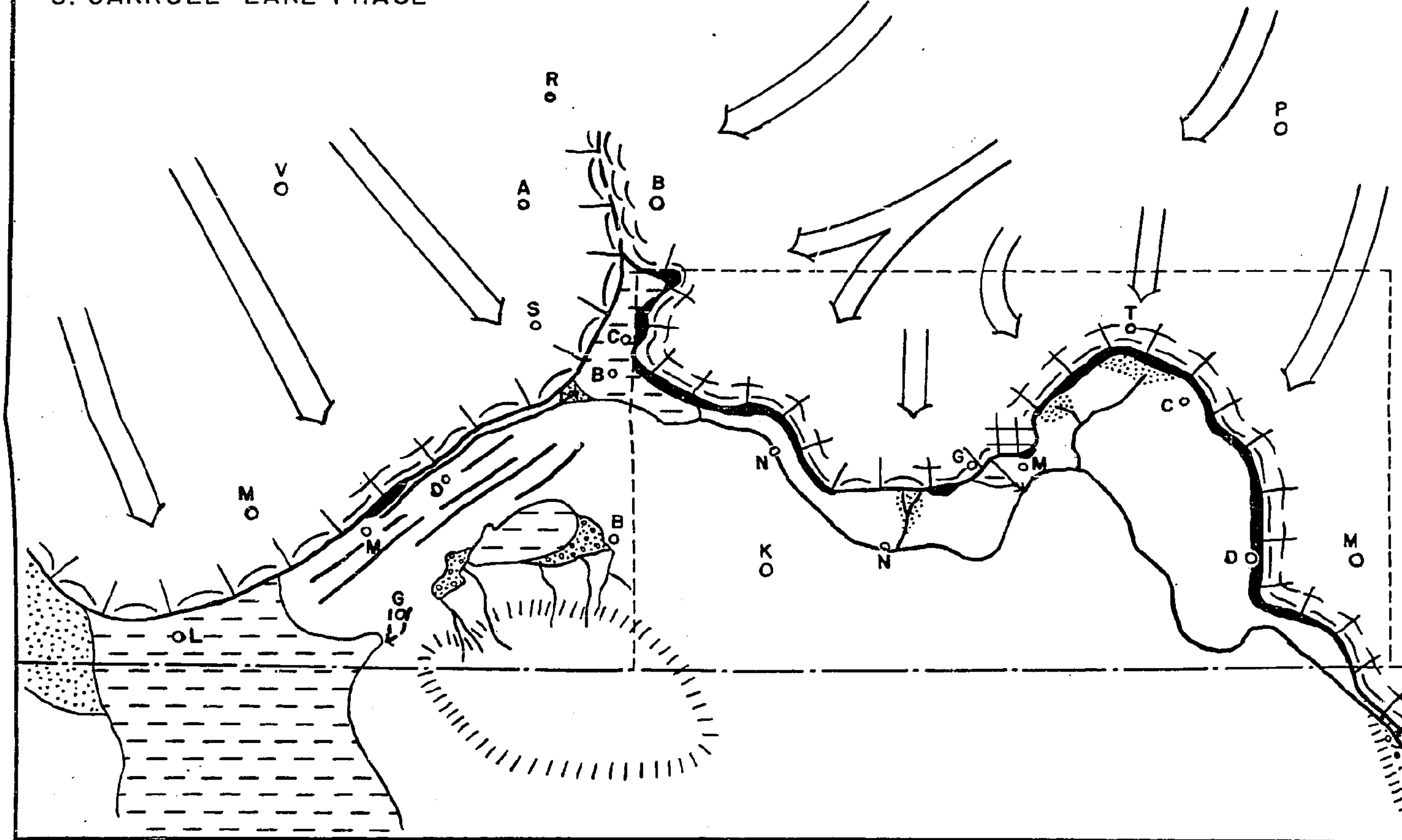
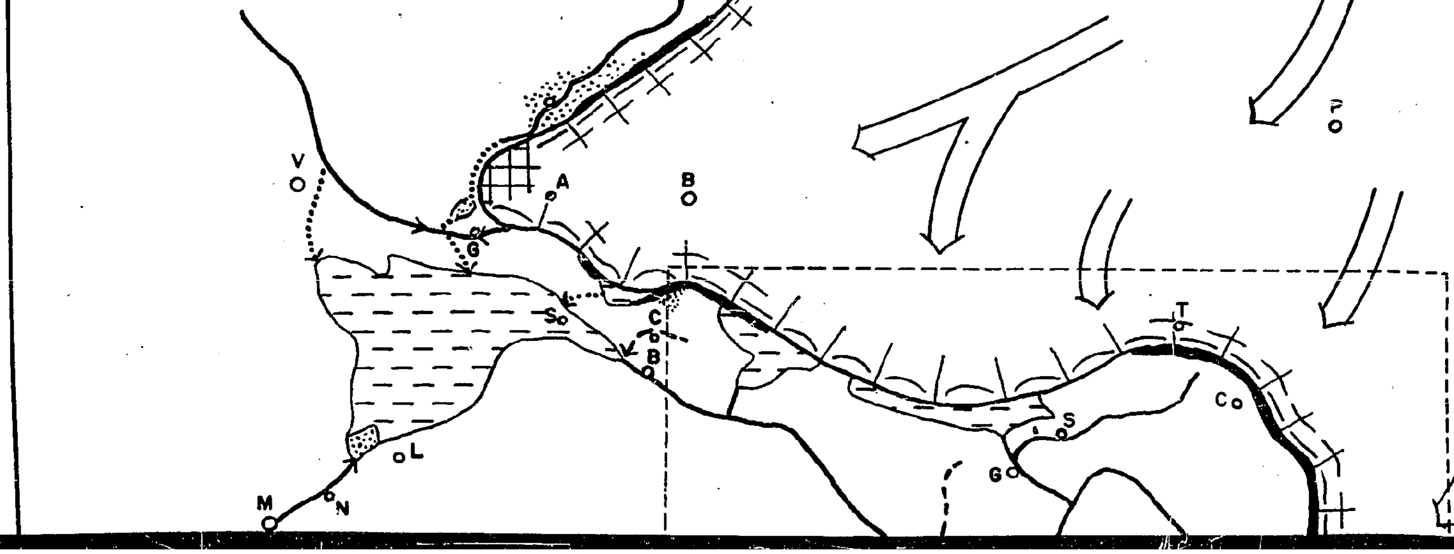
W
(1)
(2)
(1&2)
N
G
D

