

SEDIMENTS IN THE SOUTH BASIN OF LAKE WINNIPEG

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of
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by
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ABSTRACT

Approximately 60 bottom sediment 'grab' samples were obtained in the south basin of Lake Winnipeg in the autumn of 1969 and spring of 1970. Textural analyses indicate that most offshore sediments contain greater than 70 percent clay-sized minerals (finer than four microns). The sedimentary units within the basin occur in three concentric units: a large clay unit in the center of the basin, a smaller silty clay unit 'shoreward' of the clay unit and a nearshore undivided unit consisting of sand, gravel, underwater 'outcrops' of glacial till and Glacial Lake Agassiz sediments and a thin discontinuous layer of silt and clay.

X-ray analysis of magnesium saturated, glycerol-treated unoriented slides of the fine clay fraction shows the mineralogy of the recent bottom sediments to be essentially homogeneous throughout the lake. The clays consist of approximately 80 to 85 percent randomly interstratified montmorillonite-illite and 10 to 20 percent kaolinite plus chlorite. The proportion of illite in the interstratified complex is 45 to 50 percent. The montmorillonite and illite are both dioctahedral. Differential thermal analysis indicates that the montmorillonite-illite interstratifica-

tion consists of 'normal' illite - 'abnormal' montmorillonite with the direction of transformation being illite converting to montmorillonite. The dominant exchange ion on the montmorillonite is calcium.

The mineralogy of the Lake Winnipeg sediments agrees, in general, with that found by other researchers for the Cretaceous Shales, surface deposits and soils of Western Canada; and from this it would appear that little or no diagenetic changes have occurred in the clay minerals from the Cretaceous Shale source through the sequence of glacial erosion and redeposition as tills and glacio-lacustrine clays, pedogenic processes of soil formation, erosion of the soil and finally to deposition in Lake Winnipeg.

The rate of sedimentation calculated from suspended load data of the Red River is approximately 0.5 millimetres per year over the entire area of the south basin.

CHAPTER I

INTRODUCTION

Purpose and Scope of Study

This study is intended as a general reconnaissance of the nature of the bottom sediments and sedimentary environment in the south basin of Lake Winnipeg, and is one part of a much larger multidisciplinary study of the entire lake being conducted by the Fisheries Research Board of Canada, Freshwater Institute, Winnipeg. Confinement of the study to the south basin was necessitated by time limitations and poor sample density in the north basin.

Location and Previous Studies

Lake Winnipeg is a large freshwater remnant of Glacial Lake Agassiz (Davies, Bannatyne, Barry and McCabe, 1962) and is situated in south central Manitoba (Fig. 1). The lake is divided into two basins by an area known as The Narrows.

Previous physical studies of the lake have been concerned with flood control, hydro-electric power and beach erosion. The most important of these were conducted by the Lakes Winnipeg and Manitoba Board (1958), the Water Control and Conservation Board of the Province of Manitoba (1966),

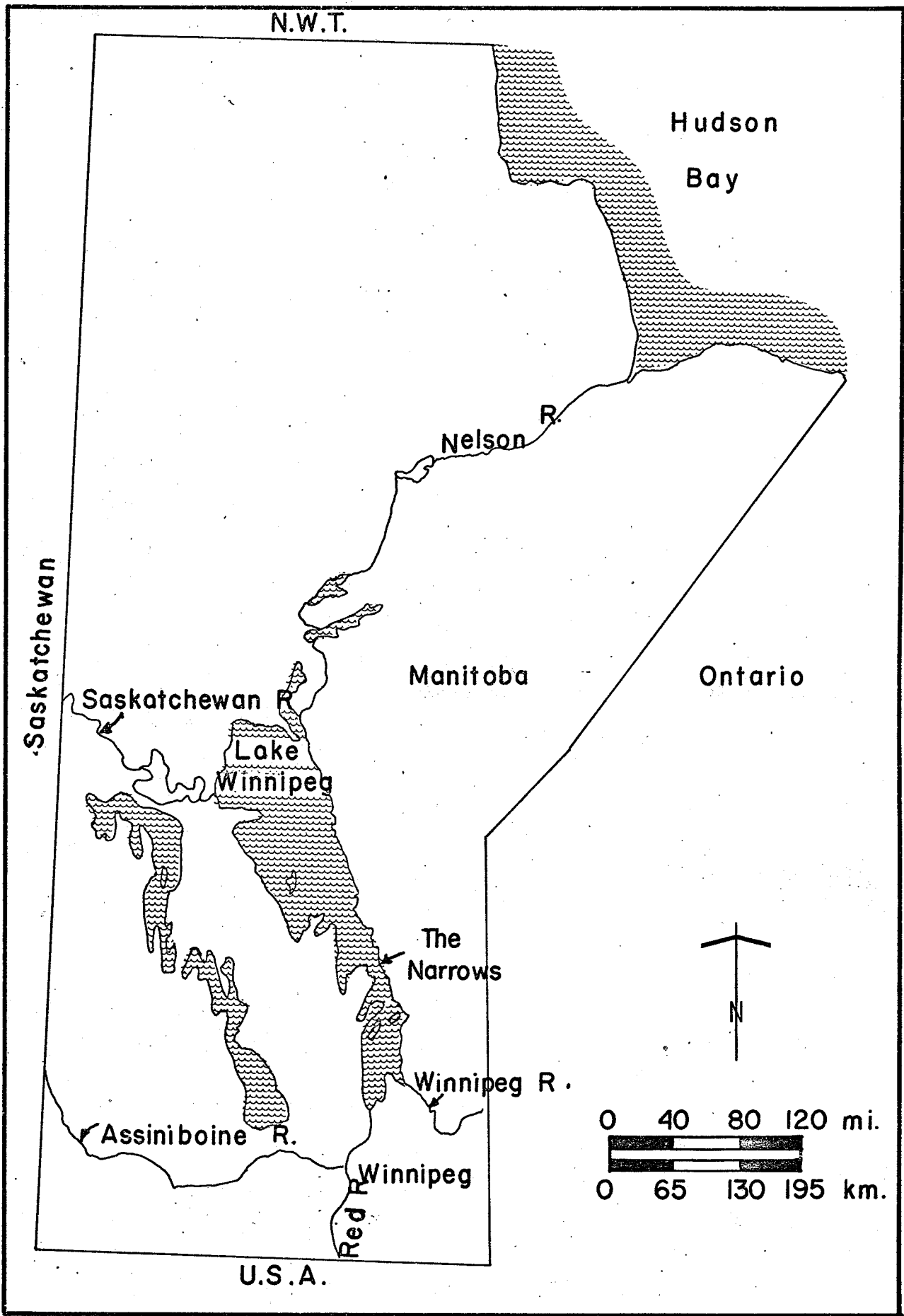


Fig. 1. Location map of Lake Winnipeg.

Solohub (1967) and Veldman (1969).

Method of Study

Bottom sediment samples were collected during two cruises aboard the Department of Public Works vessel, the BRADBURY, which is about 150 feet in length and has a six foot draft. The first cruise was conducted during the first two weeks of October, 1969, and the second cruise in early June of 1970. Approximately 100 samples were collected of which 60 were in the south basin (Fig. 2). Sampling was done on a square grid system (as much as possible) with the distance between sample stations ranging from 3 to 4 miles. Bottom 'grab' samples were collected by a double-Shipek on the 1969 cruise, and by a tall weighted Ekman (18 pounds) dredge in 1970. Those samples collected in 1969 are indicated by the 700 series of numbers in Fig. 2, and those collected in 1970 by an 800 series number. The Red River samples were collected in 1970. Samples followed by a B, C, or D are labelled thusly to maintain continuity with the numbering of Fisheries Research Board sample stations. Positions of sample stations were 'fixed' by radar and gyrocompass bearings to landmarks. Continuous echo sounding records (Bendix Echo Sounder Model BR with a frequency of 9 Kc/sec and powered by a 12 volt direct current) of the ships track, approximately 1,500 miles, were collected (Fig. 3). Grain size data was obtained by

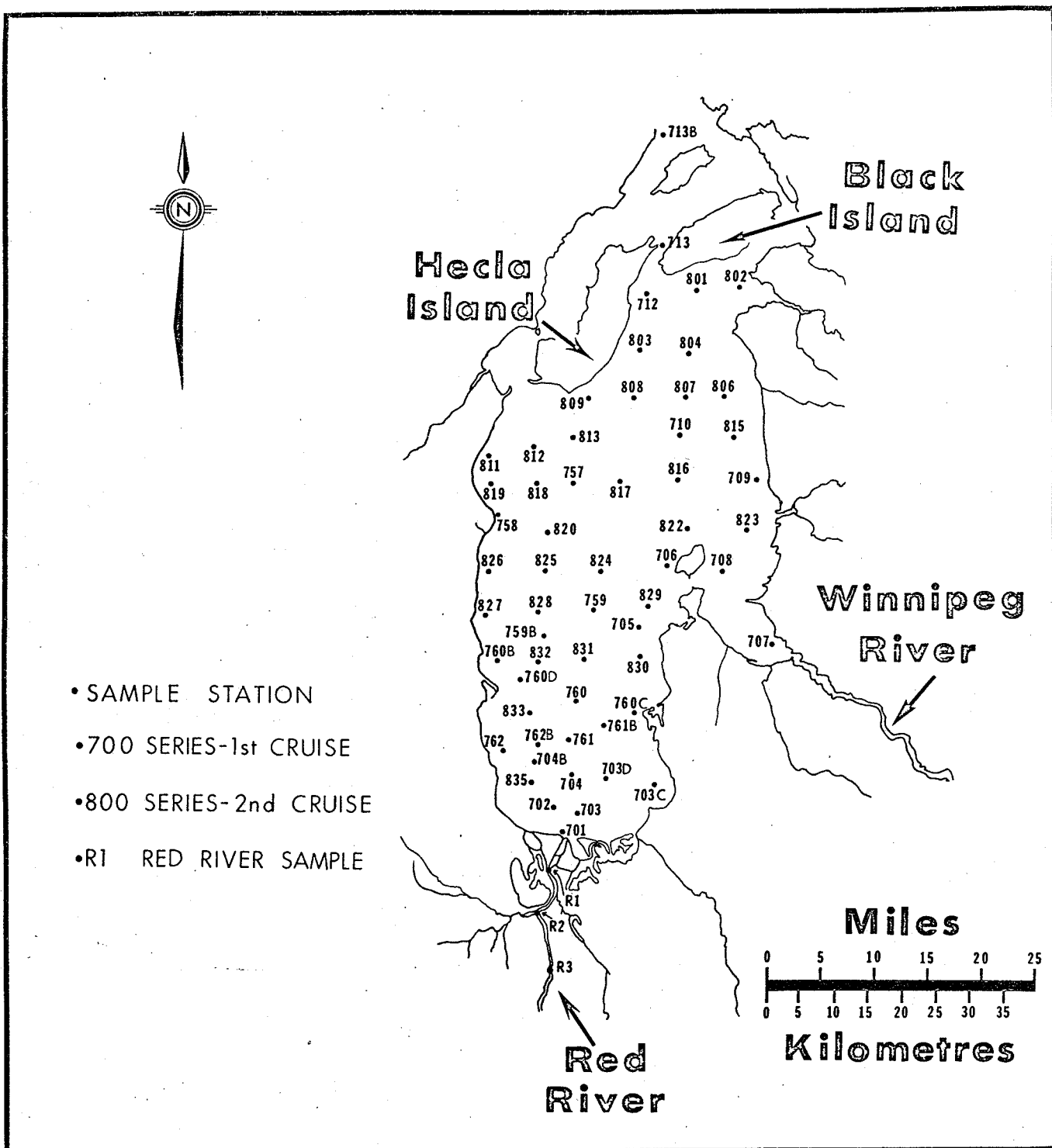


Fig. 2. Location of sample stations in the south basin of Lake Winnipeg.

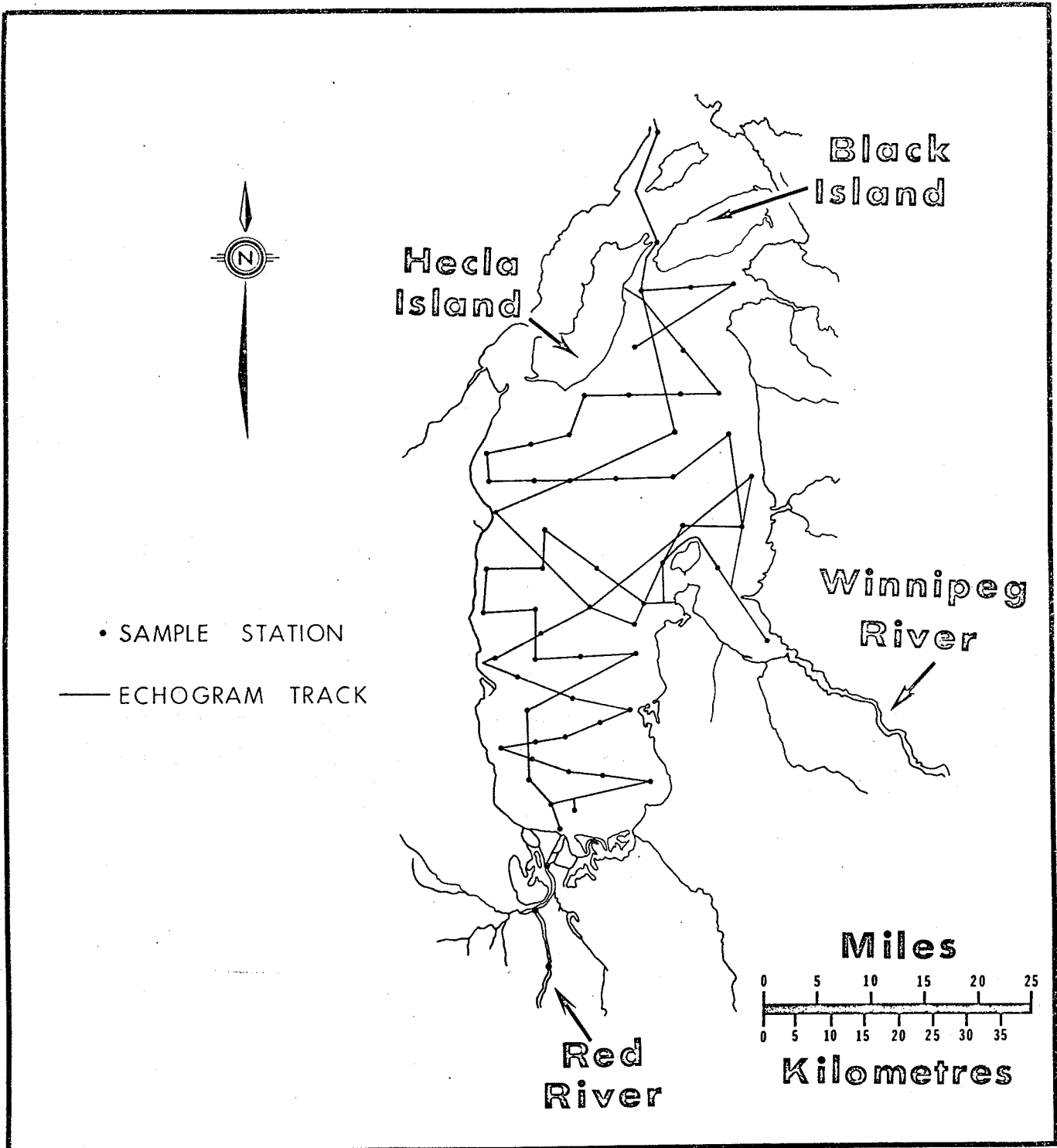


Fig. 3. Echogram track between sample stations.

pipette technique (Folk, 1968) and mineralogy was determined by use of X-ray and Differential Thermal Analyses (Appendix A).