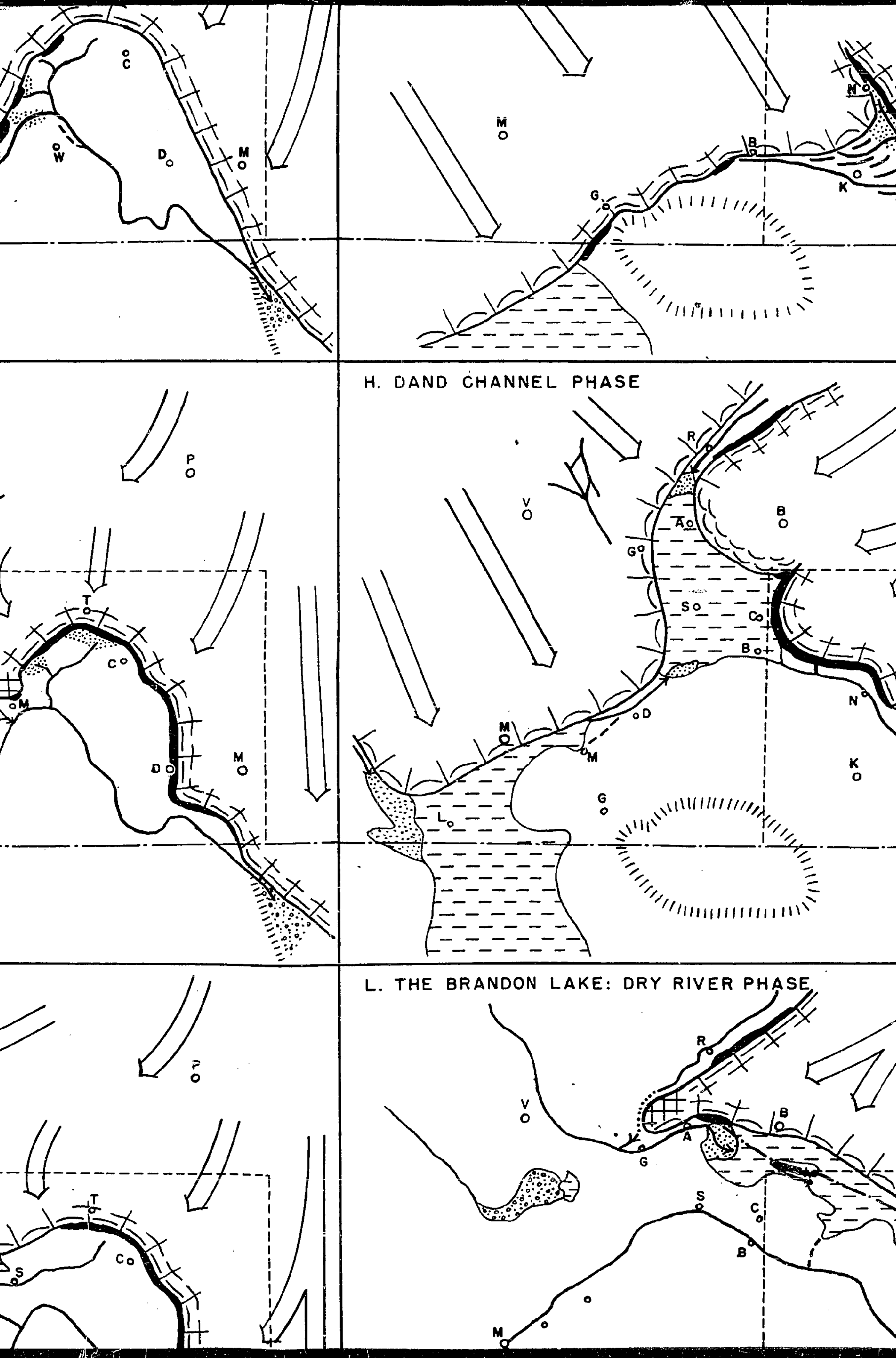


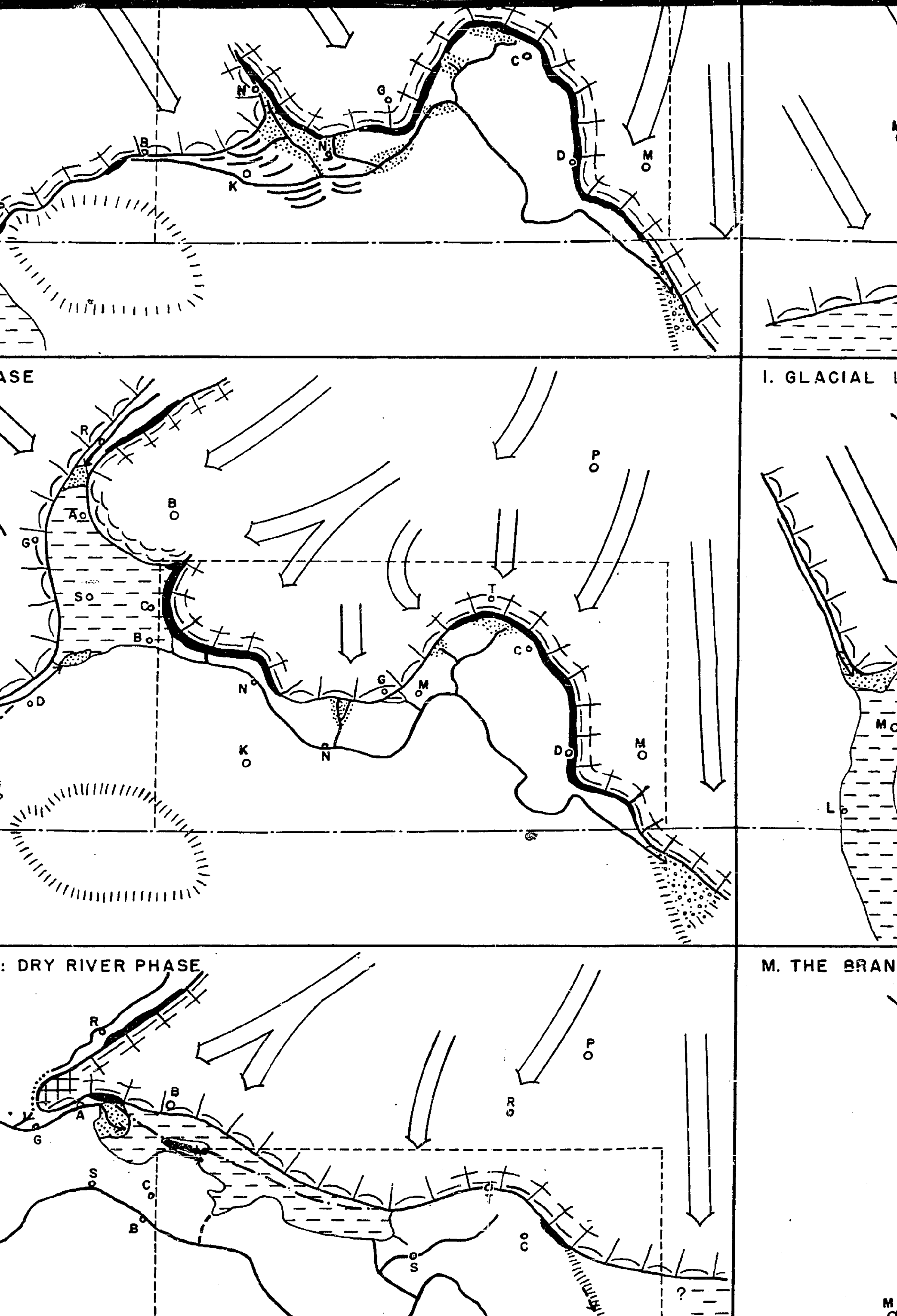
G. CARROLL LAKE PHASE



K. LAKE HIND: LAUDER PHASE




H. DAND CHANNEL PHASE
L. THE BRANDON LAKE: DRY RIVER PHASE


ASE
I. GLACIAL L
: DRY RIVER PHASE
M. THE BRAN
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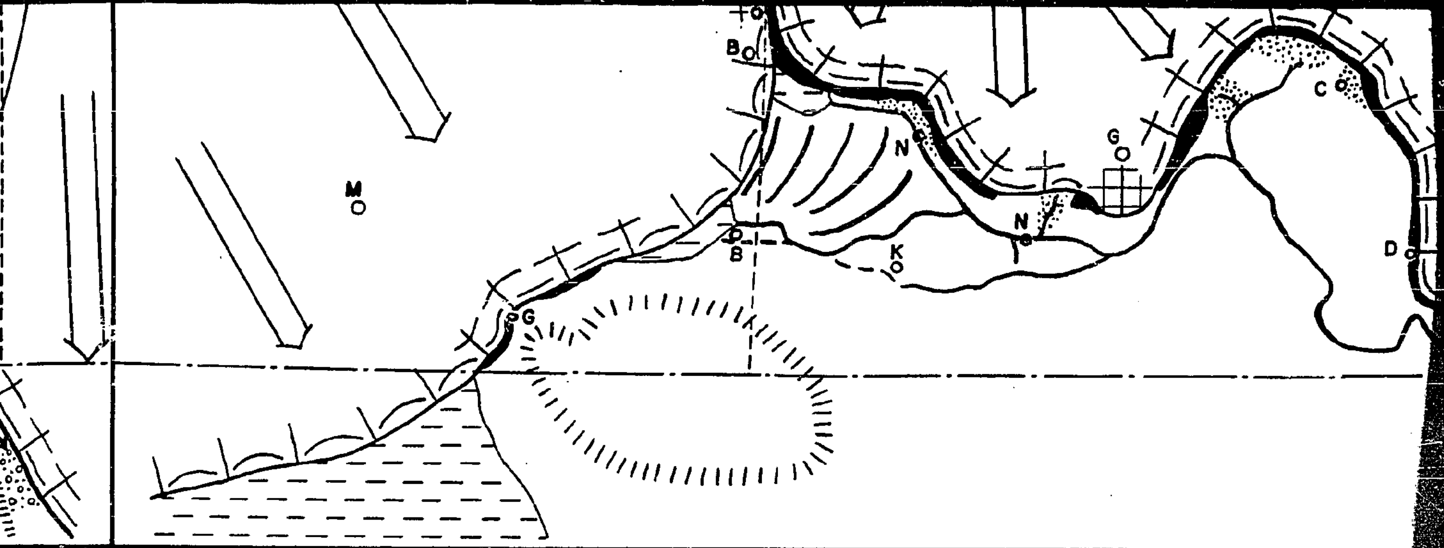
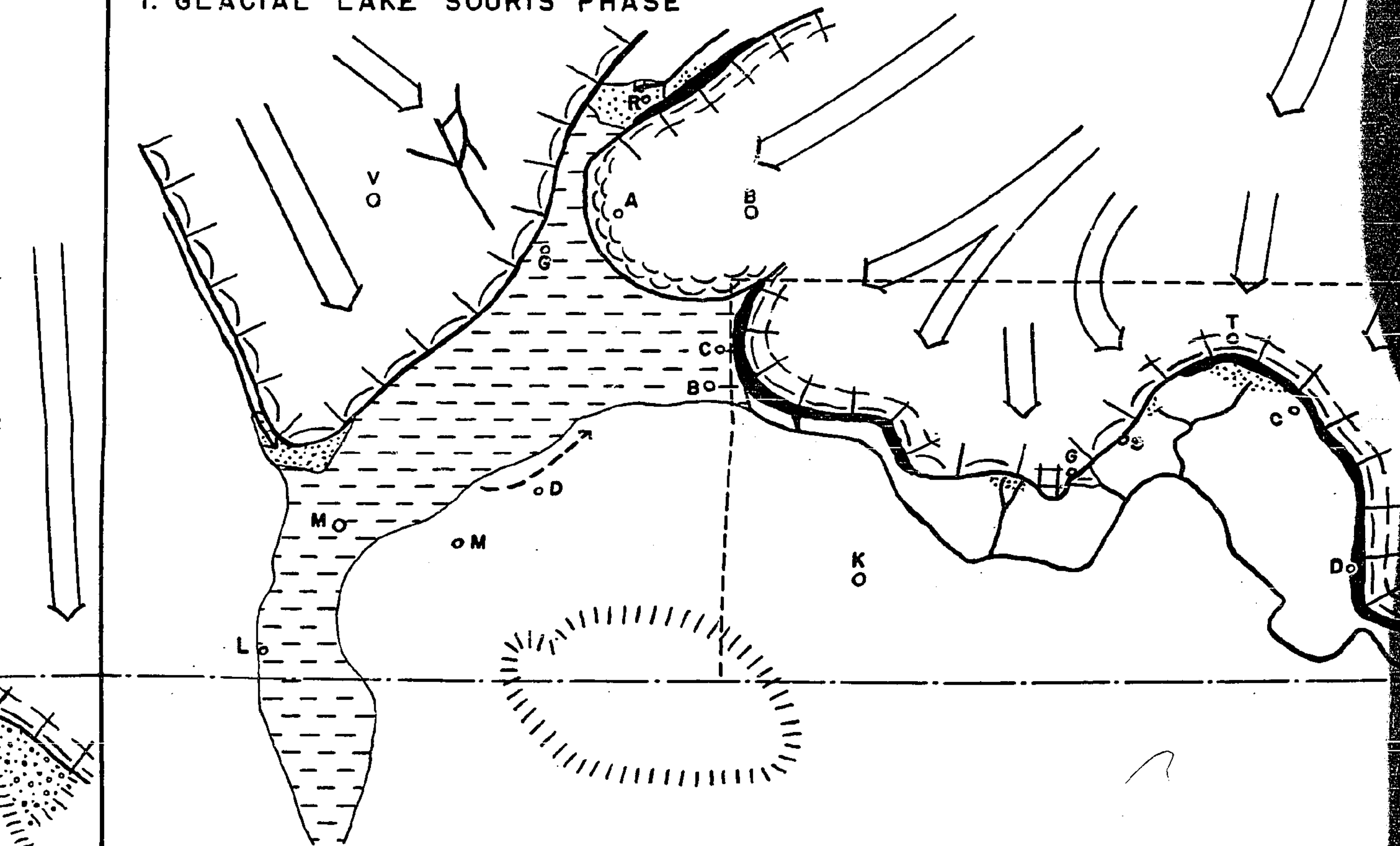
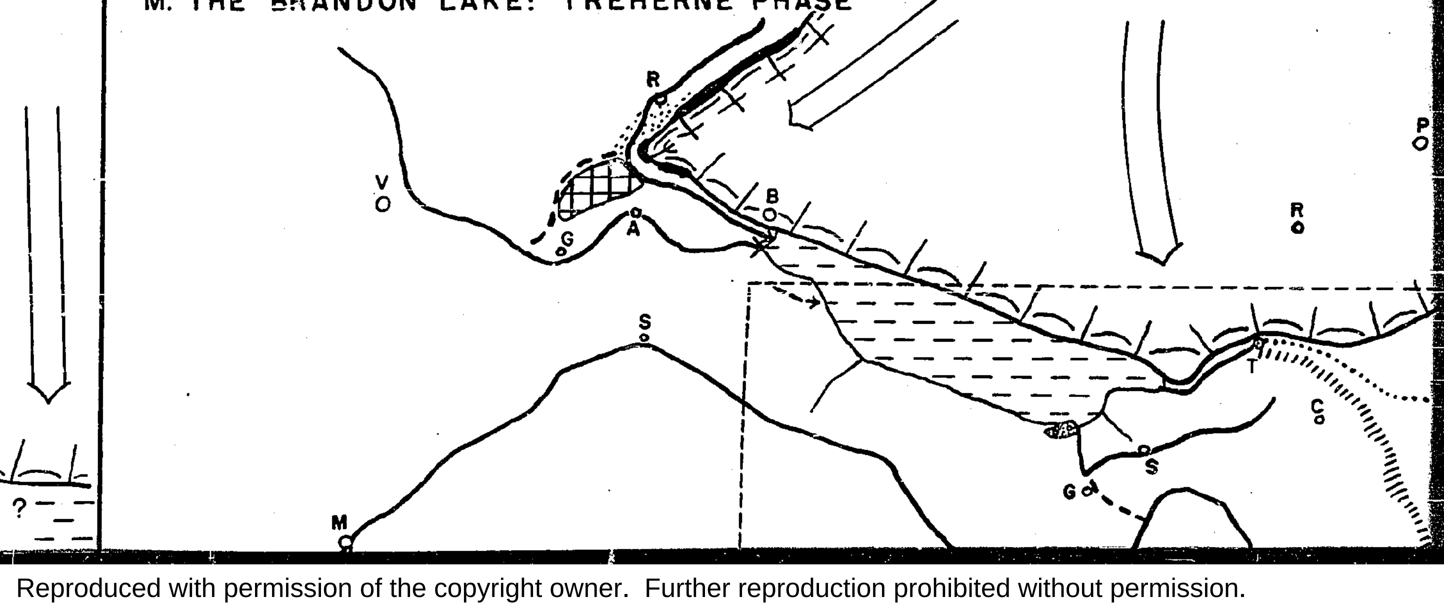
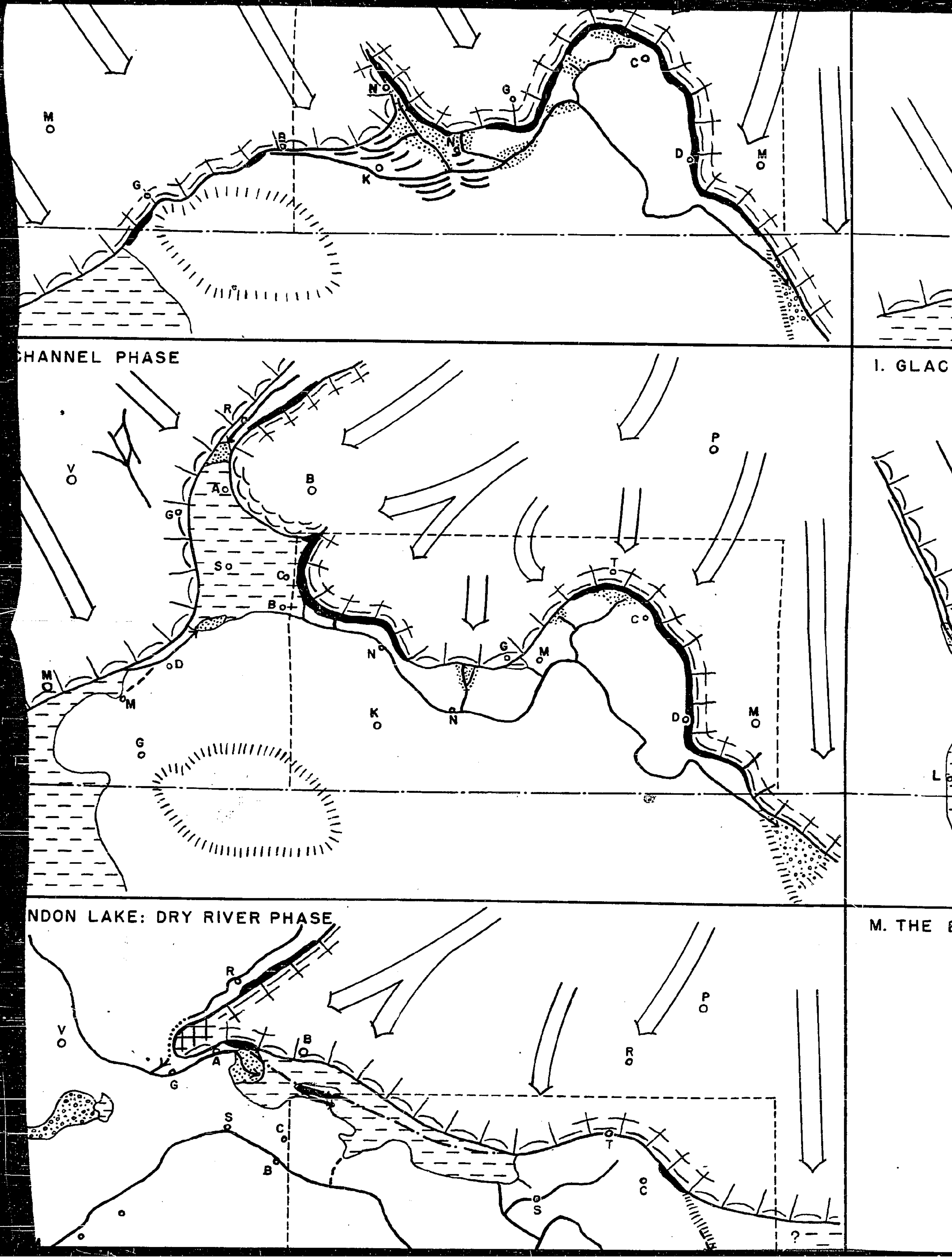


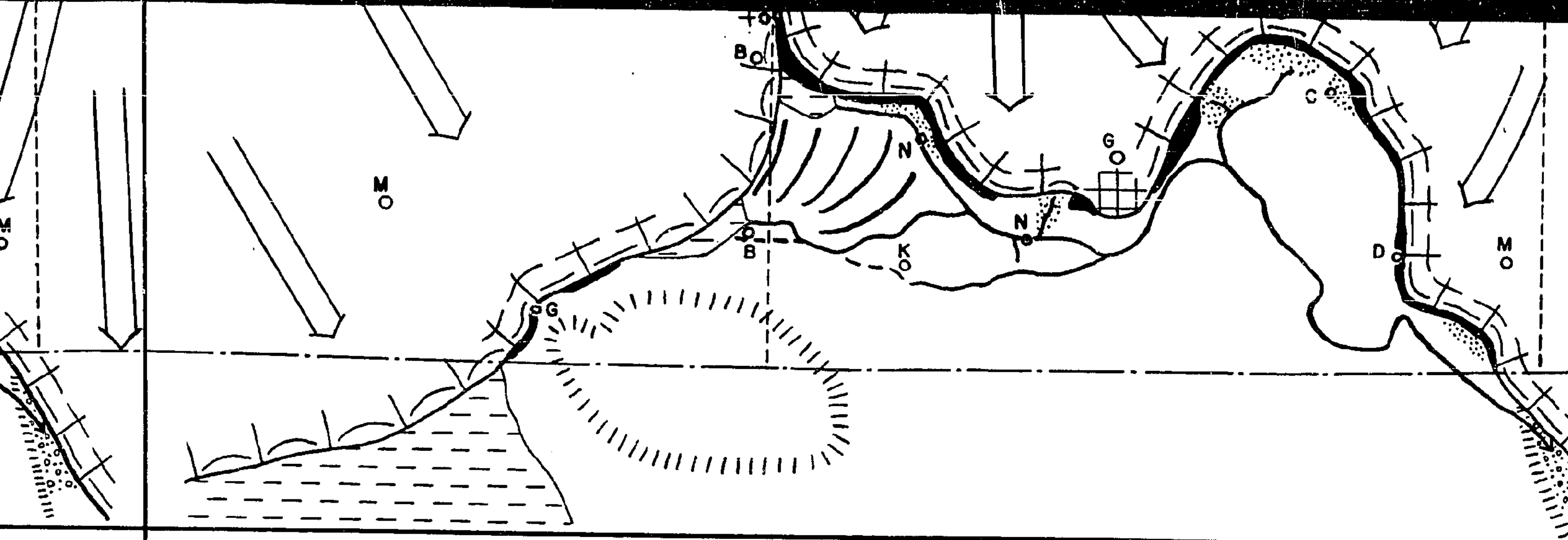
I. GLACIAL LAKE SOURIS PHASE



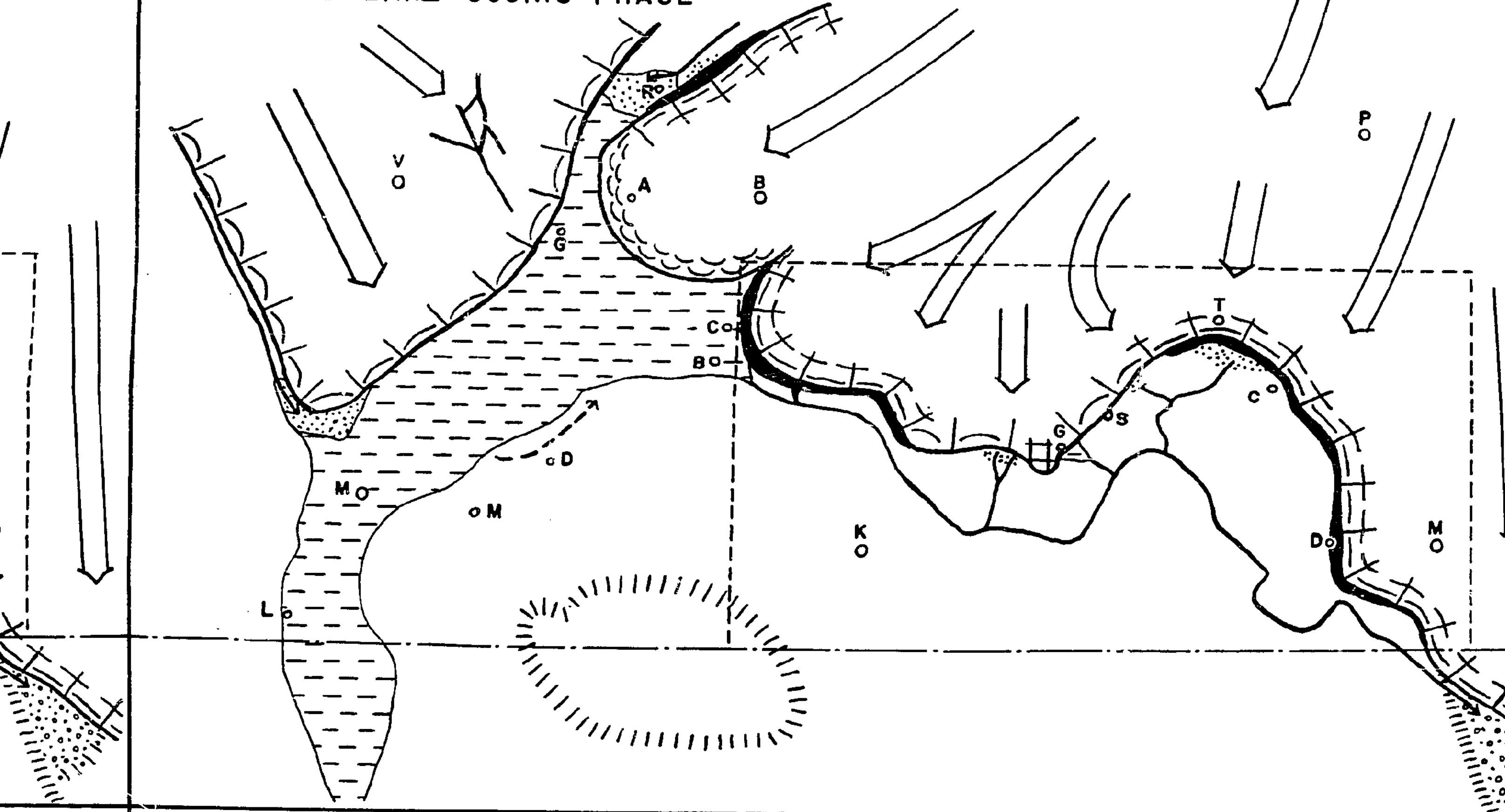
M. THE BRANDON LAKE: TREHERNE PHASE



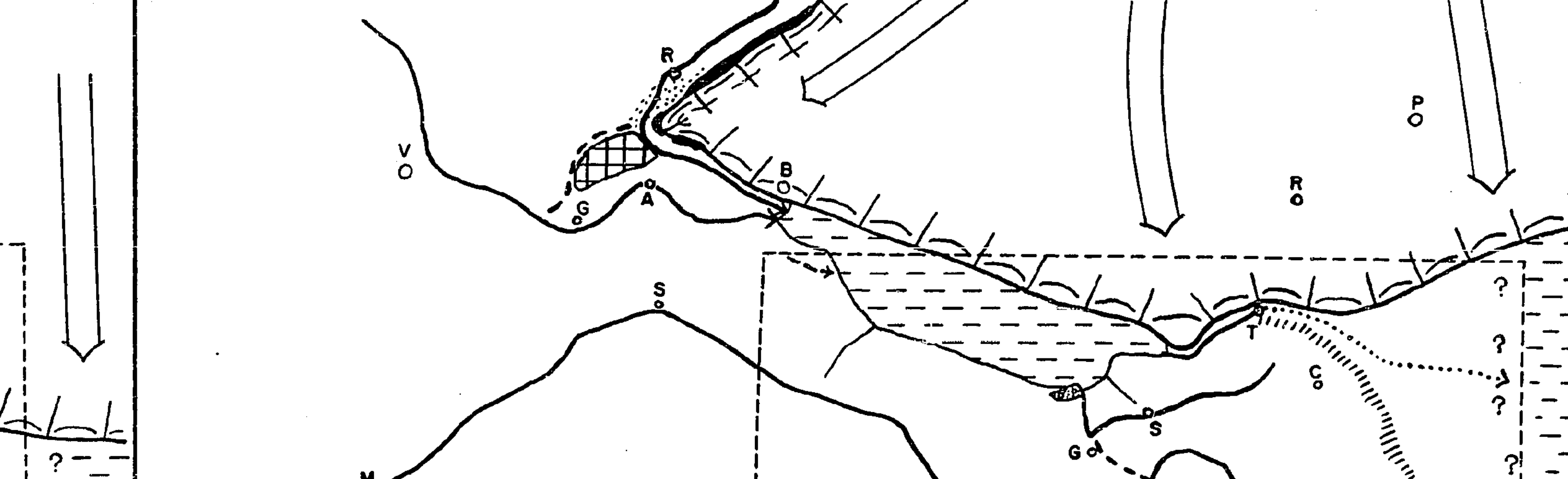

CHANNEL PHASE
I. GLAC
NDON LAKE: DRY RIVER PHASE
M. THE E

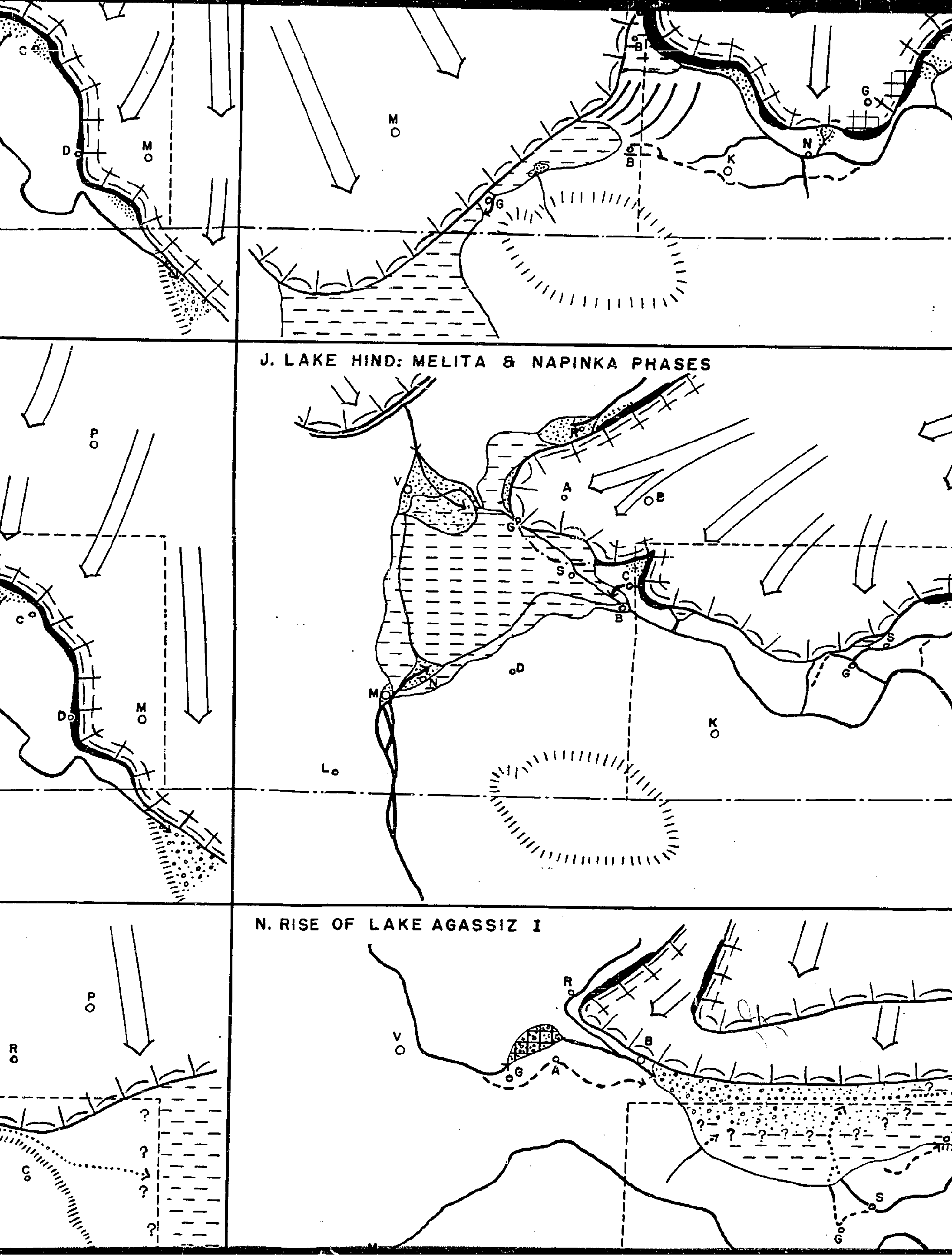