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CHAPTER II

GENERAL GEOGRAPHIC AND GEOLOGIC SETTING

Physiography and Drainage

The south basin of Lake Winnipeg is situated along part of the contact of two of the major physiographic regions of Canada, which are the Precambrian Shield to the east and the Interior Lowlands to the west. The main rivers which drain into the south basin are the Red and Winnipeg. These and several minor rivers all drain areas which have been glaciated and are at least partially covered with Glacial Lake Agassiz sediments.

Surficial Deposits of the Lake Winnipeg Region

The surficial deposits of the Lake Winnipeg region consist of a complex mosaic of glacial, glacio-lacustrine and glacio-fluvial deposits (Fig. 4). The glacial deposits consist mainly of ground moraines deposited by the Patrician ice-sheet, centered west of James Bay, which advanced into the study area from the northeast, and the Keewatin ice-sheet, centered west of Hudson Bay, which advanced into the study area from the northwest (Davies, Bannatyne, Barry and McCabe, 1962). The glacial drift of the Patrician sheet

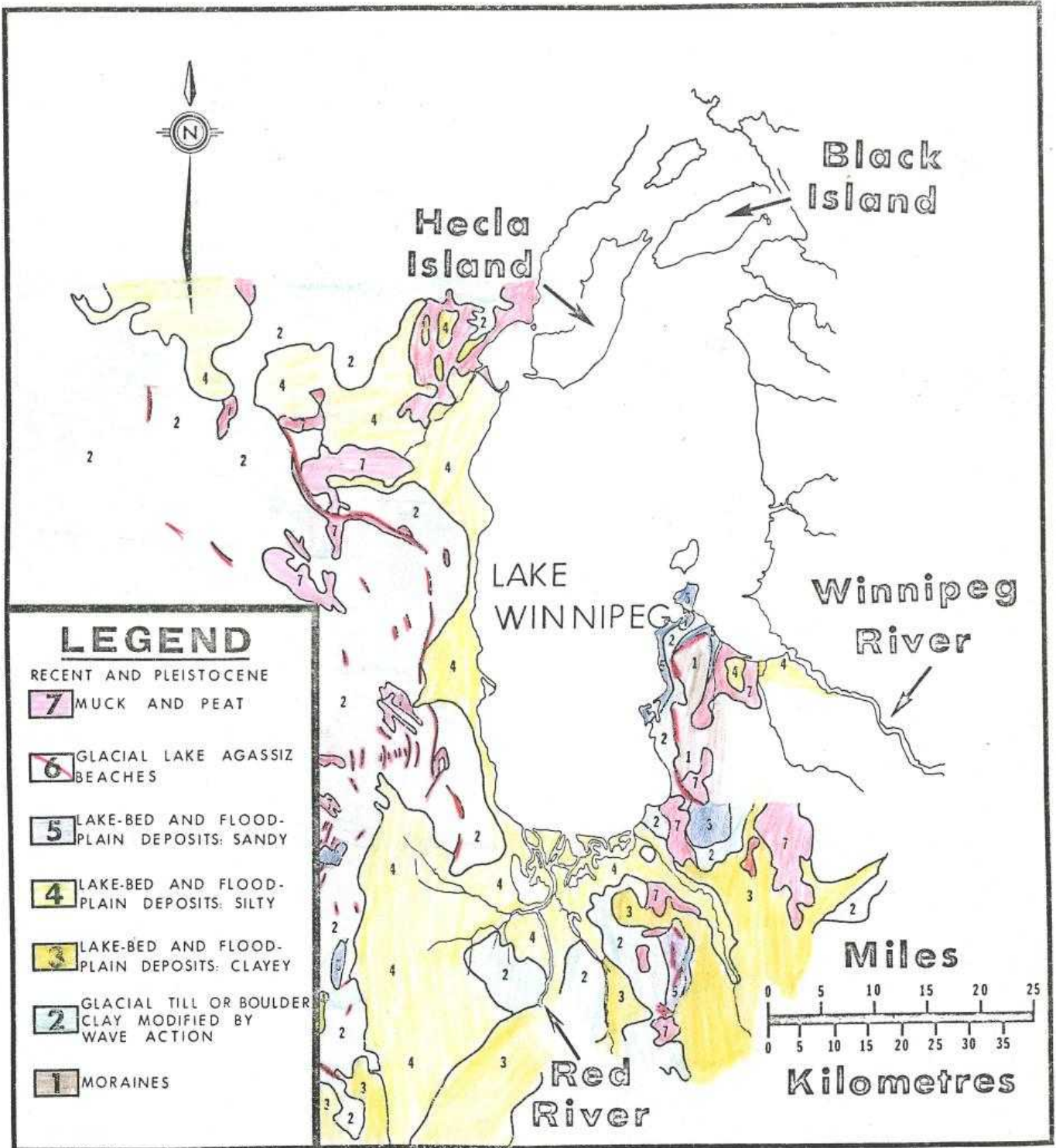


Fig. 4. Surficial deposits of the area surrounding the south basin of Lake Winnipeg (modified from Geological Survey of Canada Map 254A).

was described by McPherson (1970) as consisting

"primarily of quartz and feldspar grains, clay materials, granitic, volcanic and metasedimentary rock fragments, with a minor number of carbonate rock fragments".

Wicks (1965) described the clay minerals of the glacial till of the Keewatin ice sheet, in the Winnipeg area, as composed of 15 to 20 percent randomly interstratified illite-montmorillonite in the main body of the till, and as low as 5 percent at the base of the till. Other minerals of the till included approximately 40 to 50 percent dolomite, and approximately equal amounts of quartz, feldspar and calcite. The clayey, silty and sandy lake bed and flood plain deposits are Glacial Lake Agassiz deposits.

Bedrock Geology

The regional bedrock geology may be described conveniently by discussing the geology of the Precambrian Shield and Interior Lowlands separately (Fig. 5 and Table I).

The rocks of the Precambrian Shield consist mainly of granites, granite gneisses and migmatites with smaller areas, 'greenstone belts', of meta-sedimentary and meta-volcanic rocks which are highly deformed structurally and have undergone a low to moderate degree of metamorphism. The meta-volcanic rocks consist of andesite, basalt, low-rank chloritic schists, volcanic breccias and metamorphosed equivalents such as hornblende-plagioclase schists and gneisses. Interbedded with or overlying the meta-volcanic

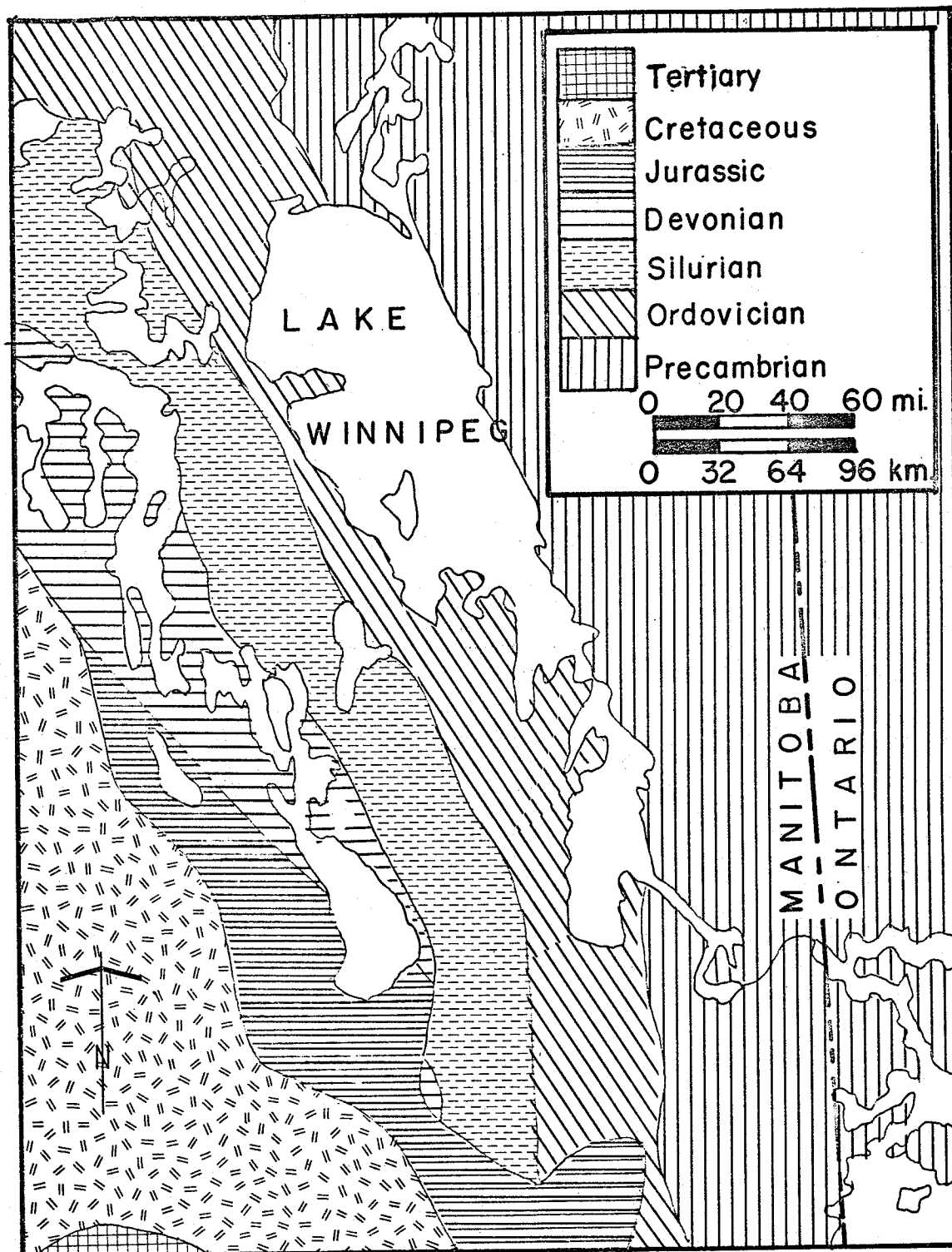


Fig. 5. Regional bedrock geology.

TABLE I

Geologic Systems in Manitoba*

Cenozoic	Paleocene ¹	Shale, sandstone, minor lignite
Mesozoic	Cretaceous	Shale, bentonite, sandstone
	Jurassic	Shale, siltstone, dolostone, anhydrite, gypsum
Paleozoic	Mississippian	Limestone, dolostone, shale, siltstone, anhydrite, petroleum
	Devonian	Limestone, dolostone, shale, salt, potash
	Silurian	Dolostone, argillaceous dolostone, shale
	Ordovician	Dolostone, dolomitic limestone, sandstone, shale
	Cambrian (?)	Glauconitic sandstone
Precambrian		Volcanic, sedimentary, metamorphic and intrusive rocks

* (modified from Davies et al., 1962)

¹ Paleocene is an epoch, other subdivisions in the column are periods.

rocks are the meta-sedimentary rocks which consist of quartzite, meta-arkose, meta-greywacke, slate and their more highly metamorphosed equivalents. Small bodies of diorite, gabbro and peridotite have intruded the meta-volcanic and meta-sedimentary rocks in most areas.

The Interior Lowlands are largely underlain by Paleozoic and Mesozoic marine sedimentary rock strata which dip gently to the southwest and outcrop in long north-west-trending belts. Cenozoic rocks occur at Turtle Mountain in southwestern Manitoba, and consist of sandstone and clay, with thin seams of low-rank coal. The Lowland rocks are underlain at depth by a Precambrian basement.