I. GLACIAL LAKE SOURIS PHASE



M. THE BRANDON LAKE: TREHERNE PHASE




J. LAKE HIND: MELITA & NAPINKA PHASES
N. RISE OF LAKE AGASSIZ I
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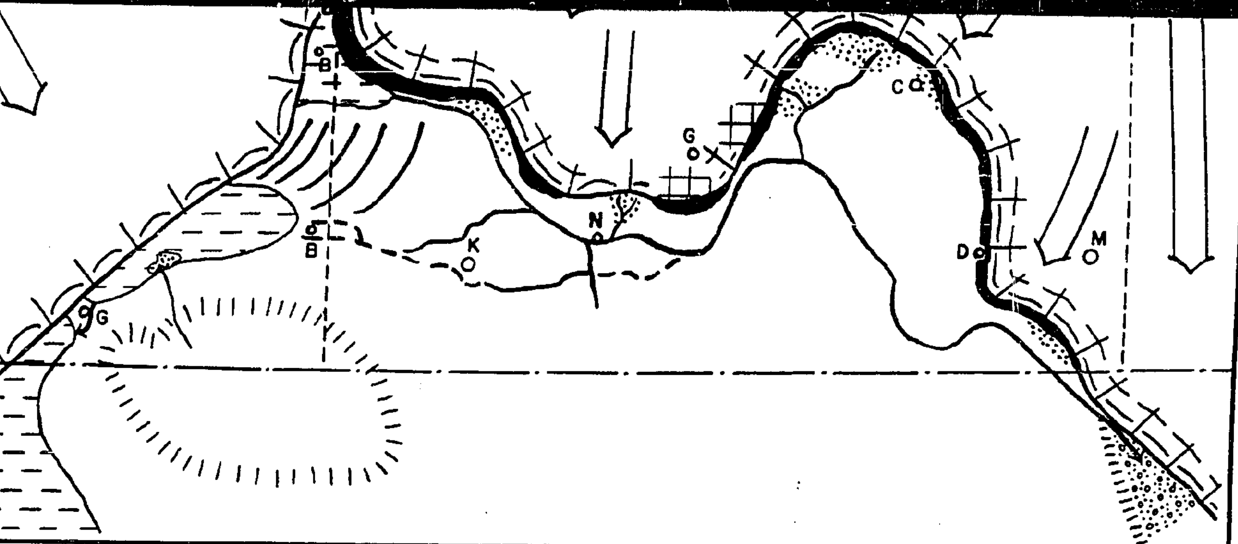
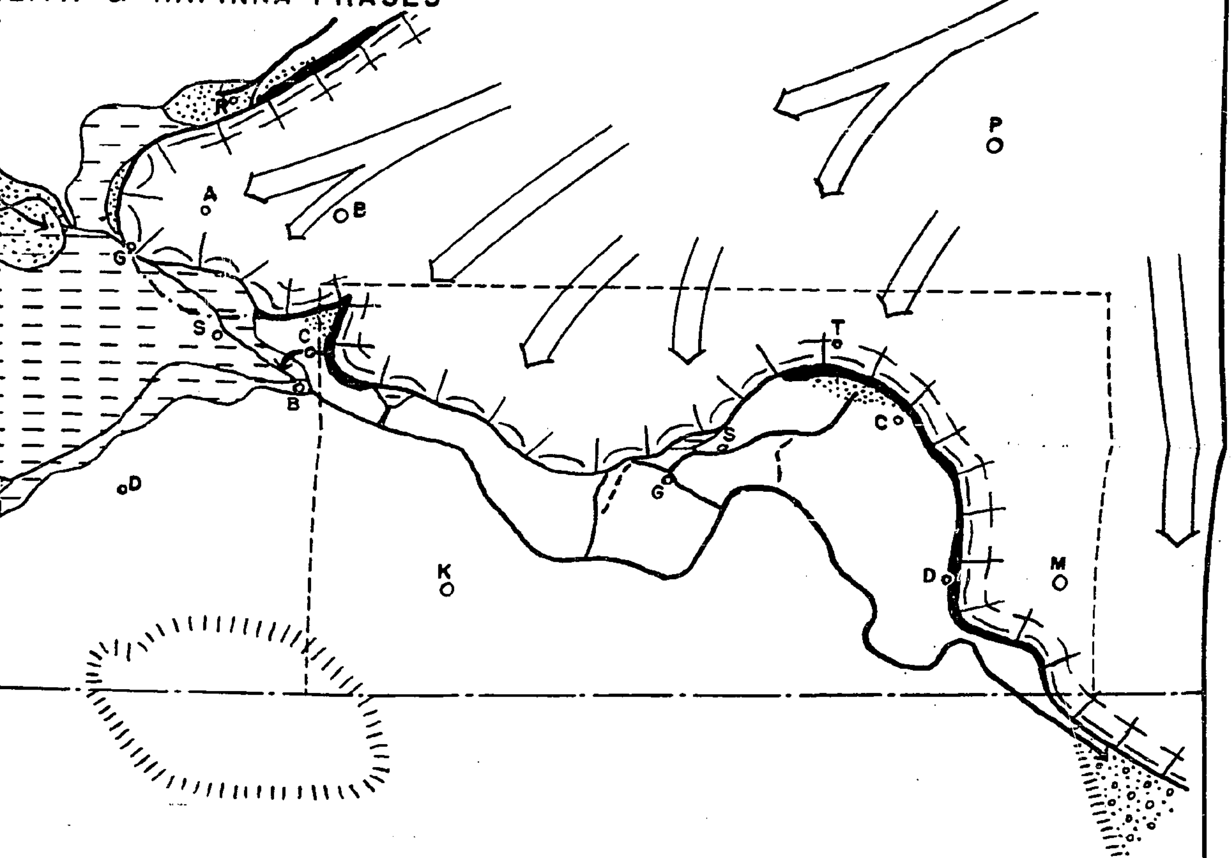
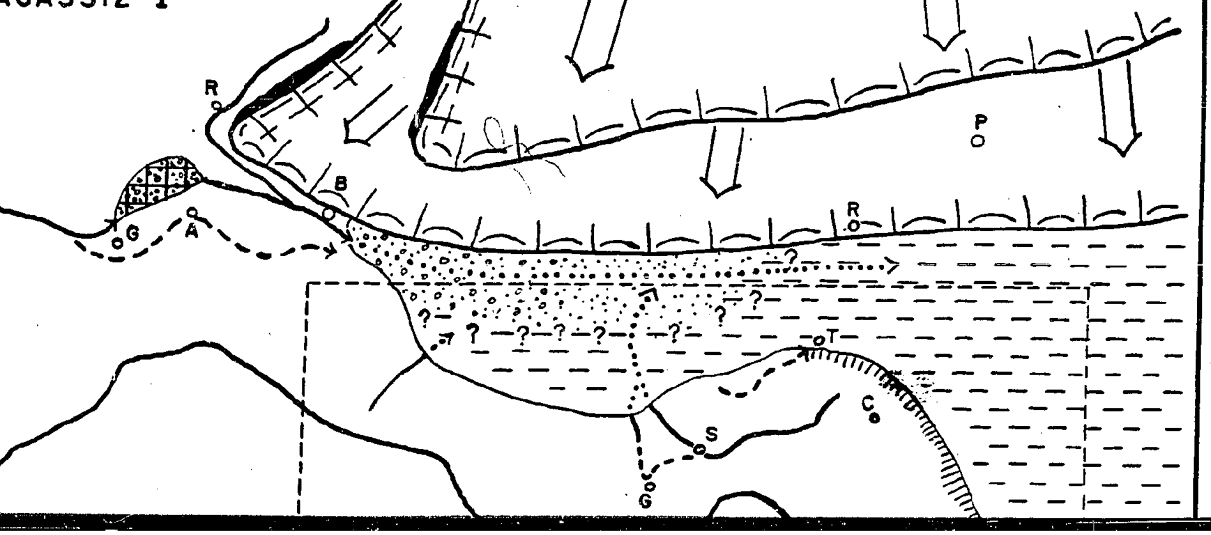


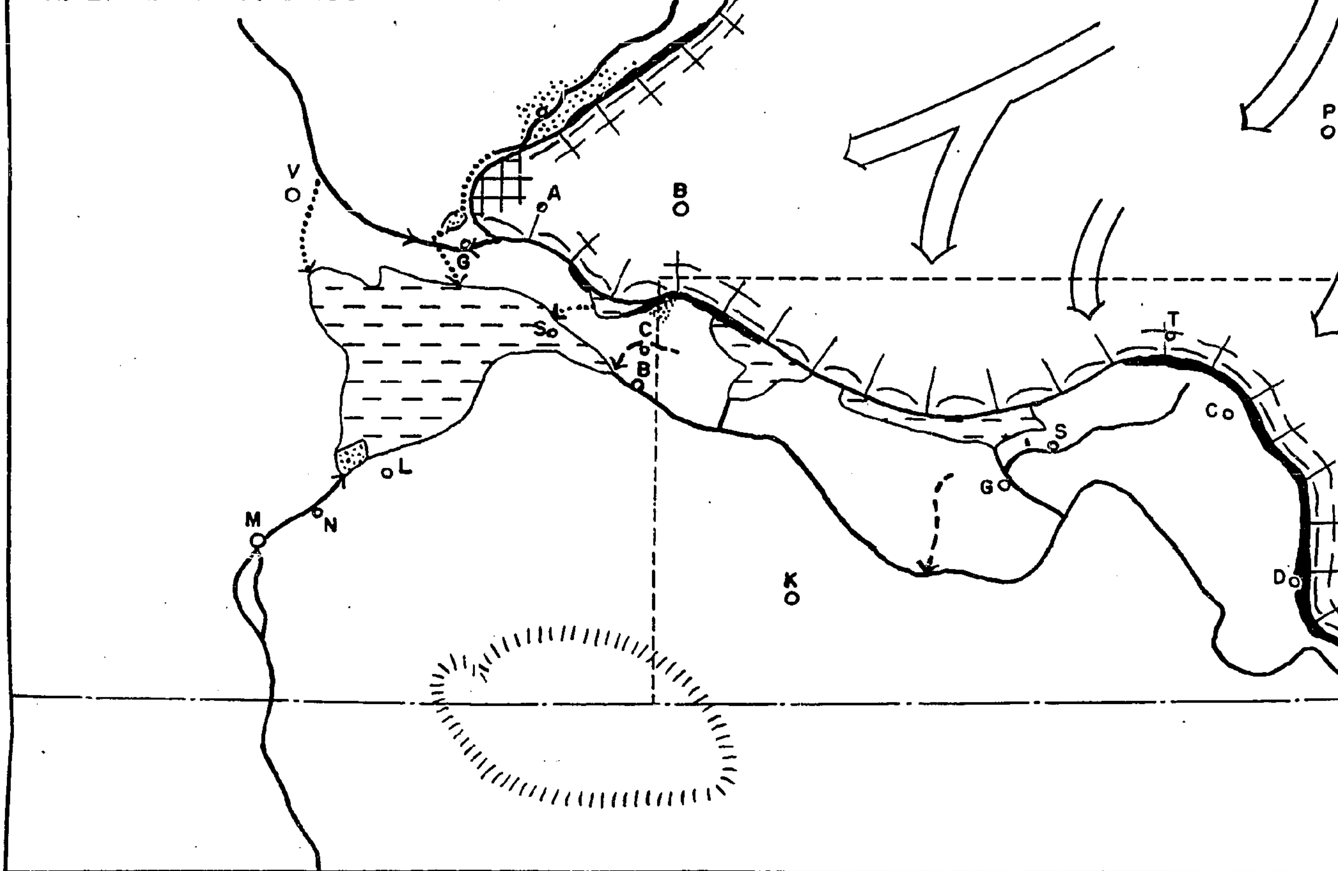
ELITA & NAPINKA PHASES



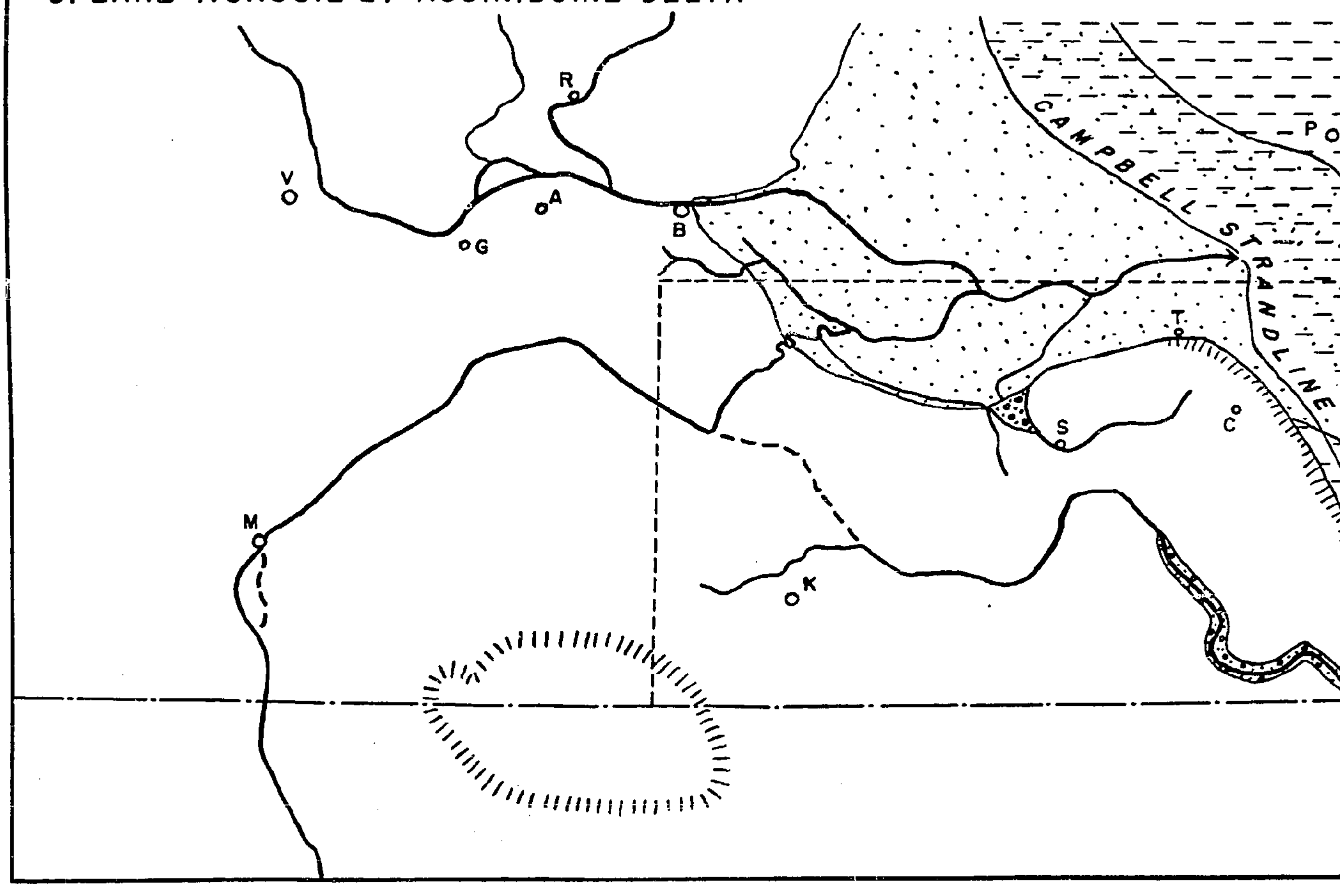
AGASSIZ I

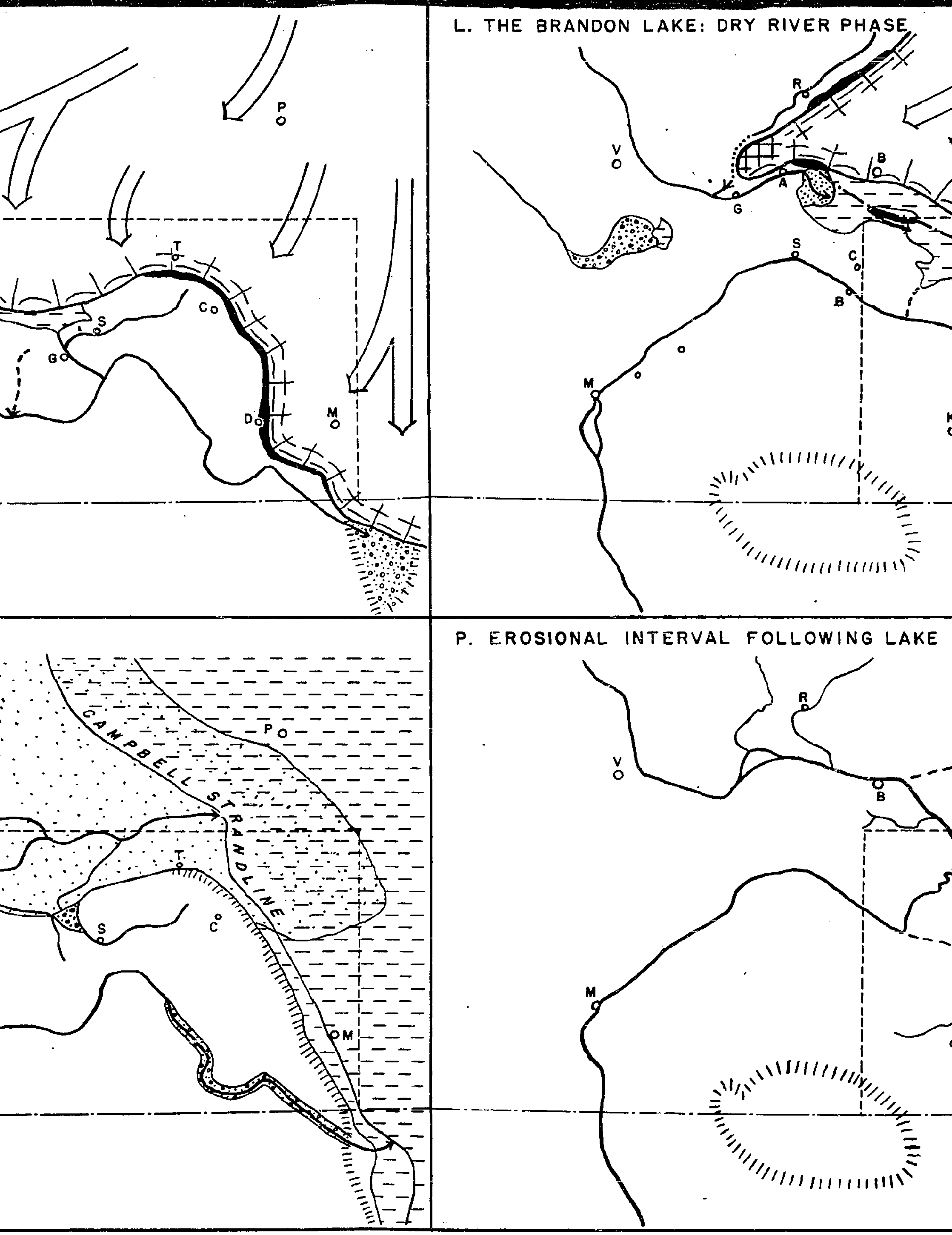


K. LAKE HIND: LAUDER PHASE



O. LAKE AGASSIZ I: ASSINIBOINE DELTA




L. THE BRANDON LAKE: DRY RIVER PHASE