Locally in the southern Lake Winnipeg region the bedrock consists mainly of Precambrian and Ordovician rocks (Fig. 6). The Precambrian rocks are mainly granites and granite gneisses and are largely covered by glacial drift. The Ordovician rocks are divided into three formations which are the Winnipeg Formation, the Red River Formation and the Stony Mountain Formation (Baillie, 1952). The Winnipeg Formation is the oldest Ordovician formation in Manitoba and lies unconformably on the Precambrian basement. It consists of pure fine-grained, well-sorted, quartzose sandstone and bluish-green shale containing interbedded sandstone. The Red River Formation consists of mottled, fossiliferous dolomitic limestone and yellowish fine-grained calcitic dolostone which contains large chert nodules. The

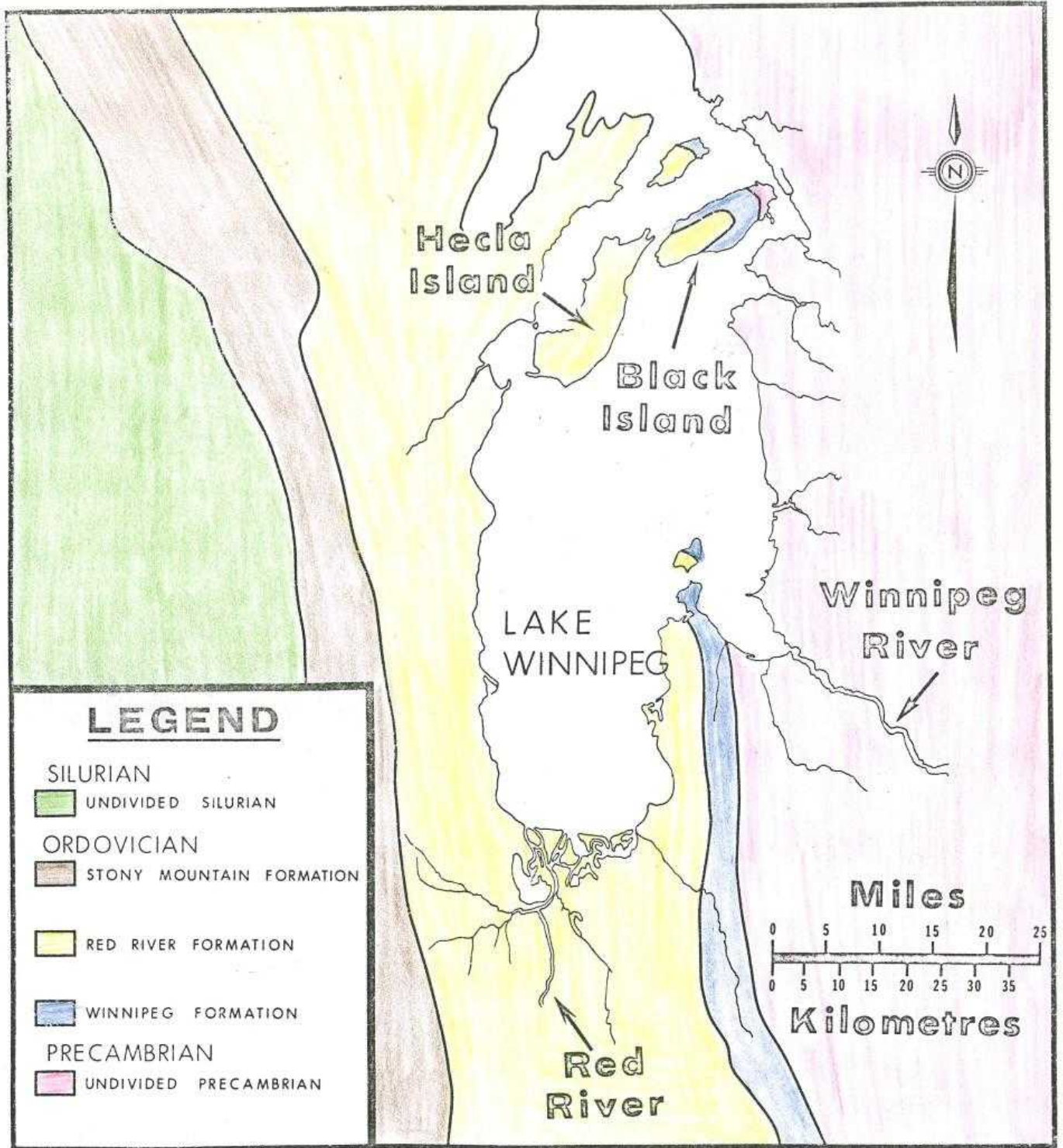


Fig. 6. Local bedrock geology (after Baillie, 1952).

Stony Mountain Formation consists of a series of calcareous shales, argillaceous dolostones and dolostones.

CHAPTER III

GLACIAL LAKE AGASSIZ

A brief history of Glacial Lake Agassiz and a description of its deposits is presented here to facilitate the understanding of the Lake Winnipeg deposits. Many studies have been conducted on Glacial Lake Agassiz. The interested reader is referred to Tamplin (1967) for a history of studies conducted on the lake, and to Elson (1967) for a review of the geology of the lake.

Lake Agassiz was a proglacial lake dammed between high ground in the south and an ice front in the north (Elson, 1967). With the oscillatory retreat of the ice, generally northeastward, the lake gradually increased in size but underwent significant fluctuations in level and area. These fluctuations occurred as new outlets were opened and controlling thresholds were eroded and/or were differentially uplifted by isostatic rebound following deglaciation.

Throughout its history, Glacial Lake Agassiz covered an area of approximately 200,000 square miles in the provinces of Ontario, Manitoba and Saskatchewan; and the states of Minnesota, North Dakota and South Dakota (Fig. 7). At no time, however, was the submerged area of the lake

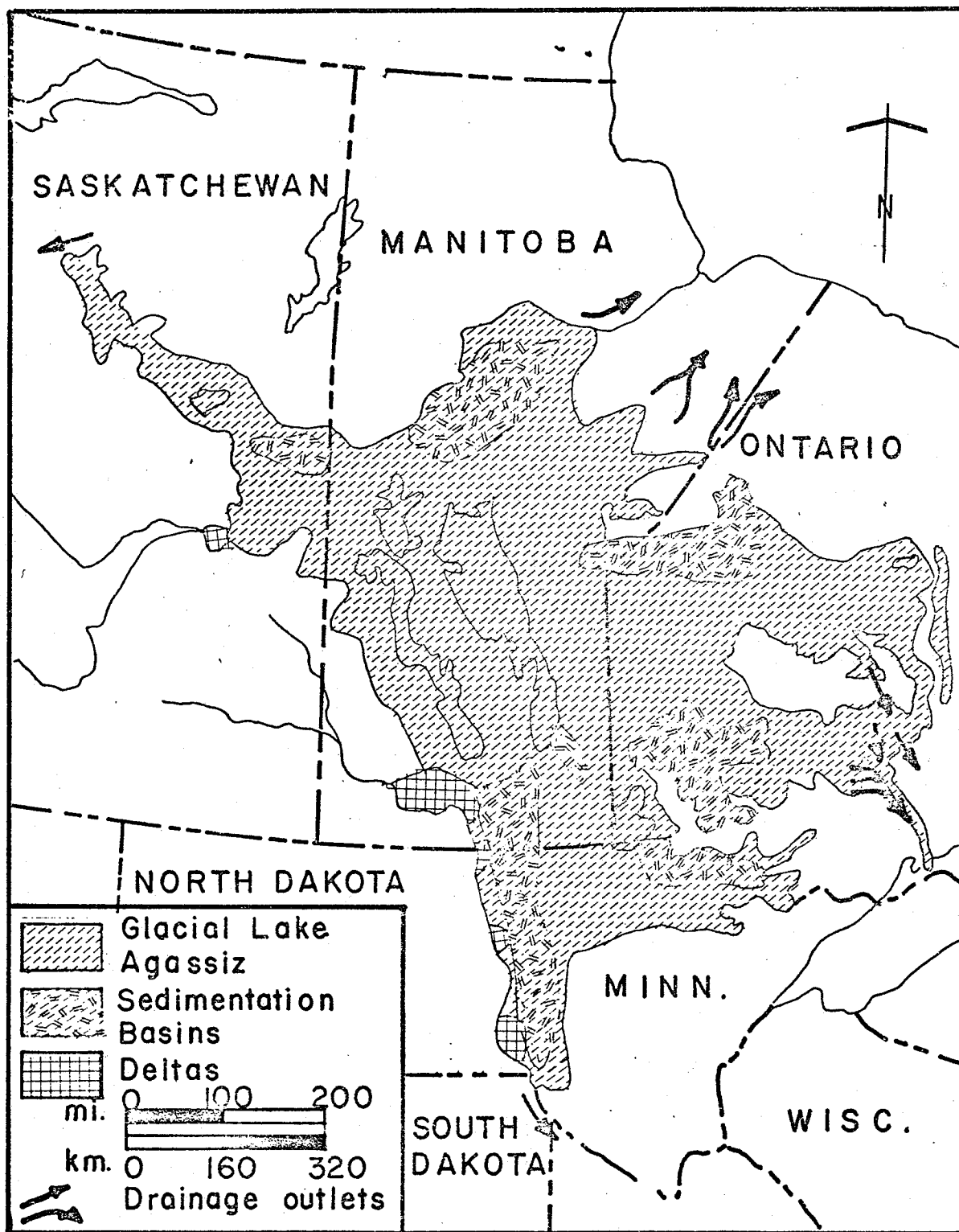


Fig. 7. Maximum extent and major sedimentation areas of Glacial Lake Agassiz (after Elson, 1967).

greater than 80,000 square miles. The time period during which the lake existed was approximately 12,900 to 7,800 years before present (Prest, 1970).

Offshore sedimentation in Glacial Lake Agassiz was controlled by bedrock topography which forms a number of partially closed basins. Most of the deep water sediments accumulated in these basins (Fig. 7).

Each of the basins has characteristically different sedimentary deposits because they accumulated sediments over different ranges of water levels during slightly different periods of time. The Red River Basin sediments should provide the most complete early historical record of Glacial Lake Agassiz because it has the highest range of beach levels and the most complete sedimentary sequence.

Wicks (1965) on the basis of work done by Elson (1961) divided the Red River Basin deposits of the Winnipeg area into two distinct lithologic units; the Lake Agassiz I unit and the Lake Agassiz II unit. Elson (1967) proposed a new classification scheme which divides the history of the lake into four episodes. Deposits which Wicks (1965) previously considered to be Lake Agassiz I and Lake Agassiz deposits are now considered to be Lake Agassiz III and IV, respectively, and these changes have been made when referring to the work done by Wicks.

The Lake Agassiz III unit in the Winnipeg area is generally 20 to 40 feet thick and has been divided by Wicks

(1965) into two beds by its colour and structure. A lower bed, called the blue-grey clay, is 20 to 30 feet thick and is massive. Isolated, small, calcareous silt lenses and limestone pebbles with a lesser number of igneous rock pebbles are common, particularly in the lower sections of the bed. An upper bed, called the brown clay, lies conformably on the blue-grey clay and is 20 to 30 feet in thickness. The distinctive feature of this bed is that it is very finely 'varved'. Both beds in this unit are glacio-lacustrine in origin.

The Lake Agassiz IV unit in the Winnipeg area is 8 to 15 feet in thickness and, according to Wicks (1965), may be divided into a basal yellow silt bed, a middle 'varved' silty-clay bed and an upper fine sandy clay bed based on the reports of Wallace and Maynard (1924), MacDonald (1937), and Riddell (1950). Wicks (1965) also states that only the middle 'varved' silty clay bed is a strictly lacustrine deposit; and that, according to Ellis and Pratt (1953), the underlying yellow silt is an aeolian deposit formed during a period of subaerial erosion between Lake Agassiz III to IV phases. Also, the overlying fine sand-sandy clay is a fluvial or fluvio-lacustrine deposit associated with a predecessor of the Red River and possibly the late stages of Lake Agassiz IV.

Along the Winnipeg River, in the Red River Basin, McPherson (1968) divided the Lake Agassiz deposits into

three units (Table II). Unit 1, the clay unit, consists of grey-brown clay and buff silty clay with silt and till clasts, rock fragments and quartz grains common in the lower part of the unit. In general, the non-clay minerals increase with depth.

The 'mud' unit (Unit 2) as defined by McPherson (1968) comprises a basal section 1 to 5 feet thick composed of alternating layers of grey mud and buff fine sand, a central portion 2 to 15 feet thick composed of alternating layers of silt and silty clay and an upper portion 2 to 10 feet thick composed of buff-colored generally massive mud with a slight indication of bedding. The 'mud' unit is essentially composed of dolomite grains, quartz grains and clay minerals.

Unit 3, the sandy silt unit, is composed of quartz and dolomite grains deposited in the shallow water of Lake Agassiz IV as a result of delta construction and offshore processes.

Table II

Pleistocene Stratigraphy along the Winnipeg River (after McPherson, 1970)

Unit	Thickness	Average Grain Size	Origin
3	0 - 15'	sandy silt	glacio-fluvial and glacio-lacustrine sandy silt erosional unconformity
2	0 - 25'	'mud'	glacio-lacustrine deposit erosional unconformity
1	0 - 35'	clay	glacio-lacustrine deposit

CHAPTER IV

PRESENT SEDIMENTARY ENVIRONMENT IN THE SOUTH BASIN OF LAKE WINNIPEG

The south basin of Lake Winnipeg has a maximum length of 55 miles and a maximum width of 25 miles. The bathymetric map (Fig. 8) indicates a maximum depth of 40 feet for the basin. Contours were drawn through soundings on Canada hydrographic charts 6240 (1963) and 6251 (1961) and from echograms using a lake level datum of 713 feet above sea level. The water depth increases quite rapidly on the eastern and western shores of the lake but increases relatively slowly away from the mouths of the Red and Winnipeg Rivers. This may be attributed to deposition of the suspended load of the rivers creating depositional 'deltas'.

Echograms indicate that these 'deltas' do not have the inflections in surface slope characteristic of deltas with topset, foreset and bottomset beds, but indicate a gentle sloping away from the mouth of each river. At the mouth of the Red River this lack of topset, foreset and bottomset beds is probably the result of the lack of deep water adjacent to the river mouth in which to develop recognizable foreset and bottomset bed slopes in addition

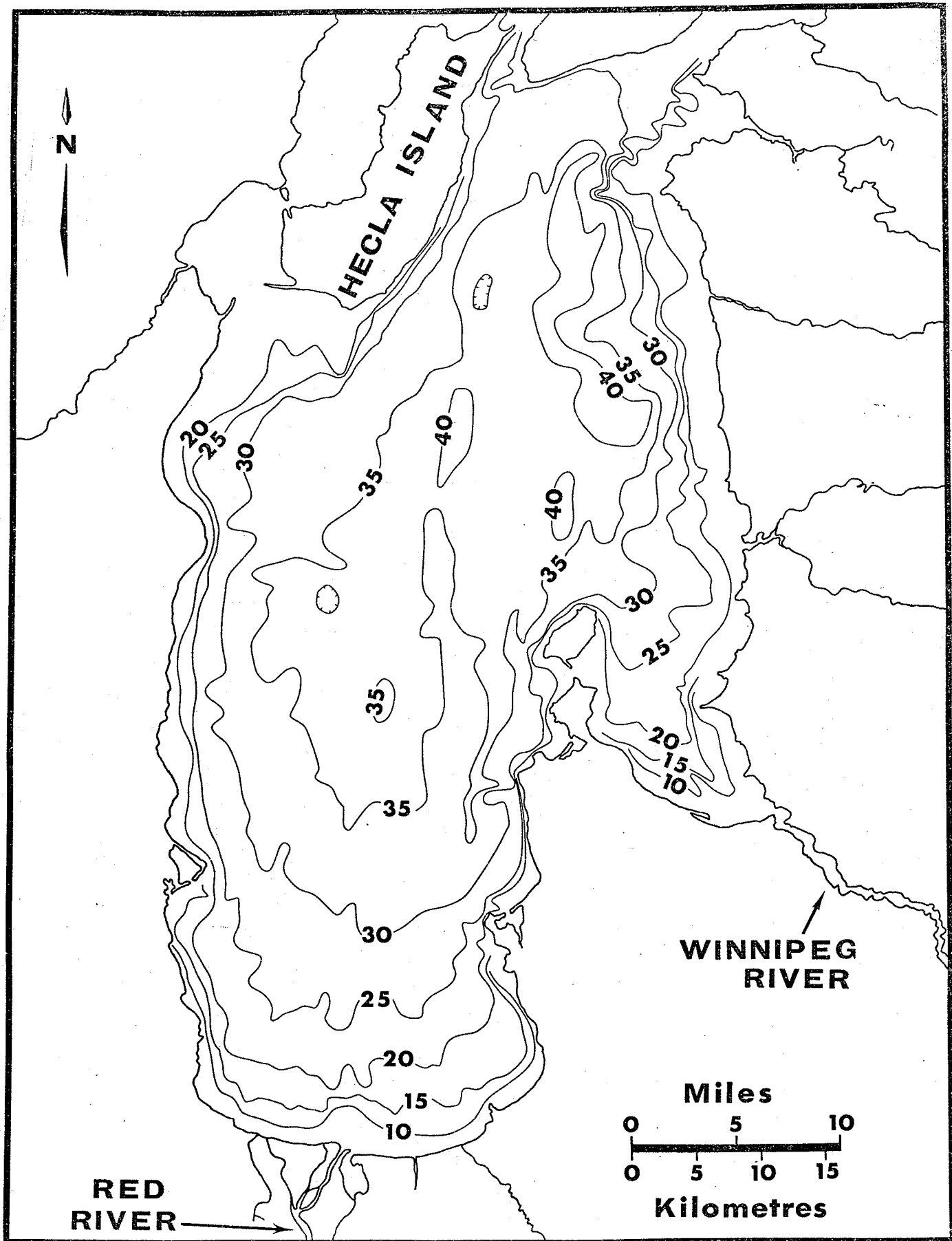


Fig. 8. Bathymetric map of the south basin of Lake Winnipeg.
(contours in feet)

to the bottom sediment homogenizing effects of littoral currents and storm waves. Veldman (1969) states that there are very strong southward-flowing littoral currents on the lakeshore on either side of the Red River Delta in areas he calls Reach 2 and Reach 5 (Fig. 9). The southward littoral drift results in sand moving into the 'delta' from the adjacent shoreline necessitating constant dredging of sand from the Red River outlet. These currents must meet at or near the mouth of the Red River and probably cause considerable mixing resulting in a homogeneous distribution of sediments.

The other factor which might prevent development of a typical delta is large storm waves. Veldman (1969) calculated wave energy distributions for Lake Winnipeg. The percentage of total wave energy from all directions are illustrated in Fig. 10.

By far the largest proportion of wave energy on the lake is distributed in a north-south direction. During storms, the force of waves entering the mouth of the Red River may be strong enough to retard, or even completely reverse, the flow of the river (personal observation).

Grain Size of Bottom Sediments

Grain size analyses (Table III) indicate that most of the surface sediments of the south basin are composed of materials containing greater than 70 percent clay-sized

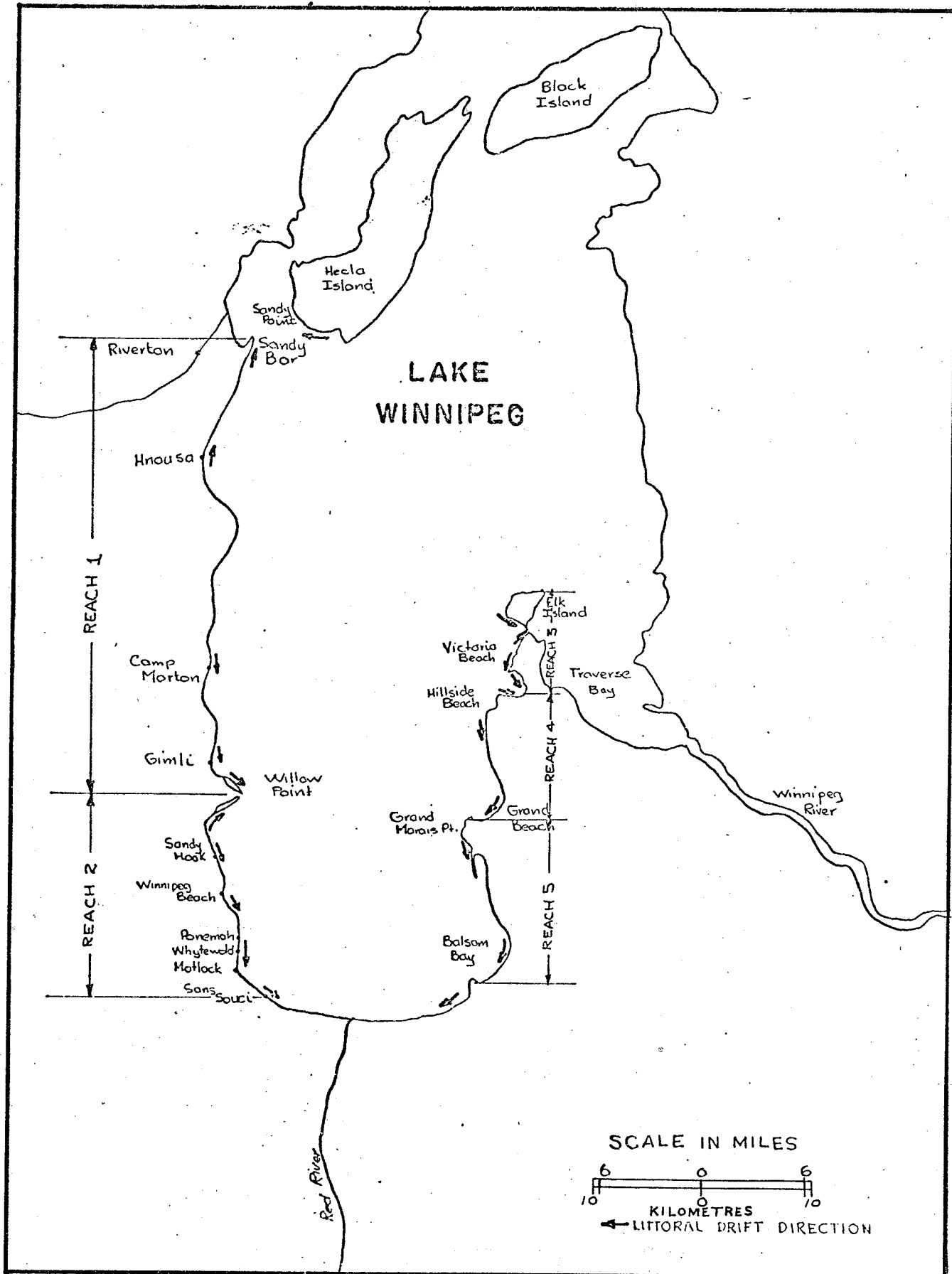


Fig. 9. Predominant littoral drift directions for the south basin of Lake Winnipeg (after Veldman, 1969).

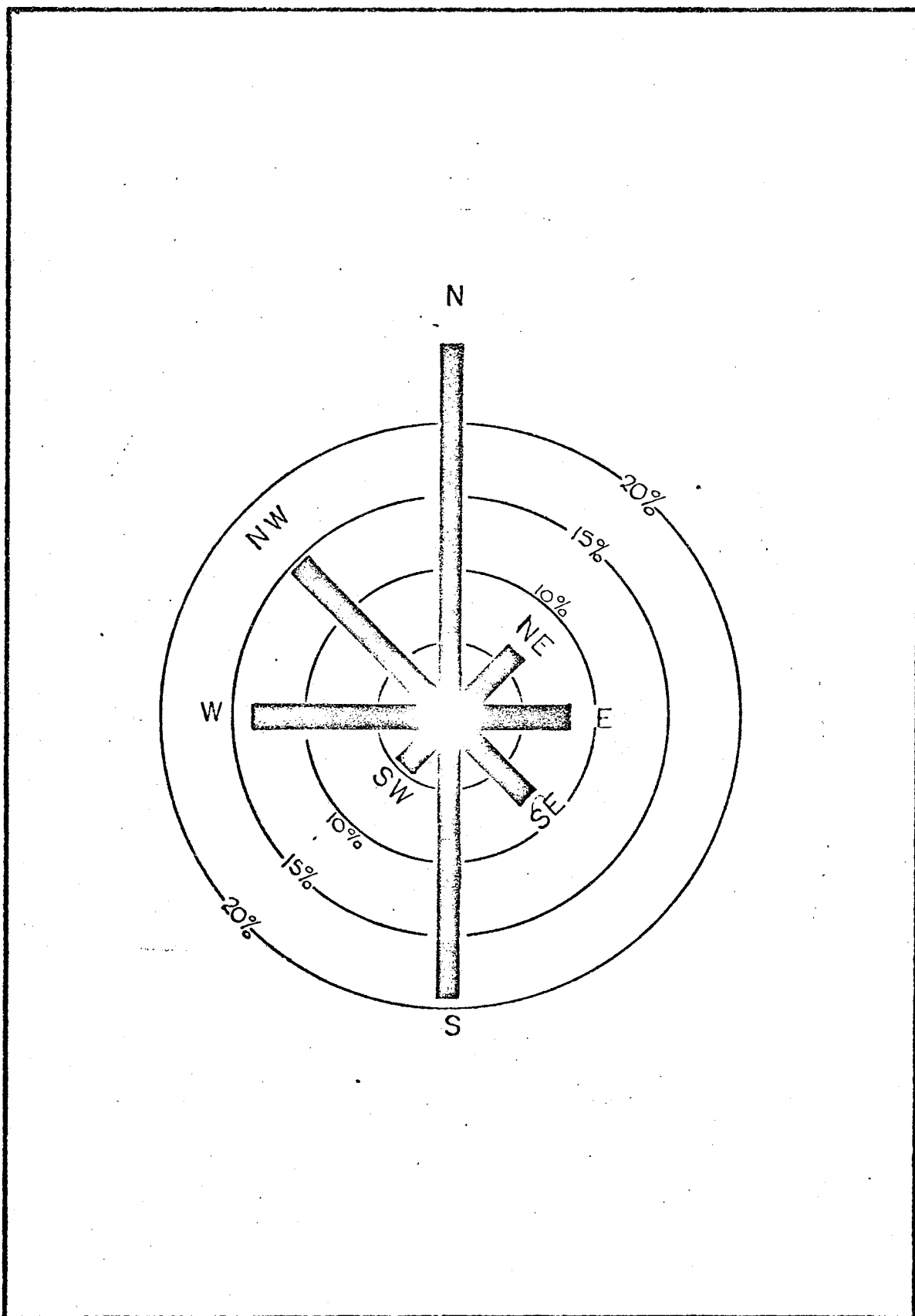


Fig. 10. Percent of total wave energy for given directions in the south basin of Lake Winnipeg (after Veldman, 1969).

TABLE III

Compositional Analyses of the Lake Winnipeg Sediments

Sample No.	Sand ¹ (%)	Silt (%)	Clay (%)
701	68	11	21
702	0	30	30
703	0	43	57
703C	0	35	65
703D	0	26	74
704	0	31	69
704B	0	19	81
705	0	14	86
706	0	19	81
707	2	55	43
708	0	49	51
709-P ²	0	4	96
710	0	7	93
712	71	8	21
713	sand and gravel		
713B	1	6	93
757	0	5	95
758	sand and gravel		
759	0	6	94
759B	0	5	95
760	0	4	96
760B	0	16	84
760C	0	19	81
760D	0	9	91
761	0	10	90
761B	0	17	83
762	sand and gravel		
762B	0	6	94
801	70	11	20
802	2	52	46
803	0	28	72

¹ Percentages are to the nearest 1 per cent.

² A sample followed by a dash and then a "P" indicates a Pleistocene clay.

TABLE III (concluded)

Sample No.	Sand (%)	Silt (%)	Clay (%)
804	0	8	91
805	23	13	64
807	0	2	98
808	0	16	84
809	0	26	74
811	0	20	80
812	0	9	91
813	0	7	93
815	28	6	66
815-P	2	11	87
816	0	4	96
817	5	10	85
818	0	8	92
819	0	16	84
820	0	8	92
822	0	11	89
823	5	11	85
823-P	0	16	83
824	0	12	88
825	0	6	94
826	n.d.		
826-P	2	21	77
827 ¹	10	15	75
827-P	1	13	86
828	0	3	97
829	0	13	87
830	0	13	87
831	0	8	92
832	1	4	96
833	0	13	87
835	0	19	81
R1	71	0	29
R2	gravel		
R3	0	44	56

¹ Sample contained large pieces of gravel which were not included in the analysis

particles (clay is defined here as material of 4 microns or finer). Figure 11 indicates the areal distribution of clay in the bottom sediments by means of percent clay contours. Two areas of very high clay content are present which contain greater than 90 percent clay-sized material. These may be areas of relatively quiet water where the clays are allowed sufficient time to settle. Unfortunately, very little data on lake flow patterns or water residence time is available for the lake and no definite conclusion can be made regarding the formation of these clay deposits.

The location of the high clay content areas may be related to the flow patterns and currents produced by the Red and Winnipeg Rivers; that is, the main flow of the Red River may be between the two areas of higher clay content and the main flow of the Winnipeg River may proceed along the eastern shore of the lake and thus not disturb these areas.

These areas of high clay content are roughly parallel to the shore on either side. It is possible that fine clay is derived from the shore by wave action eroding Glacial Lake Agassiz sediments or glacial drift. The fine material may be carried in suspension to areas of 'quiet water' where the clay has a chance to settle out. A combination of both of these effects may be responsible for the location of these areas of very high clay content.