P. EROSIONAL INTERVAL FOLLOWING LAKE
CAMPBELL STRANDLINE
P
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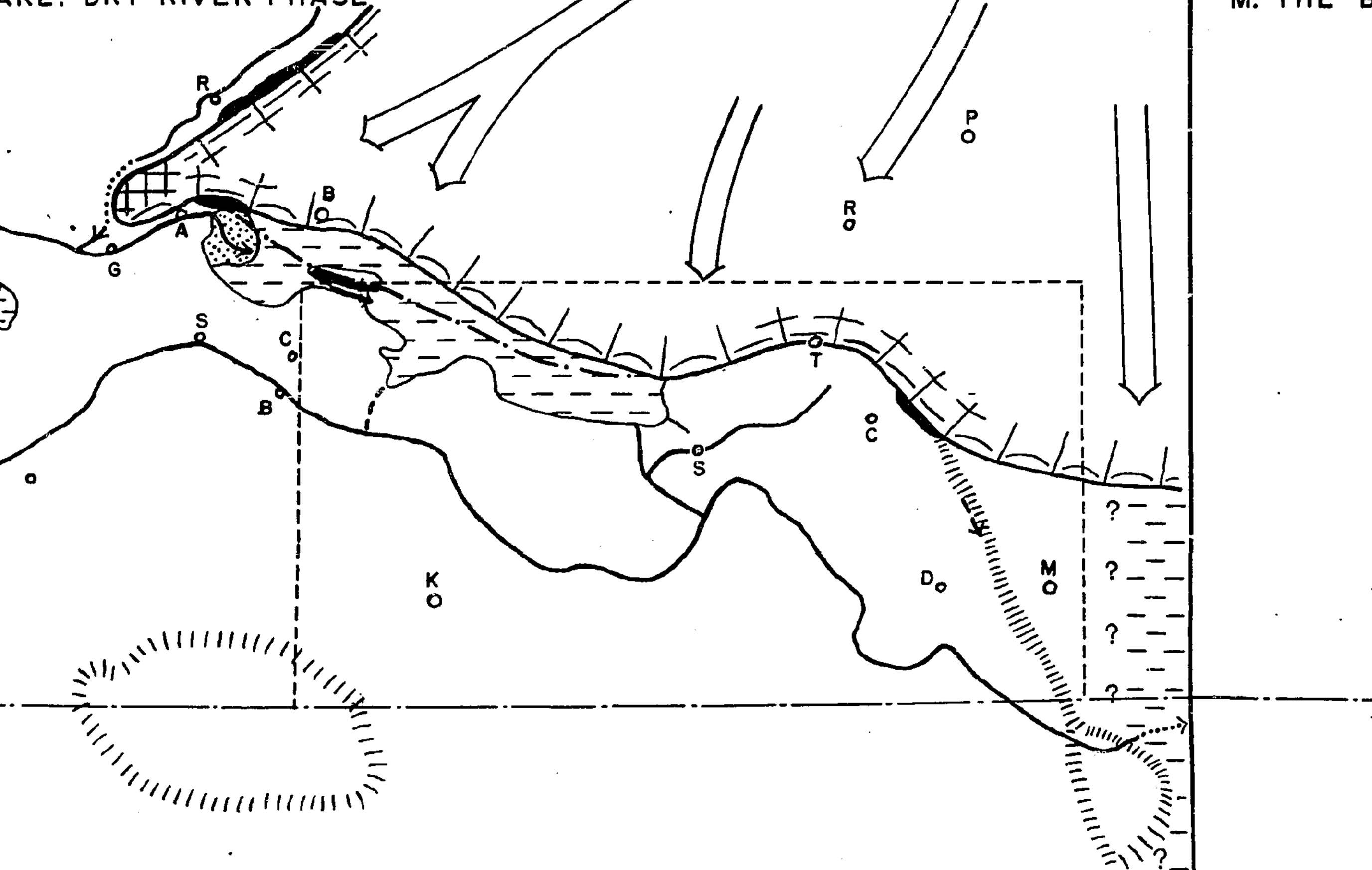
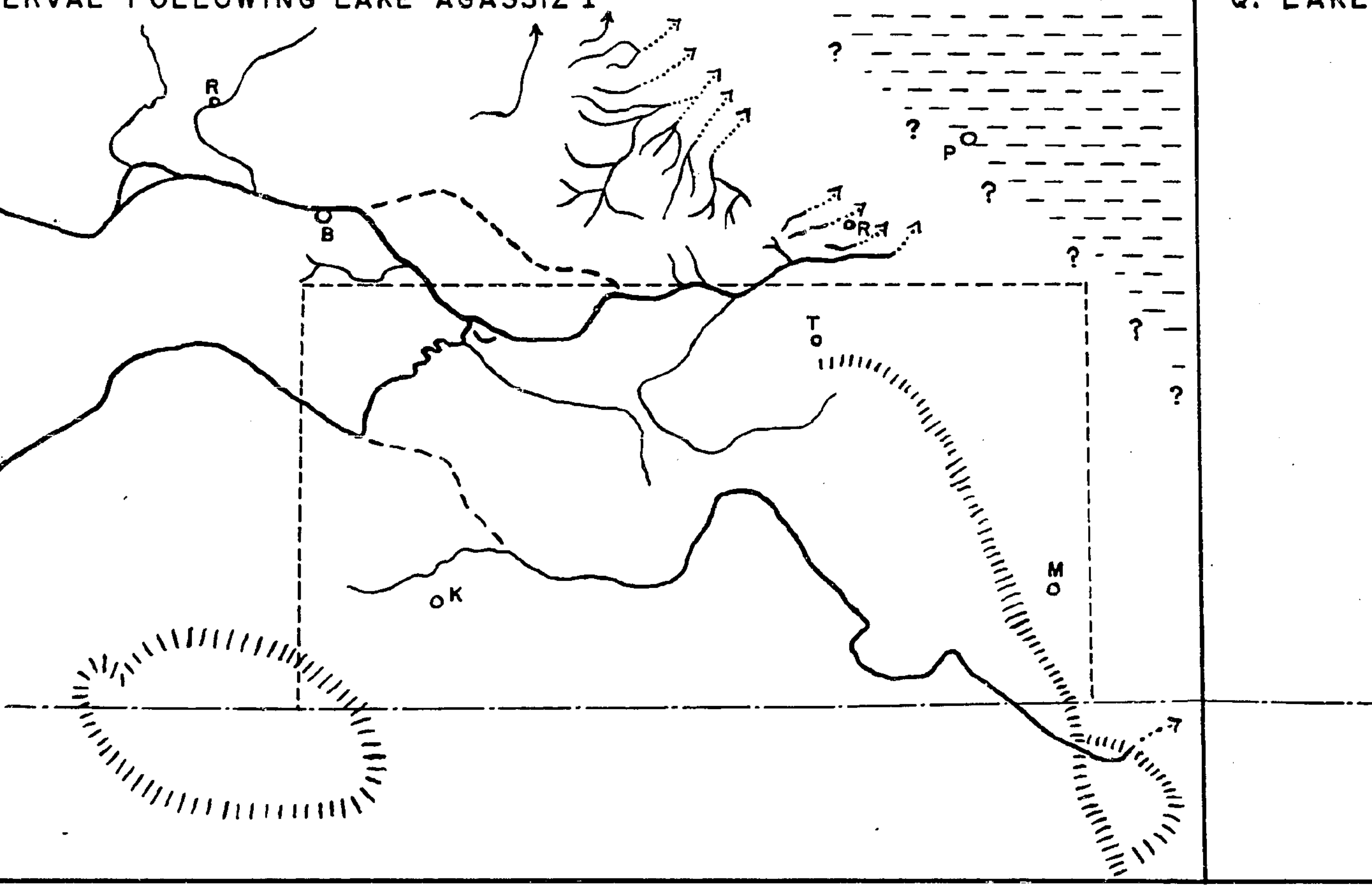
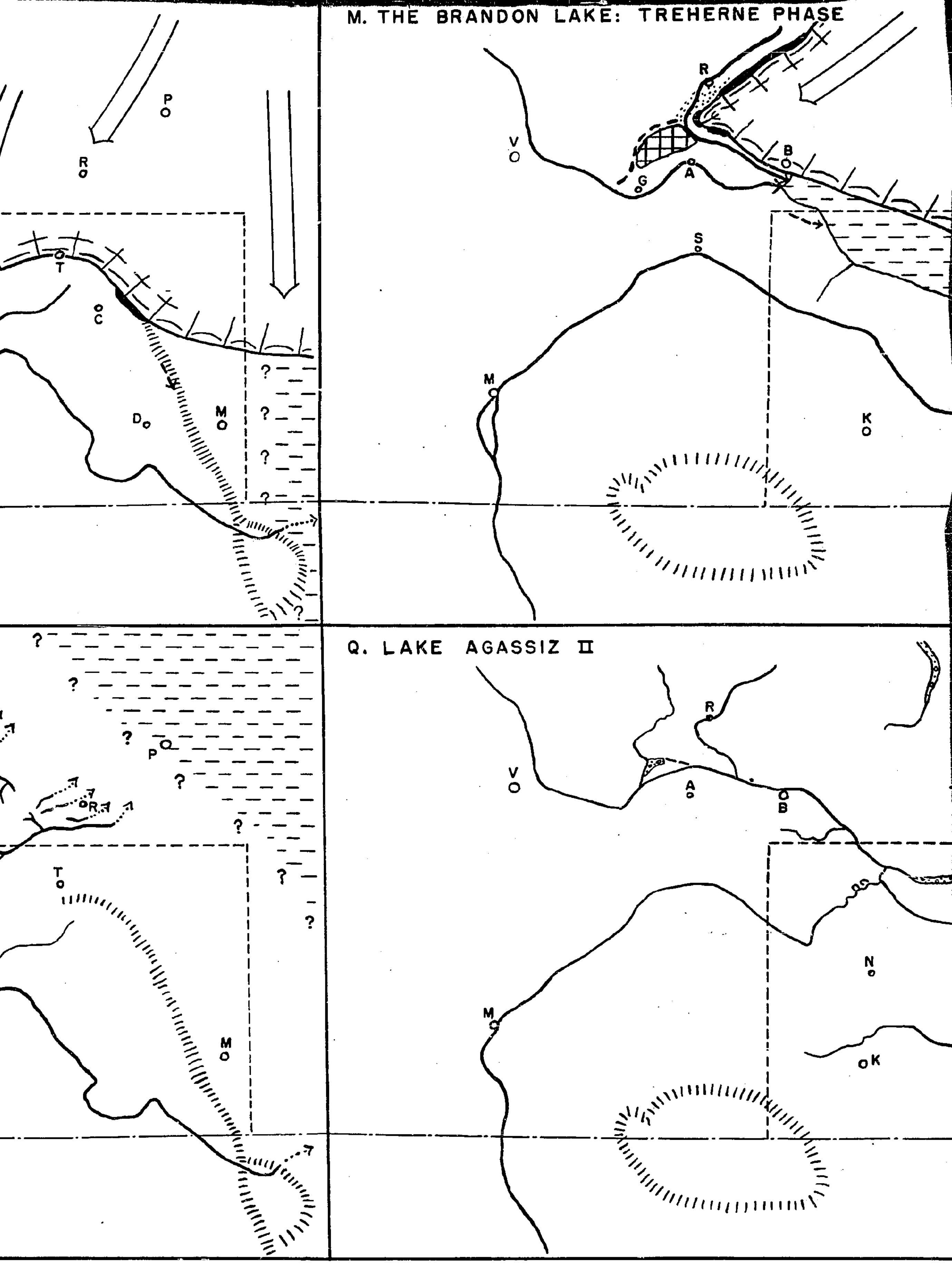
AKE: DRY RIVER PHASE M. THE B



ERVAL FOLLOWING LAKE AGASSIZ I Q. LAKE




M. THE BRANDON LAKE: TREHERNE PHASE
Q. LAKE AGASSIZ II
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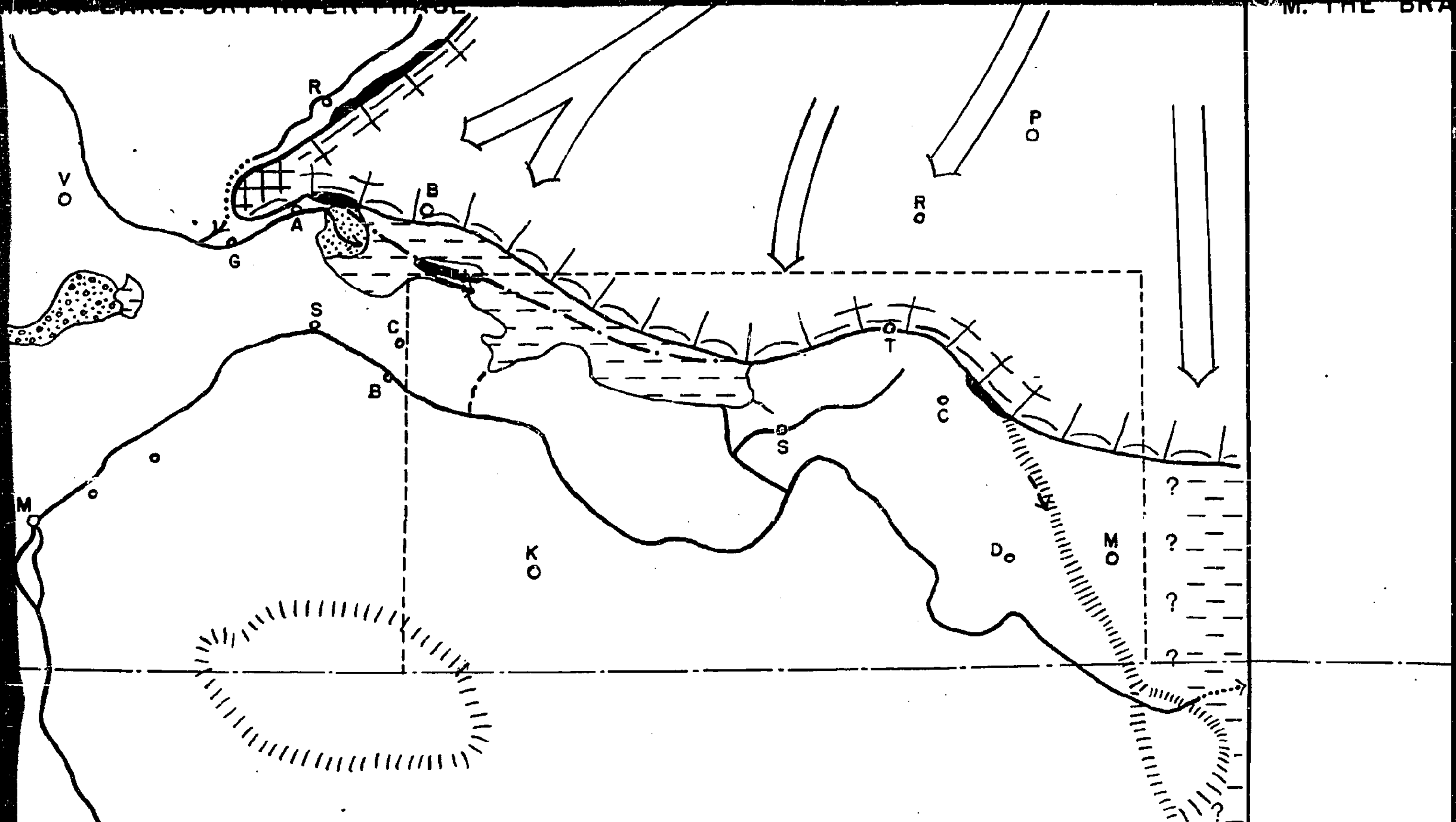
M. THE BRA
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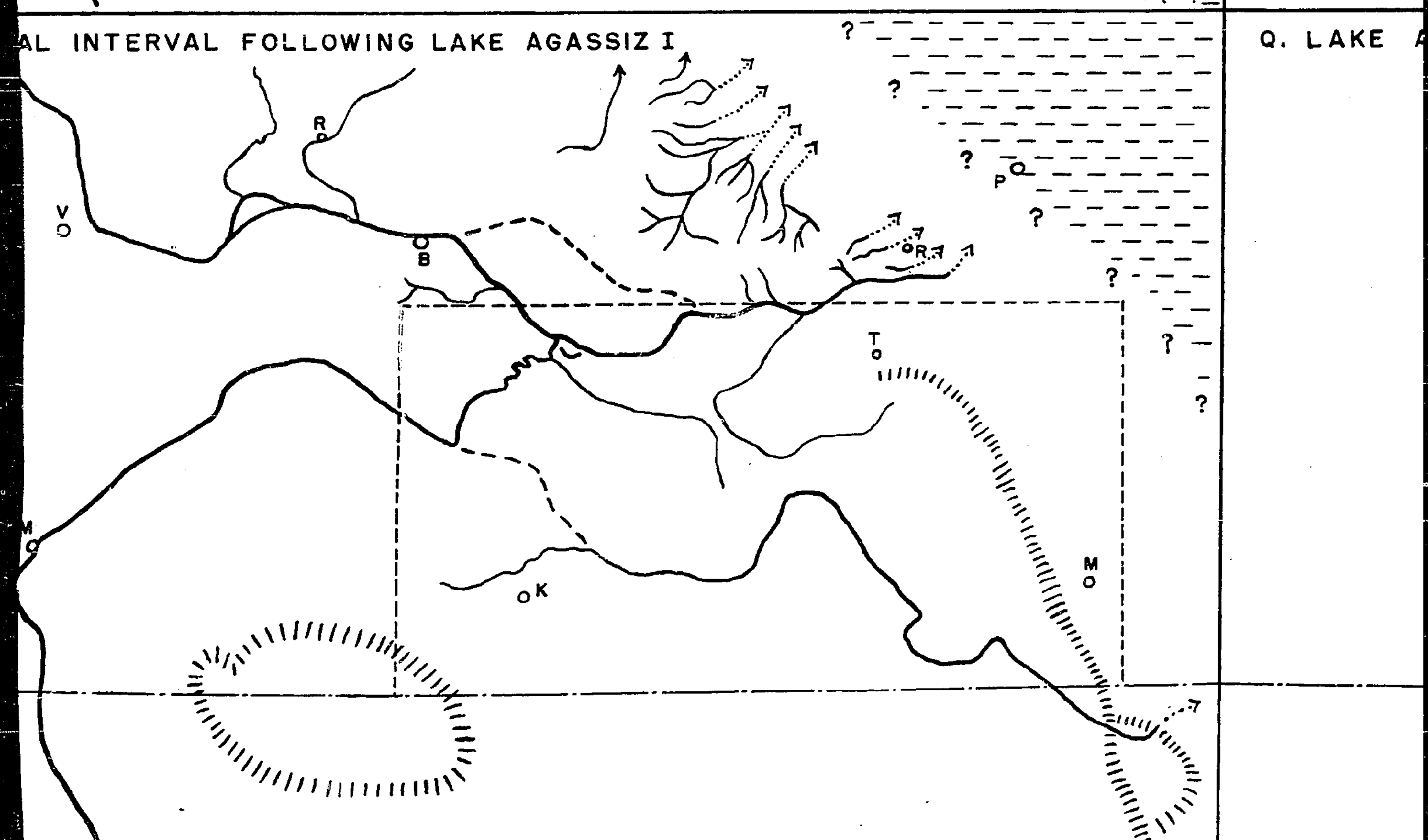
AL INTERVAL FOLLOWING LAKE AGASSIZ I
Q. LAKE A
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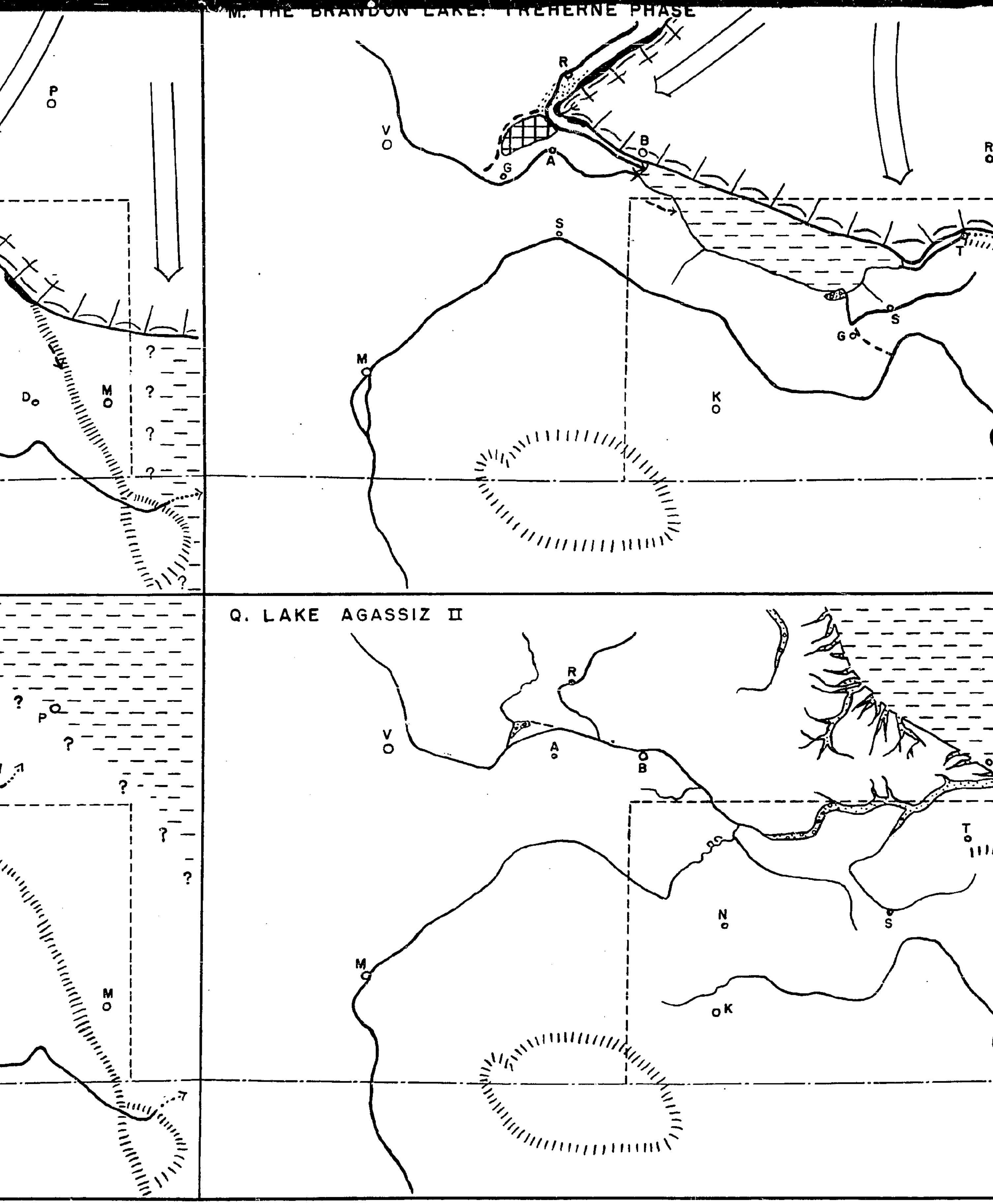
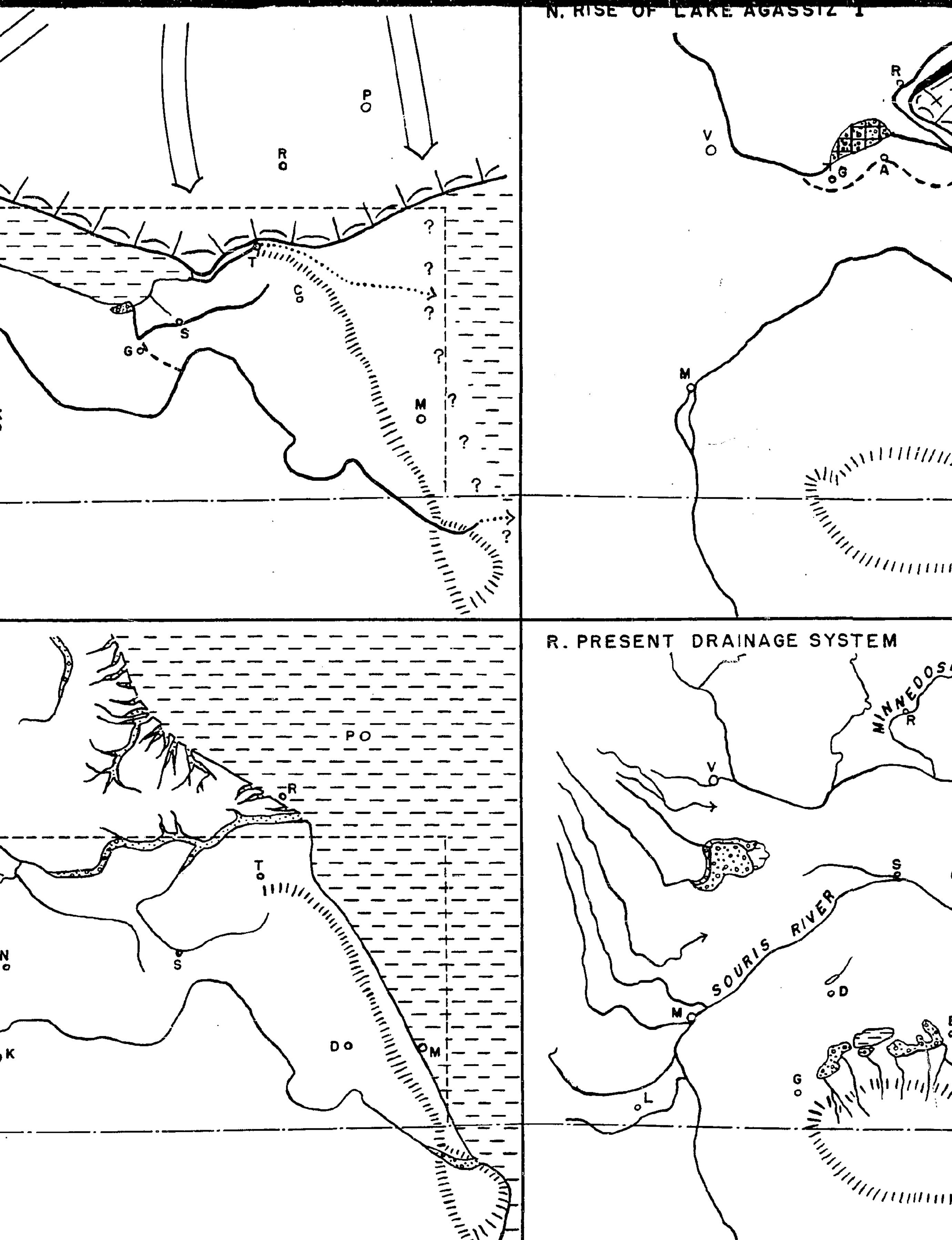