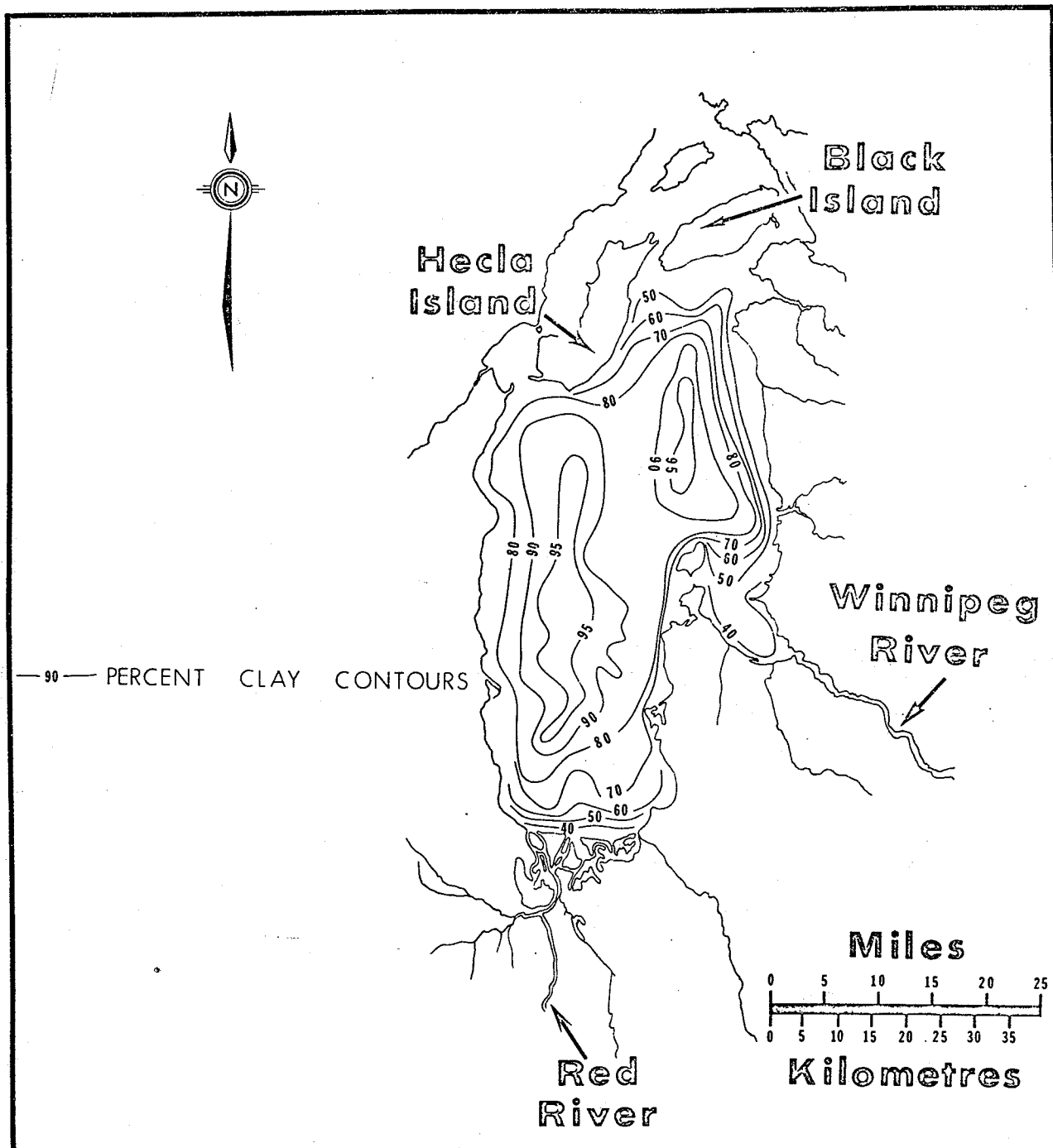


Fig. 11. Percent clay contours in the surface sediments of the south basin of Lake Winnipeg.

Bottom Sediment Distribution and Character

The micro stratigraphy of the clayey bottom sediments of the south basin was similar at all stations. Generally, the top layer consisted of a light buff-colored clay which ranged in thickness from about 1 millimetre to about 2 centimetres; below this was a dark chocolate brown layer, usually 1 or 2 millimetres thick, which was not present in all samples; and below this was a light grey to dark grey layer containing numerous black sulphidic laminations which continued without change to the bottom of the sample, 15 to 20 centimetres below the sediment-water interface.

The bottom sediments of the south basin were divided into three sedimentary units (Fig. 12) by means of echogram interpretation and grain size analyses. These sedimentary units take the form of three generally concentric zones in the basin; a large clay unit in the center of the basin, a mud unit (silty clay and clayey silt) 'shoreward' of the clay unit and an undivided unit (consisting of sand, gravel and Glacial Lake Agassiz deposits) near the shore.

The clay unit has the largest areal distribution of the three with the silty clay and clayey silt being intermediate in size and the undivided unit having the smallest distribution.

The boundary between the clay unit and the mud unit, though generally gradational, is well-defined and lies within the 70 and 80 percent clay contours (Fig. 11).

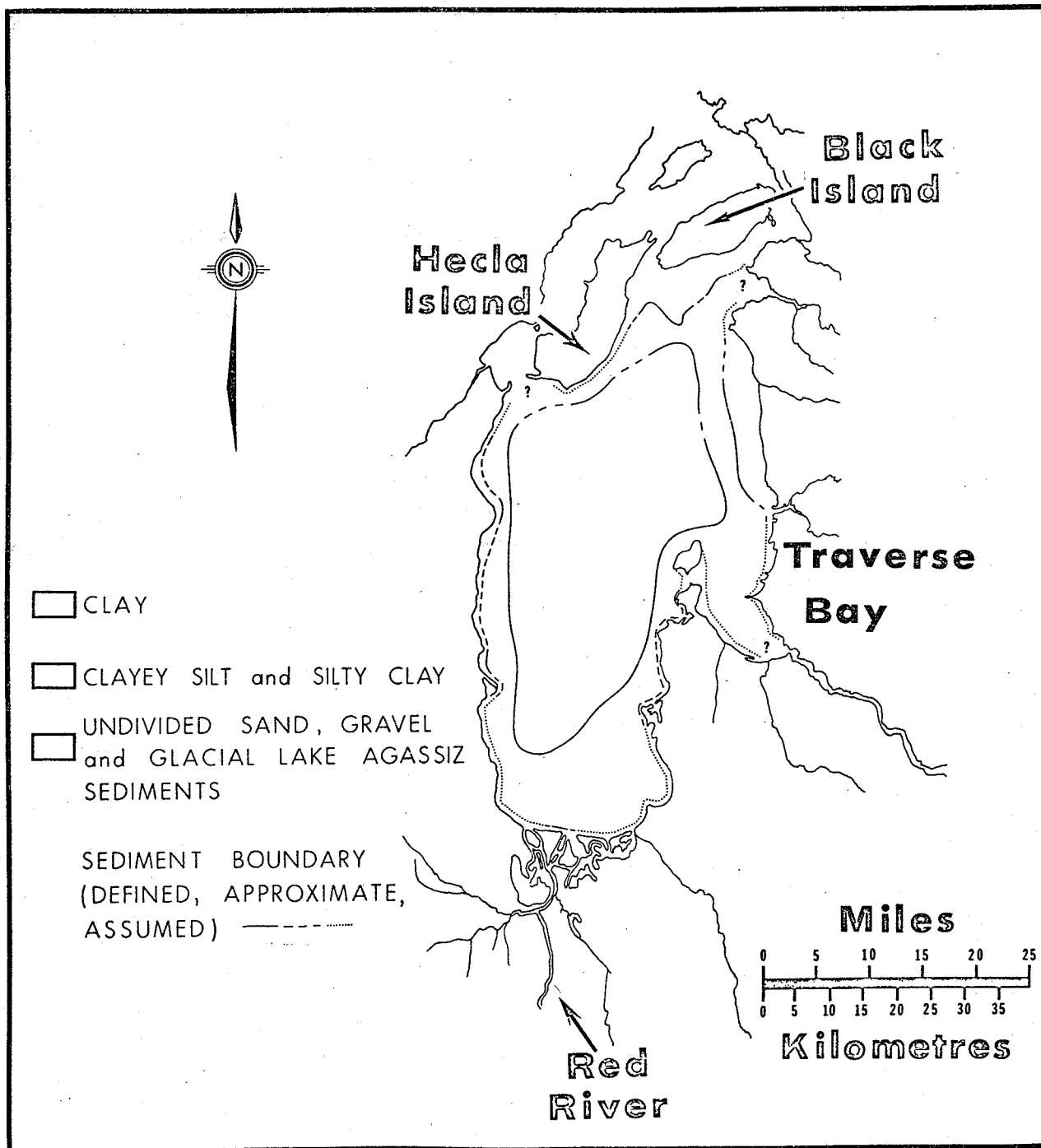


Fig. 12. Areal distribution of the sedimentary units in the south basin of Lake Winnipeg

Compositional analyses of all samples (to the nearest one percent) are plotted on a ternary sand-silt-clay composition diagram (Fig. 13). Those samples which are in the clay unit all fall into the area of the diagram defined as clay. These samples contain minor amounts of sand, usually less than one-half of one percent, and plot on the zero percent sand line. For the purpose of illustration these points have been 'moved out' from the zero percent sand line and appear to contain one to two percent sand.

The apparent thickness (Appendix B) of this clay unit is at least 25 feet in the centre of the basin.

The mud unit as defined by the echograms is essentially a silty clay unit with fewer samples of clayey silt (Fig. 13). The apparent thickness of this unit ranges from approximately 15 feet in deeper portions of the basin to less than 1 foot in shallow areas. The contact or boundary between the silty clay and clayey silt unit and the undivided nearshore unit is generally poorly defined. The reason for this is two-fold. Firstly, the boundary is close to shore in most places and the shallow water depth limited the access to the nearshore areas by the BRADBURY (6 foot draft); thus, shallow water samples are not numerous as no ship to shore transects were conducted. Secondly, the unit thins shoreward and in many places was too thin to be observable on the echograms, but was still thick enough to be sampled. Thus, silt and clay may be present on a relatively hard bottom but may

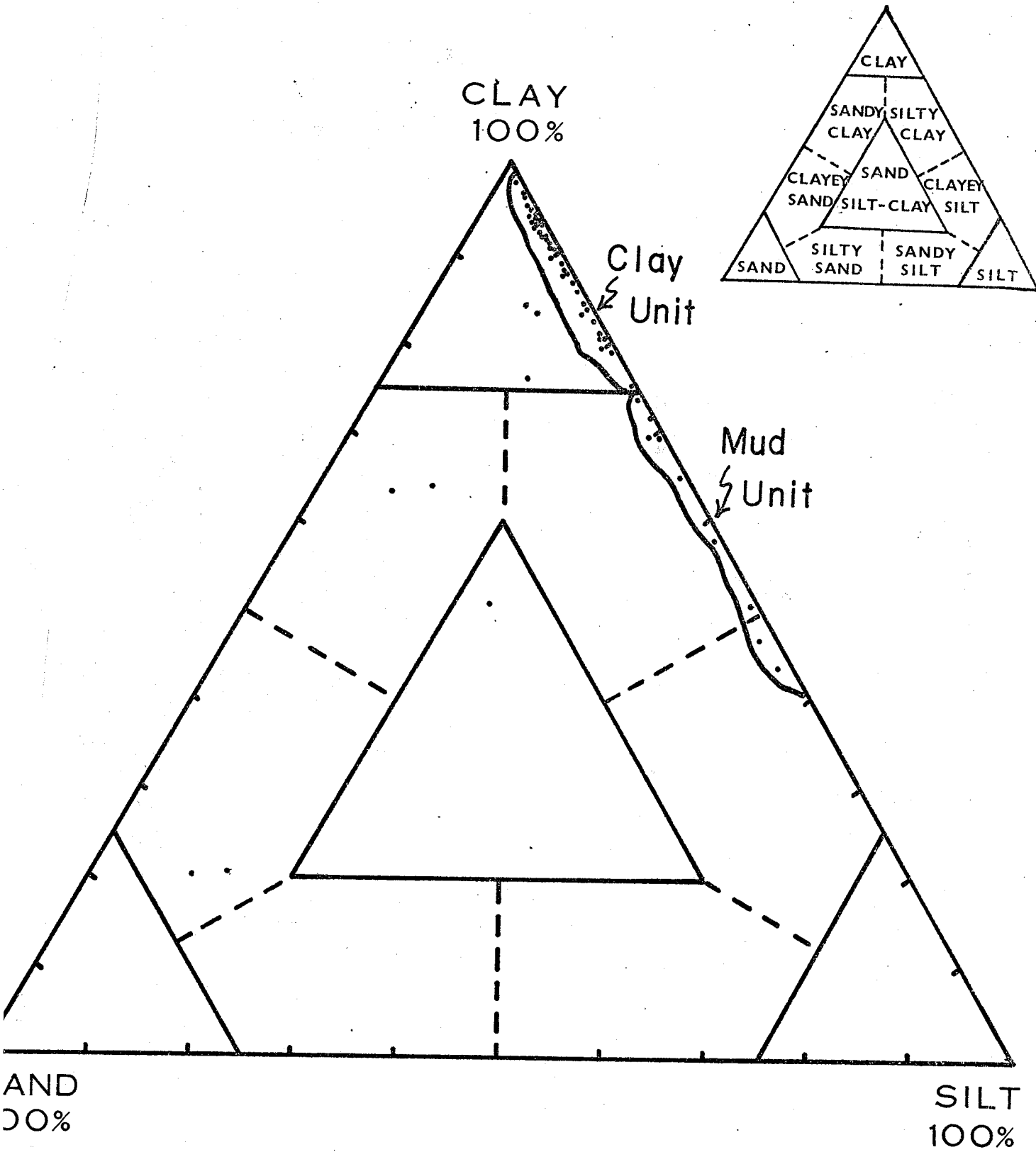


Fig. 13. Ternary sand-silt-clay composition diagram of the sedimentary facies in Lake Winnipeg (classification after Shepard, 1954).

be impossible to detect on echograms.

The sedimentary unit closest to the shore consists of undivided sand, gravel and Glacial Lake Agassiz deposits as well as silt and clay in small to minor amounts.

This unit is undivided because of the great variability of the bottom sediments from station to station. On the west side of the lake the unit consists of wave-modified glacial drift (determined from echograms) and 'varved' compact Glacial Lake Agassiz clays. With these deposits occurs considerable amounts of sand and gravel which consist of fine to medium-grained fragments derived from the Precambrian Shield (sub-rounded to angular grains of quartz, feldspar and other mafic igneous rock particles), larger amounts of fine to very coarse-grained, well-rounded limestone and dolostone fragments, which have brown iron oxide crusts or staining on them, and also fine-grained, well-rounded, frosted and pitted quartz grains (which are interpreted to be derived from erosion of the Winnipeg Sandstone Formation).

On the east side of the lake from sample station 823 to 713 (Fig. 2) the bottom consists of irregular 'outcrops' of glacial drift and Lake Agassiz clays, with considerable amounts of sand, silt and clay. The sands are mostly igneous and metamorphic in origin (quartz, feldspar, hornblende, pyroxene, muscovite, weathered biotite, rounded fragments of sericite schist and chlorite schist) with

occasional fine to coarse-grained, well-rounded fragments of limestone and dolostone and fine-grained, well-rounded, frosted and pitted quartz grains.

One feature of this sedimentary unit which is present on the eastern side of the lake but not on the west is the presence of very well-rounded, generally tabular clay clasts which range in size from approximately 1 millimetre in diameter to sizes of 3 centimetres long and 1 centimetre wide and one-half centimetre thick. Many have the appearance of a disc and resemble a ten-cent piece, but are thicker. Many of the smaller clay clasts are extremely oxidized and have a rust color both on the surface and in the interior. Some of these clasts (the larger ones) are not oxidized to the same degree as the smaller ones (these have only a light buff brown discoloration on their surface) and are composed of alternating light and dark colored layers, while others show no apparent layering. These clay clasts are interpreted to be Glacial Lake Agassiz deposits which have been re-worked. The time and mode of formation of these clasts is unknown. It is possible that they are the result of late glacial ice-rafting from Shield areas where they had been rounded previously or that they have been rounded by the action of present-day littoral currents and possibly waves.

Neither of these hypotheses explain the severe oxidation observed on most of the clasts. Another possible origin might be that the clasts were eroded from subareally-

exposed Agassiz clays by streams which flowed into a previous low level phase of Lake Winnipeg.

Low lake levels probably did occur in early post-glacial time when the outlet threshold north of Lake Winnipeg was still isostatically depressed relative to the south basin area. Isobases on the water plane of the last glacial lake, the Pipun Phase (Johnston, 1946), indicate that differential uplift of about 30 feet has occurred since Pipun beach formation. Because the present outlet came into operation after the Pipun Phase this value of uplift is a maximum estimate of the magnitude of basin tilting and the level of early Lake Winnipeg below its present level in the north basin. The figure for the south basin is obviously less as tilting decreases southwards. Taken from Johnston's (1946) uplift curves the figure for the south basin is a minimum of 25 feet. The echograms of the Narrows area between station 712 and 713B (Fig. 2) indicate four separate areas approximately 5 miles apart which appear to be possible near-shore terraces at an approximate elevation of 684 feet above mean sea level (Fig. 14). It is doubtful that these surfaces could be forming today at a depth of 32 feet below the present level of the lake. These terraces are considered to be representative of a former lower level of Lake Winnipeg.

Some samples of 'varved' Glacial Lake Agassiz sediments appear to have been sampled in situ as the sampler 'cut' or 'sliced' the clay. A characteristic of this clay is



Fig. 14. Terraces of a possible former lower Lake Winnipeg.

cylindrical tubes varying in diameter from one millimetre to approximately 5 millimetres. The cylindrical tubes may be fossil root casts dating from a period of extremely low lake level and subaerial exposure; or they may be the result of some burrowing or boring organism. The latter hypothesis is preferred by the writer as no organic matter was found in the tubes; that is, root fragments might be expected in at least some of the tubes if roots had once filled them. These clays are considered to be of Lake Agassiz III or IV in origin, but the exact position in the Lake Agassiz sequence cannot be determined.

Figure 13 illustrates the wide range of sand, silt, and clay compositions that samples taken in the undivided unit possess (these are the points which are not included in the clay unit or the silty clay and clayey-silt unit). The grain sizes of most of these points are actually apparent as many of the samples contained gravel-sized fragments which were not included in the grain size analysis.

Rate of Sedimentation

Ward (1926) conducted a study on the seasonal variation in the quantity of suspended sediment carried by the Red River and stated that

"In the month of June (1925) there was carried to Lake Winnipeg 629.8 parts per million of suspended matter. By the time this water reached Black Island, its suspended matter had diminished to 6.3 parts per million."

and

"... the amounts of material remaining in the lower end of the lake is found to be enormous."

From this, it would appear that almost the entire suspended load of the Red River (as well as the Winnipeg River) is being deposited in the south basin. Sedimentation rates were calculated for the south basin assuming the Red River to be the basin's only contributor of suspended sediment. The estimated rates are minimal because sediment contributions from shore erosion and other rivers are not considered. The effect of unknown inputs may be offset, in part, by the indicated sediment outflow from the basin through the Narrows. Suspended sediment data were obtained (Water Resources Papers S1, S2, S3 and Sediment Data for Canadian Rivers 1965, 1966 and 1967) for the water years (October 1 to September 30) of 1963 to 1967 inclusive. The yearly suspended load data in tons was converted to pounds and then into cubic feet (according to Ward, 1926, it has been stated in Water Supply Paper 174, U.S.G.S. that 107 pounds of load represents one cubic foot of sediment). For purposes of calculation, the dimensions of length and width for the south basin were assumed to be an average of 50 miles by 20 miles respectively, or 1000 square miles.

Table IV shows the suspended load for each water year from 1963 to 1967 and the calculated rate of sedimentation. The rates vary from almost 0.3 millimetres a year to almost

Table IV

Suspended Load in the Red River and Sedimentation Rates in the
South Basin of Lake Winnipeg during the Water Years of 1963 to 1967

<u>Water Year (Oct.1-Sept.30)</u>	<u>Suspended Load</u>	<u>Yearly Deposition</u>
1963	1433569 tons	0.27 mm
1964	2178459 tons	0.43 mm
1965	3807466.1 tons	0.76 mm
1966	3307511.4 tons	0.67 mm
1967	2663802.1 tons	0.5.4

0.8 millimetres a year with the average being 0.5 millimetres. Thus an average of 0.5 millimetres is deposited over the entire bottom of the south basin in one year. This figure is probably not absolutely right but should give the order of magnitude of the rate of sedimentation.

CHAPTER V

MINERALOGY OF SEDIMENTS

Mineral identifications were made primarily by X-ray techniques, but Differential Thermal Analysis of selected samples was also performed. Methods of sample preparation and procedure are described in Appendix A.

The relative proportions of quartz, dolomite and feldspar for the 62.5 microns and finer fraction of each sample were estimated from diffractograms of oriented slides by assuming peak heights as indicators of the relative amount of each mineral present though not necessarily proportional to the absolute amount of each mineral present.

Quantification of clay mineral content was achieved using method number two of Pierce and Siegel (1969) in which the integrated intensity of the 17 Å glycolated peak is considered equal to the relative amount of montmorillonite; the area of the 10 Å peak (glycolated trace) multiplied by four is equivalent to the relative amount of hydromica (illite) and the 7 Å peak area multiplied by two is equal to the relative amount of kaolinite plus chlorite. Unfortunately, circumstances necessitated the use of this method with glycerolated rather than glycolated peaks.

Johns and Tettenhorst (1959 and 1964) found that ethylene glycol produced a more enhanced expansion of montmorillonite than did glycerol.

As a check on possible differential diffraction effects caused by the glycolation and glycerolation treatment of Lake Winnipeg sediments, two arbitrarily selected samples (samples 703 and 708) were treated with glycerol and glycol and the peak areas compared (Figs. 15 and 16). The peak areas were very similar (within 5 percent for the first order montmorillonite peak) and for the present study it was concluded that the use of glycerol-treated samples rather than glycol-treated samples produced no great error in quantification of clay minerals.

Glycerolation was accomplished using the method of Rex (1968) with some modifications (Appendix A). In addition to glycerolated samples, oriented slides were prepared (pipette on glass slide method) of the silt (62.5 microns) and clay (3.9 microns) particle size fractions for each sample, from which qualitative non-clay mineralogy was determined.

Results of X-ray Analyses

As an aid in understanding the mineralogy of the Lake Winnipeg sediments, a brief summary of the mineralogy of the Prairie surface deposits is presented here. A more detailed and excellent coverage of this topic is given by

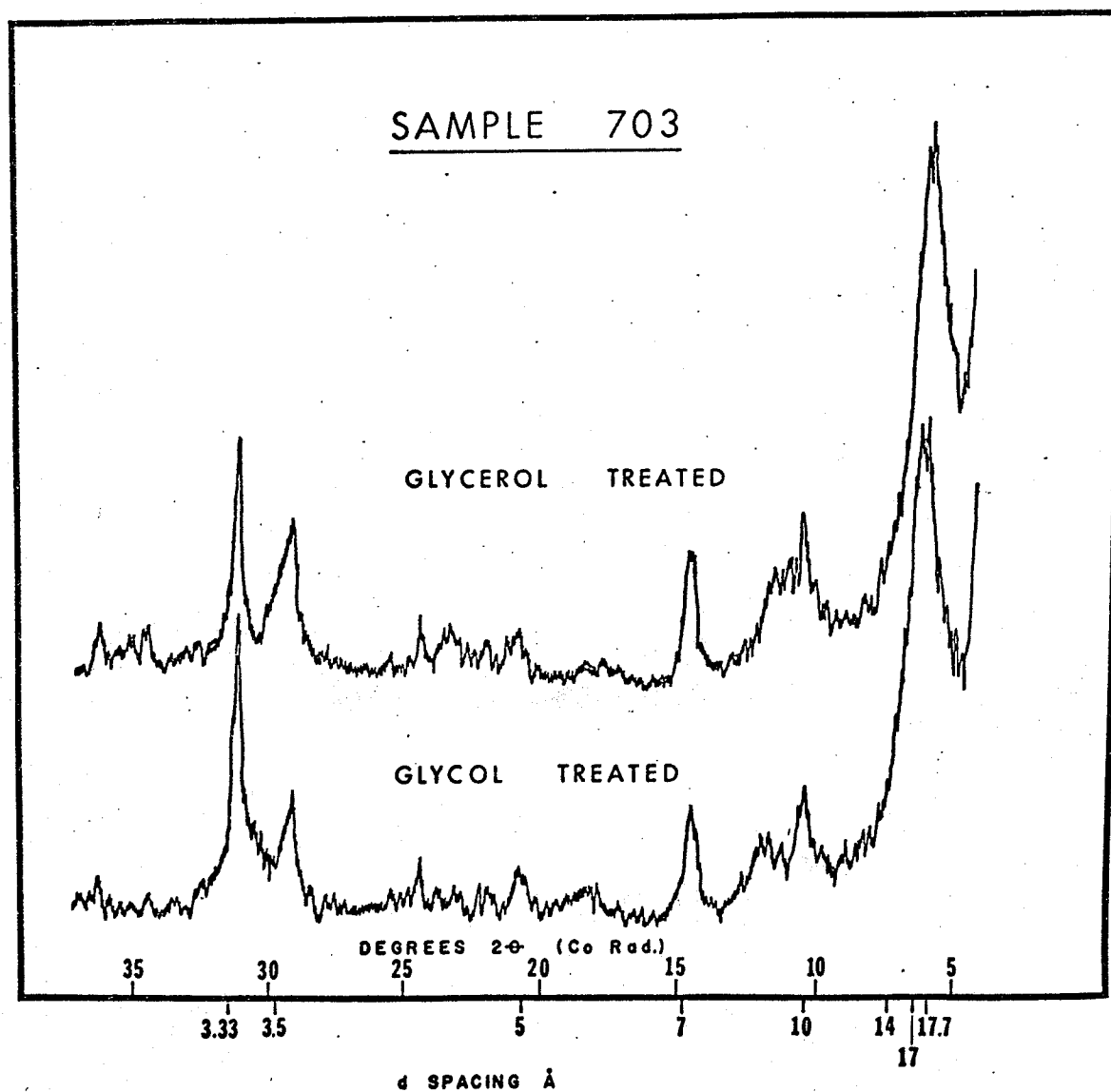


Fig. 15. Comparison of X-ray peak sizes for glycerol and glycol-treated unoriented slides of sample 703.

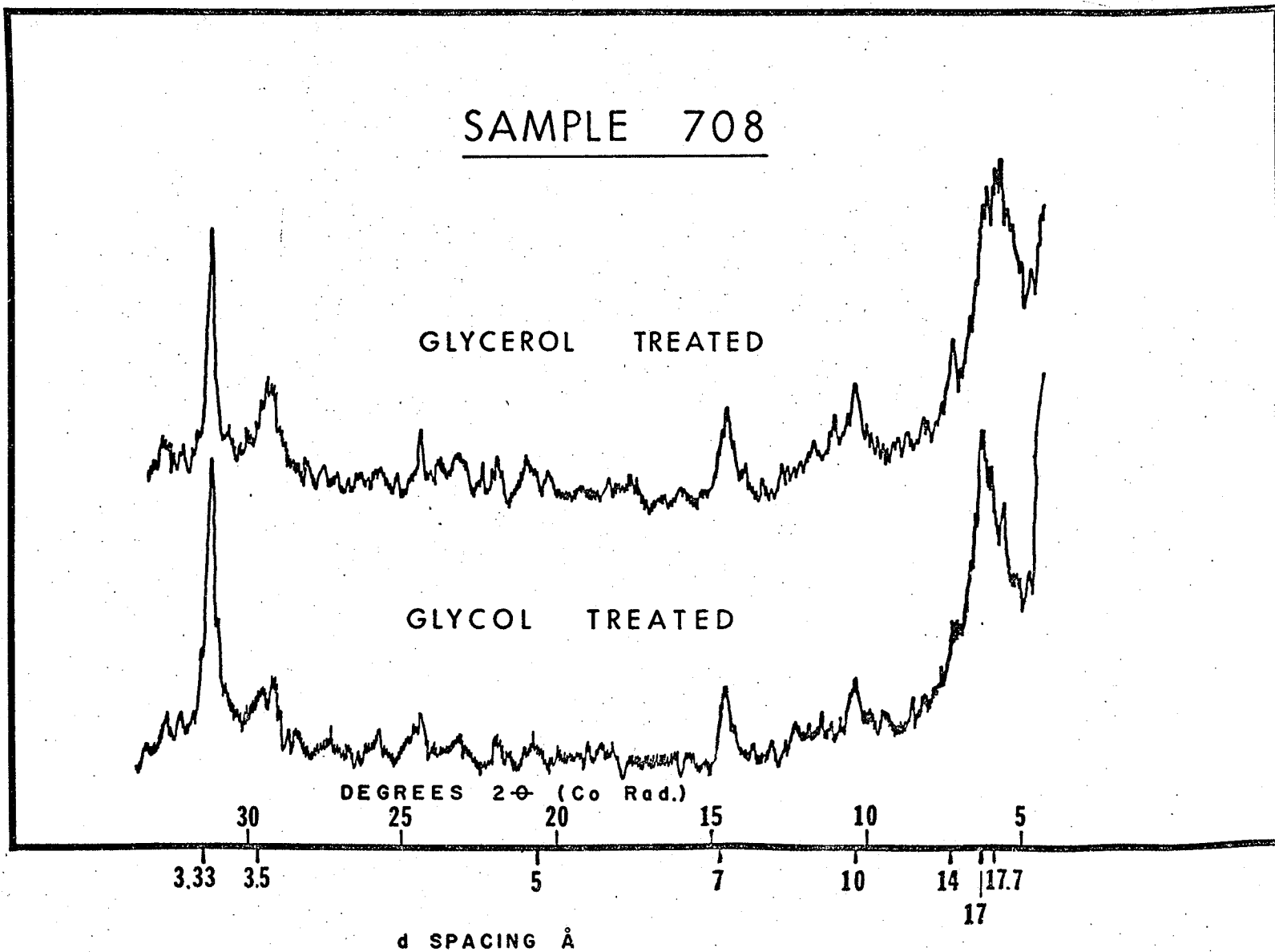


Fig. 16. Comparison of X-ray peak sizes for glycerol and glycol-treated unoriented slides of sample 708.