M. THE BRANDON LAKE: TREHERNE PHASE
Q. LAKE AGASSIZ II



N. RISE OF LAKE AGASSIZ I
R. PRESENT DRAINAGE SYSTEM
SOURIS RIVER
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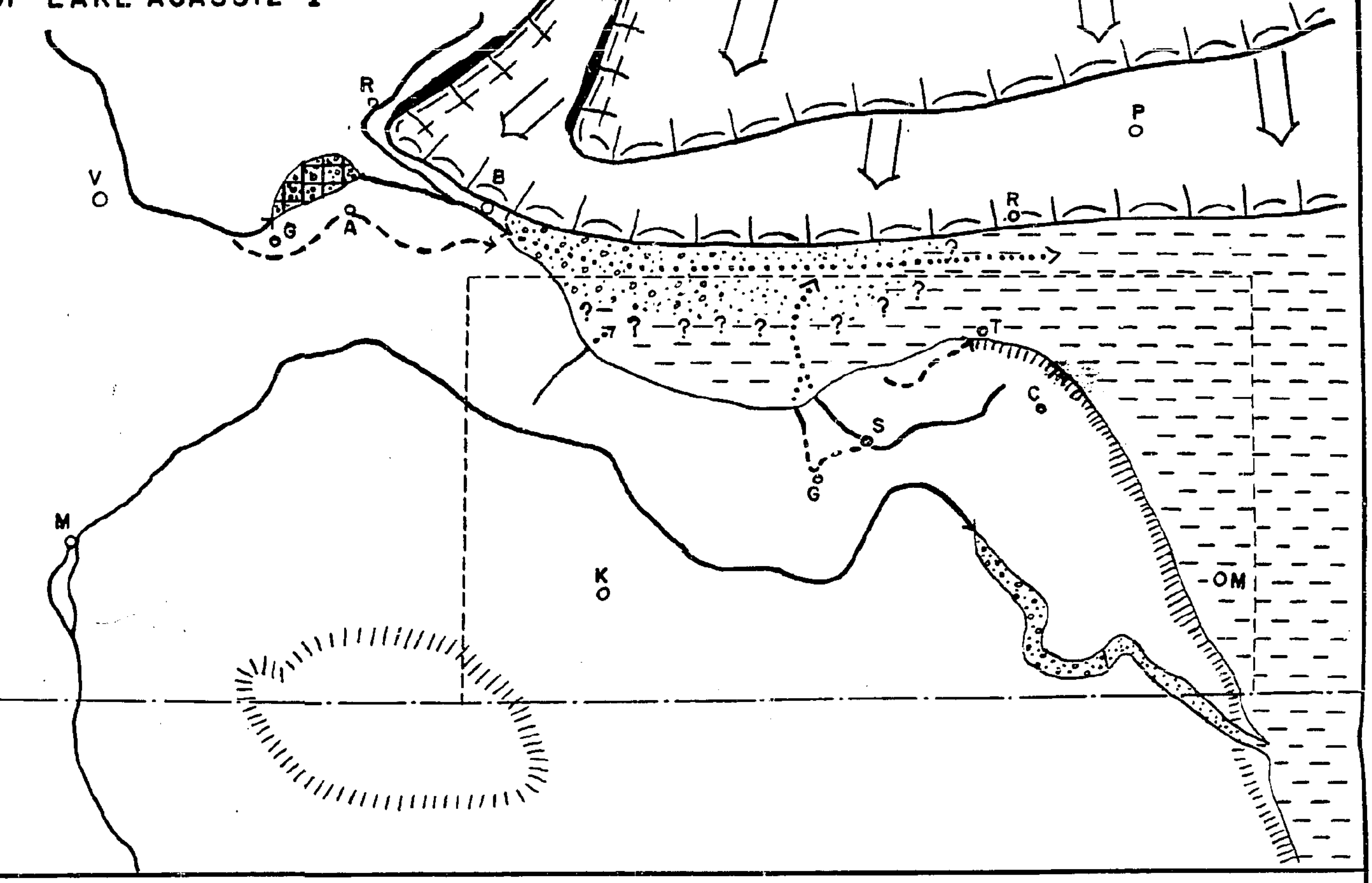
N
L

F LAKE AGASSIZ I



NT DRAINAGE SYSTEM