Wicks (1965) from which much of the following information is derived.

Table V presents a summary of the clay mineralogy of the Prairie surface deposits. The material studied consists of tills, loess, glacio-fluvial sands and lacustrine clays. In general, the mineralogy of all deposits is very similar. Montmorillonite is the dominant mineral in almost all studies with major to minor amounts of illite, minor amounts of kaolinite and minor trace amounts of chlorite. Minor amounts of quartz and feldspar are also present. Montmorillonite is the dominant mineral in the very fine clays while illite is the major mineral in the coarser clay fraction.

Table VI lists the results of clay mineral analyses of Cretaceous Shales of the northwestern United States and of the Prairie Provinces. A comparison of Tables VI and VII reveals a striking similarity between the clay mineralogy of the Cretaceous Shales and of the glacial and glacio-fluvial deposits. Wicks (1965) states that "Many authors have noted this similarity... and all have reached the conclusion that the Cretaceous Shales are the source of the clay minerals in the glacial and glacio-fluvial deposits". The significance of this conclusion is that very little diagenetic change has occurred (Kodama and Brydon, 1965) during erosion from the source area to redeposition in tills and glacio-lacustrine clays.

TABLE V

Published Data on the Clay Mineralogy of Prairie Surface Deposits

Reference	Ehrlich, Rice and Ellis (1955)			Warder and Dion (1952)	Christiansen (1959)	Christiansen (1960)	Greer and Christiansen	
Province	Manitoba			Saskatchewan	Saskatchewan	Saskatchewan	Saskatchewan	
Area	General			General	Swift Current	Qu'Appelle	Wynard	
Type of Deposit	Tills			Varied	Tills, Lacustrine Loess	Tills	Tills and Lacustrine	
No. of Samples	10			8	9	7	25	5
Size Studied (microns)	2-0.2	0.2-0.1	<0.1	<1.0	<2.0	<2.0	<2.0	
Montmorillonite	nil-20 ¹	10-40	15-70	55 ¹	55-90 ¹	dominant	dominant	minor
Illite	5-25	5-25	nil-15	45	5-30	minor	minor	major
Mica	nil-25	nil-20	nil-15	-	-	-	-	-
Mixed-layer	nil-10	nil-20	nil-20	-	-	-	-	-
Kaolinite	nil-10	nil-10	nil	trace	5-20	minor	minor	major
Chlorite	nil-15	nil-15	nil-10	-	-	-	-	-
Quartz	1-30	nil-5	nil	-	-	-	-	-
Feldspar	1-25	5-15	5-15	-	-	-	-	-

¹ Figures opposite minerals are %. (after Wicks, 1965)

TABLE V

Reference	St. Arnaud and Mortland (1963)		Rice, and Forman and Patry (1959) ²			Rice, Forman and Patry (1959) ²			Pawluk
Province	Saskatchewan		Saskatchewan			Alberta			Alberta
Area	Touchwood Hills		Sceptre, Regina, Melford			Three Hills, Nampa			Fort McMurray
Type of Deposit	Tills		Lacustrine Clays			Lacustrine Clay			Glaciofluvial
No. of Sample	4		3			2			2
Size Studied (microns)	2.0-0.2	<0.2	2.0-0.2	0.2-0.1	<0.1	2.0-0.2	0.2-0.1	<0.1	<2.0
Montmorillonite	major	74-80	dominant -major	dominant	dominant	major -minor	dominant	dominant -major	major
Illite	major	19-22	major -minor	major	trace	dominant -major	major -minor	nil- dominant	dominant
Mica	-	-	included with illite			included with illite			-
Mixed-layer	(possible illite-mont.) ³		-	-	-	-	-	-	major (illite-)
Kaolinite	minor	trace	minor	minor	tr-nil	minor	minor	tr-minor	minor
Chlorite	minor	trace	minor-tr	nil	nil	tr-minor	nil	nil	trace
Quartz	minor	nil	minor	nil	nil	major -minor	nil	nil	minor
Feldspar	minor	nil	trace	nil	nil	trace	tr-nil	nil	-

² Same Report

³ Mont. is used as an abbreviation for montmorillonite

TABLE V

Reference	Pawluk (1961) ²		Pawluk (1961) ²		Kodama and Brydon (1965)
Province	Alberta		Alberta		Manitoba, Saskatchewan and Alberta
Area	General		Alcan		General
Type of Deposit	Tills		Till		Tills, Lacustrine
No. of Samples	4		1		7
Size Studied (Microns)	2.0-0.2	<0.2	2.0-0.2	<0.2	0.2-0.04
Montmorillonite	minor-major	dominant	trace	trace	reported as mixed-layer
Illite	major	tr-minor	major	minor-major	10 Å mica-mont. phase
Mica	-	-	-	-	1 - 7
Mixed-layer	trace (illite-chlorite-mont.)	nil	minor	minor-major (illite-mont.)	89 - 97 (mont.-mica) ^a
Kaolinite	minor	trace	minor	minor	2 - 4
Chlorite	trace	nil	trace	nil	nil
Quartz	minor	trace	minor	trace	trace
Feldspars	-	-	-	-	-

^a Three values of illite and montmorillonite in the interstratified material were obtained with three analytical methods. X-ray diffraction peak heights 50-65% mont., Fourier transforms from X-ray diffraction intensities 55% mont., and chemical analysis 76-82% mont. The balance is mica-like mineral (illite, F.J.W.) in all cases. (after Wicks, 1965).

TABLE VI.

Published Data on the Clay mineralogy of Prairie Cretaceous Shale and Associated Rocks

Reference	Christiansen (1959)		Christiansen (1960)	Proctor (1959)	Greer and Christiansen (1963)
Province	Saskatchewan		Saskatchewan	Saskatchewan	Saskatchewan
Area	Swift Current		Qu'Appelle	Southwest	Wynyard
Formation	Bearpaw	Whitemud	Marine Shales, Bearpaw and Belly River	Blairmore Vanguard Shale	Bearpaw and Marine Shales
Rock Types	Shale	Sand-clay	Marine Shales	Shale and Siltstone	Shale
Size Studied (microns)	<2.0	<2.0	<2.0	?	<2.0
Montmorillonite	80-85 ¹	-	dominant	major	dominant
Illite	15-20	-	minor	dominant-major	minor
Mica	-	-	-	-	-
Mixed-layer	-	-	-	major-minor (mont.-illite) ²	-
Kaolinite	-	100	minor	minor	minor
Chlorite	-	-	-	minor-nil	-
Quartz	-	-	-	-	-
Feldspars	-	-	-	-	-

¹ Figures opposite minerals are %.

² Mont. is used as an abbreviation of montmorillonite (after Wicks, 1965)

TABLE VI.

Reference	Forman and Rice (1959)		Byrne and Farvolden (1959)	Lerbekmo (1963)	Tourtelot (1964)
Province	Saskatchewan		Alberta	Alberta	N.S., S.D., Neb., Mont.
Area	South of Saskatoon		Southern Alberta	Southern Foothills	and Wyoming, U.S.A.
Formation	Bearpaw		Bearpaw	Belly River	Pierre Shale
Rock Types	Shale		Shale	Mudstone and Shale	Shale
Size Studied (microns)	2.0-0.2	<0.2	<2.0	<2.0	<2.0 (?)
Montmorillonite	dominant	dominant	dominant	5-65 ³	10-20
Illite	major-minor	tr-nil	major	30-80 ³	10-20
Mica	-	-	-	-	-
Mixed-layer	-	-	-	15-25 (mont.-illite)	30-50 (mont.-illite)
Kaolinite	minor	nil	-	5-20	-5
Chlorite	trace	nil	minor	nil	-5
Quartz	tr-nil	tr-nil	-	-	-
Feldspar	tr-nil	tr-nil	-	-	-

³ Lerbekmo also found samples of both montmorillonite and illite, but only the polymineralic samples are included in the table. (after Wicks, 1965)

TABLE VII *

Qualitative Estimation (Peak Heights) of the Amount of
Quartz, Dolomite and Feldspar in the Lake Winnipeg Sediments

<u>Sample No.</u>	<u>Quartz</u>	<u>Dolomite</u>	<u>Feldspar</u>
701	M	M	S
702	M	M	S
704B	M	M	M
705	M	S	S
706	L	M	M
707	L	VL	M
708	L	L	L
709	M	-	S
710	M	-	M
712	L	L	VL
713B	M	-	M
757	L	L	M
759	M	S	M
759B	M	S	M
760	M	-	M
760B	M	L	M
760C	L	L	M
760D	M	S	M
761	M	S	M
761B	M	S	M
801	L	S	L
802	L	-	L
803	L	-	M
804	L	-	L
806	L	-	M
807	L	-	M

TABLE VII (concluded)

<u>Sample No.</u>	<u>Quartz</u>	<u>Dolomite</u>	<u>Feldspar</u>
808	L	S	M
809	L	M	L
811	L	L	M
812	L	S	L
813	M	-	S
815	M	-	M
816	S	-	S
817	M	-	M
818	M	S	M
819	M	M	M
820	M	-	M
822	M	S	M
823	M	S	M
823-P	M	VL	L
824	M	-	M
825	L	S	L
826-P	M	M	M
827	M	M	M
827-P	M	S	M
829	M	S	M
830	M	S	M
832	M	-	M
833	S	S	S
835	M	M	M
R3	L	M	M

* VL = very large, L = large, M = medium, s = small
and a dash (-) indicates no peak.

X-ray data of the Lake Winnipeg sediments indicates that the clay mineralogy of all samples is very similar and that mineralogically speaking the south basin appears to be homogeneous. Montmorillonite is generally the dominant clay mineral with major amounts of illite and minor amounts of kaolinite plus chlorite. The non-clay minerals consist mainly of quartz, dolomite and feldspar with minor amounts of calcite, muscovite and other granitic minerals. Table VII lists the qualitative estimations of quartz, dolomite and feldspar in each sample as determined from peak heights on diffractograms. The non-clay minerals increase in abundance at locations in the lake where the sediment becomes silty or sandy which usually occurs in shallow areas or at the mouths of rivers. In each sample the non-clay minerals (especially dolomite) are present in larger proportions in the silt fraction than in the clay fraction. This is well illustrated in Fig. 17 which shows diffractograms for an air-dried, untreated, unorientated sample; an oriented untreated slide containing mainly the silt fraction of the sample; an oriented untreated slide containing only the clay fraction (finer than 3.9 microns) of the sample, and an unoriented magnesium-saturated glycerol-treated slide. The main dolomite peak at 2.89 \AA on trace number 2 is hardly noticeable, while for the trace number 3 the peak is very large. Also the main quartz peak at about 3.33 \AA is larger on curve 3 (the silt fraction) than on trace number 2,

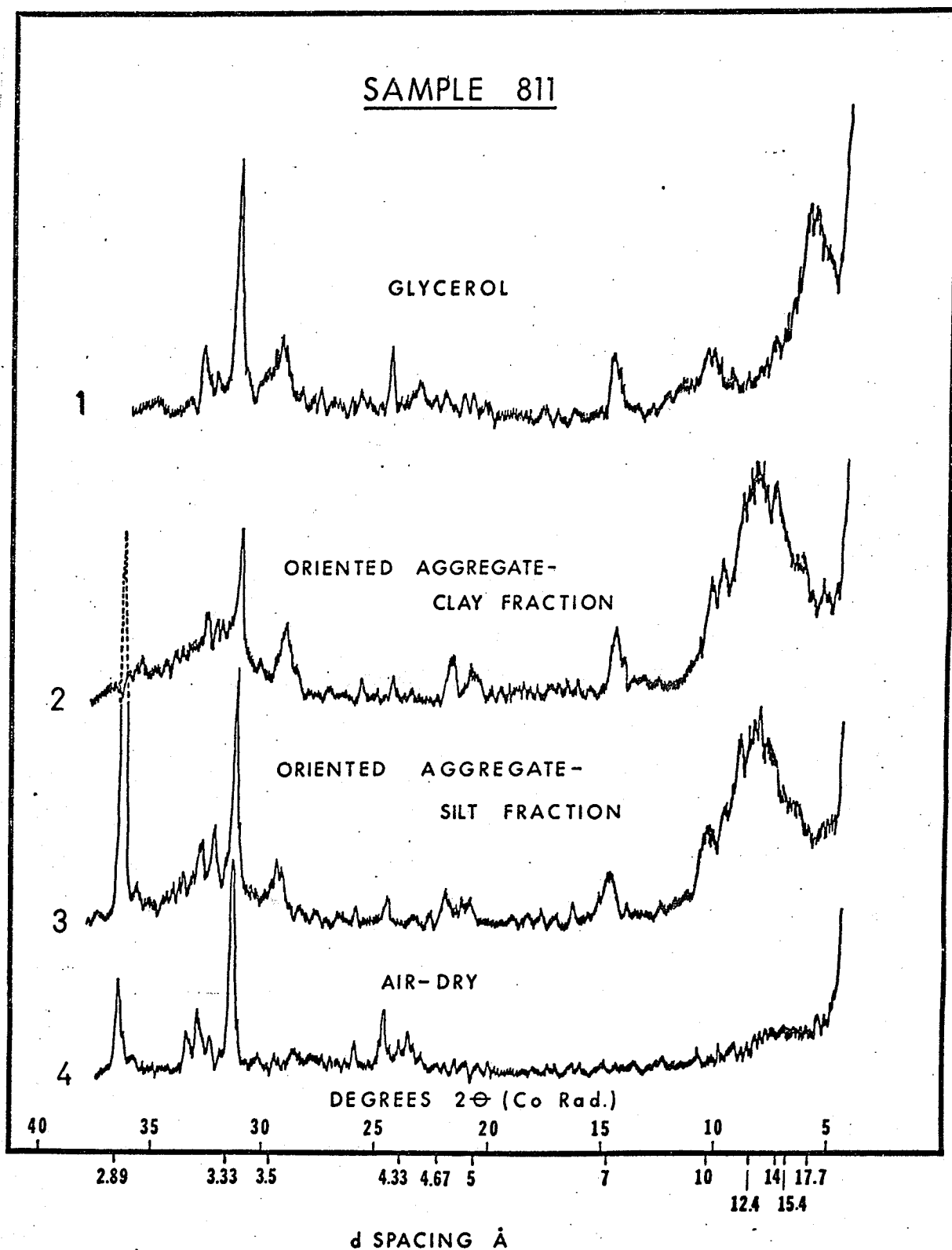


Fig. 17. Comparison of diffractograms for various treatments of sample 811.

the clay fraction. It is interesting to note here that the peaks for the clay minerals on trace number 2 are not significantly larger than on trace number 3.

Calcite is present only in minor amounts in the south basin of the lake with its main occurrence being at or near the mouth of the Red River. This is what might be expected by virtue of the fact that the Red River supplies most of the south basin sediments and because of the significant southward littoral drift in the basin.

Oriented aggregate slides (Fig. 17) exhibit a dominant phase at approximately 13 \AA with a smaller 'shoulder' at 10 to 10.5 \AA and a small peak at 7 \AA . The 13 \AA peak is interpreted to be the 15.4 \AA phase of montmorillonite which has shifted to 13 \AA because of interstratification with illite. The clays were considered to be dioctahedral in nature by the presence of a 1.49 to 1.50 \AA reflection; however, the peak was generally indistinct and not pronounced. Glycerol caused the 13 \AA basal reflection peak to shift to 17.5 to 18.0 \AA and caused the 10 \AA peak to shift to 9.7 to 9.8 \AA . The 17.7 \AA and 10 \AA phases in general when glycerolated occur as separate peaks but the 10 \AA phase is partially merged with the second order basal reflection of the 17.7 \AA phase. The 14 \AA peak was not visible on slides of oriented aggregates as it was included in the larger 13 \AA peak. When glycerolated, the 14 \AA peak at times appeared as a small shoulder on the 17.7 \AA peak

(or did not appear at all as it was encompassed in the larger 17.7 \AA peak). In each case, when the 17.7 \AA peak was small the 14 \AA peak was present and strong. Interstratification of montmorillonite and illite was considered to be occurring because of the migration of the illite and montmorillonite peaks to form one large peak. Glycerol had no effect on the 7 \AA phase. Heating to 550°C caused the 7 \AA peak to collapse but not disappear. From this it was concluded that both kaolinite and chlorite were present. No attempt was made to determine the relative amounts of kaolinite and chlorite; and no attempt was made to determine how much (if any) of the 14 \AA peak was attributed to vermiculite.

The exceptions to the above were the compact clays (both massive and 'varved') which are interpreted to be glacial and glacio-fluvial deposits. Non-treated samples (oriented aggregates) showed the montmorillonite peak to be much smaller, and the 10 \AA illite peak and the 7 \AA kaolinite plus chlorite peak to be much larger than most of the samples of Recent clays.

Figure 18 illustrates the diffractograms for four of the compact clays which have been magnesium saturated and glycerol treated. Each sample number is followed by the letter P which stands for Pleistocene. In each case these clays when collected from the lake were mixed with Recent clays in the sampler. The fragments of 'varved' and massive

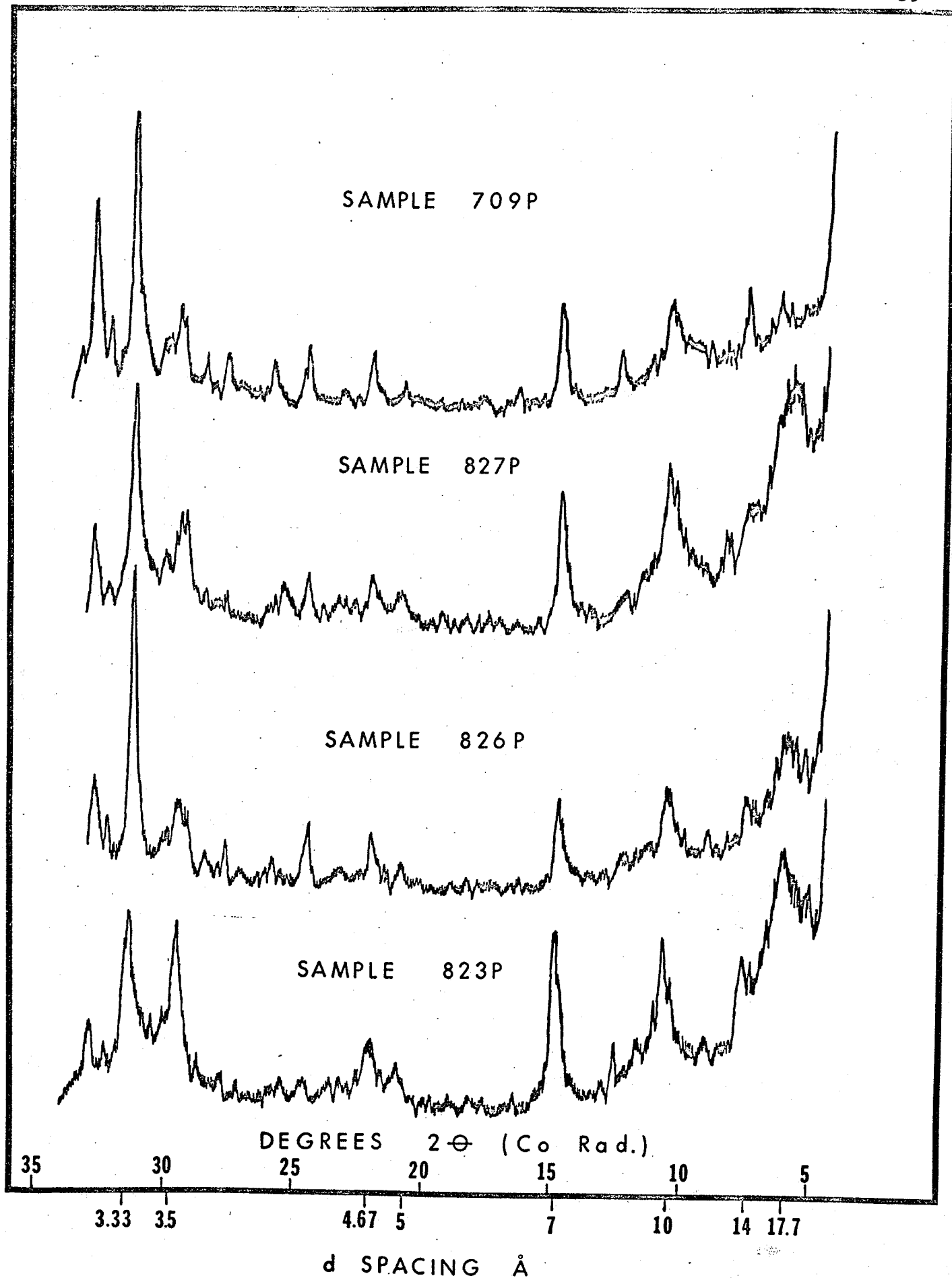


Fig. 18. Diffraction patterns of four glycerol-treatment magnesium saturated clays of glacial origin obtained from bottom sediment samples.

clays were removed from the recent sediment and washed with distilled water to remove any Recent clay 'contaminant'. These fragments were then subjected to all laboratory procedures. It at once appears obvious on comparing any of the four diffractograms with any of the Recent clay samples which have been magnesium saturated and glycerol-treated (Figs. 16, 17 and 18) that the size of the 7 Å, 10 Å and 14 Å peaks are much greater in the Pleistocene clays than in the Recent clays compared to the size of the main 17.7 Å montmorillonite peak. The curve for sample 709 P (Fig. 18) shows the 17.7 Å peak to be even smaller than the 7, 10 and 14 Å peaks. This sample is definitely of glacio-lacustrine origin as it is compact and 'varved'.

For a quantitative description of the amounts of each clay mineral present, the 17.7 Å glycerolated trace was considered to represent the total amount of montmorillonite though this is not strictly true as this peak really represents a random montmorillonite-illite interstratification, and the amount of illite was considered to be represented by the 10 Å peak, although it represents a random illite-montmorillonite interstratification.

Percent montmorillonite, illite and kaolinite plus chlorite (Table VIII) expressed as a percent of total clay minerals, not percent of all minerals in the sample, indicate that the lake is very homogeneous in this respect.

The average amount of each clay mineral as a percent

TABLE VIII

Montmorillonite, Illite and Kaolinite Plus Chlorite
as Percentages of Total Clay Mineral in Lake Winnipeg Sediments

<u>Sample No.</u>	<u>Montmoril- lonite (%)</u>	<u>Illite (%)</u>	<u>Kaolinite plus Chlorite (%)</u>
701	53	33	14
702	48	39	13
703	60	28	12
703C	49	36	15
703D	48	34	18
704	60	27	13
704B	54	32	14
705	52	34	14
706	60	27	13
707	62	27	11
708	56	30	14
710	36	49	15
712	60	27	13
713B	48	35	17
757	61	28	11
759	47	40	13
759B	29	45	26
760	43	40	17
760B	61	28	11
760C	61	29	10
760D	50	35	15
761	58	30	12
762B	58	29	13
801	50	37	13
802	55	31	14
803	51	34	15

TABLE VIII (Concluded)

<u>Sample</u>	<u>par Montmoril- lonite (%)</u>	<u>Illite (%)</u>	<u>Kaolinite plus Chlorite (%)</u>
804	59	27	14
806	54	32	14
807	45	37	18
808	41	43	16
809	50	34	16
811	53	30	17
812	56	29	15
813	49	34	17
815	65	24	11
816	55	32	13
817	52	34	14
818	57	29	14
819	45	39	16
820	56	29	15
822	59	27	14
823	57	29	14
824	53	31	16
825	53	31	16
828	50	35	15
829	60	27	13
830	58	29	13
831	51	34	15
832	60	28	12
833	51	35	14
835	61	27	12
R1	66	26	8
R3	53	34	13
708-P	10	54	36
815-P	59	28	13
823-P	30	39	31
826-P	30	46	24
827-P	39	42	19

of the total clay minerals in the bottom sediments (51 values) excluding the clays of Pleistocene origin is: 54 percent montmorillonite, 32 percent illite and kaolinite plus chlorite 14 percent. These values represent the clay to fine clay fraction of the sample although no specific clay size range from the clays can be given due to the method of slide preparation.

Peak positions for magnesium saturated glycerol-treated unoriented slides of the recent Lake Winnipeg clays were plotted on the peak migration curves of Brown and MacEwan (1951) with the result that generally the proportion of illite and montmorillonite in the random interstratification is 50 percent illite and 50 percent montmorillonite.

Kodama and Brydon (1966) studied the 0.2 to 0.04 micron size fraction of Prairie glacial till and lacustrine clays (including one glacio-lacustrine clay sample from the Winnipeg area) and found the mineralogy to be very similar in all samples. They found that most clays consisted predominantly of a dioctahedral randomly interstratified mixture of montmorillonite and mica-type layers. Based on peak positions the proportion of montmorillonite was about 50 percent in the lacustrine samples and 65 percent in the till samples while Fourier transforms gave a value of 55 percent montmorillonite for both a till and a lacustrine clay.

Quigley (1967) studied glacio-lacustrine clays in the

Winnipeg area (the minus 2 micron fractions) and found the clays to consist of 80 percent interlayered montmorillonite-illite, 5 to 10 percent kaolinite and 10 to 15 percent quartz with approximately 55 percent of the interlayered mixture being composed of montmorillonite.

The results of the present study agree very well with those of Kodama and Brydon (1966) and Quigley (1967).

The source for most of the sediment of the south basin is probably the result of erosion of soils in the drainage areas of rivers flowing into the lake. According to Zwarich (personal communication, 1970) the soils of Manitoba show very little, if any, changes in clay mineralogy between the parent material (glacial tills and glacio-lacustrine deposits) and the soils developed on these parent materials. It would then appear that very little diagenetic change has occurred in the clay minerals from the Cretaceous Shale source, through the sequence of glacial erosion and redeposition as tills and glacio-lacustrine clays, pedogenic processes of soil formation, erosion of the soil and finally to deposition in Lake Winnipeg.

The glacial and glacio-lacustrine clays obtained from the bottom of Lake Winnipeg differ in mineralogy from the recently deposited clays in that the amount of montmorillonite is considerably lower than the Recent clays. In addition, illite and kaolinite plus chlorite are present in significantly greater amounts with illite being the dominant mineral

in these Pleistocene clays. Some of the bottom samples, especially those adjacent to the eastern shore contain considerable amounts of biotite, muscovite and potassic feldspar which are probably weathering in their present environment. The weathering of these minerals releases potassium which may become 'fixed' onto the montmorillonite structure, reduce the amount of montmorillonite present in the Pleistocene clays and increase the amount of illite. This is merely speculation, however, and the unusual mineralogical composition of these clays cannot be explained at the present time.

Results of Differential Thermal Analysis

Differential Thermal Analysis was carried out only on selected samples. Samples were stored at approximately 45 percent relative humidity for several days prior to firing. The samples were fired to 1,000°C at a heating rate of approximately 10°C per minute.

The data suggest that the clays consist of a 'normal' illite-'abnormal' montmorillonite interstratification of montmorillonite and illite with illite transforming to montmorillonite. Cole and Hosking (1957) state that Nagelschmidt (1944) and Jackson *et al.* (1952) have shown that certain stages of the weathering sequence of layer silicates may be represented by the series:

mica ⇌ illite ⇌ intermediate ⇌ smectites

Thermograms of clays containing randomly interstratified montmorillonite and illite may be divided into two series (Fig 19). In one series, the main endothermic peak lies between 525°C and 625°C and in the other series between 650°C and 725°C. The curves show that the sizes of the two endothermic peaks in the 500 to 700 C region are independent of the I:M ratio in each series. The curves in series 1 are 'illite-like' and the curves in series 2 are 'montmorillonite-like'. Thermograms may not be used to identify the presence of illite or montmorillonite in a sample but once the presence is established by X-ray analysis (or other means) it is possible to predict, according to Cole and Hosking (1957):

"... from differential thermal analysis the direction in which the transformation is taking place".

In series 1 (Fig. 19) it would appear that illite is altering to abnormal montmorillonite in the direction shown and in series 2 montmorillonite is altering to abnormal illite. The DTA curves of selected samples in this study (Fig. 20) show that the main endothermic peak lies at approximately 530 to 540°C which is in the 525 to 625°C range. Thus, the clays of this study (if the samples selected are representative of all samples; and there seems to be no reason to doubt this, based on the homogeneity of the mineralogy as determined by X-ray analysis) are of a normal illite-abnormal montmorillonite nature with the

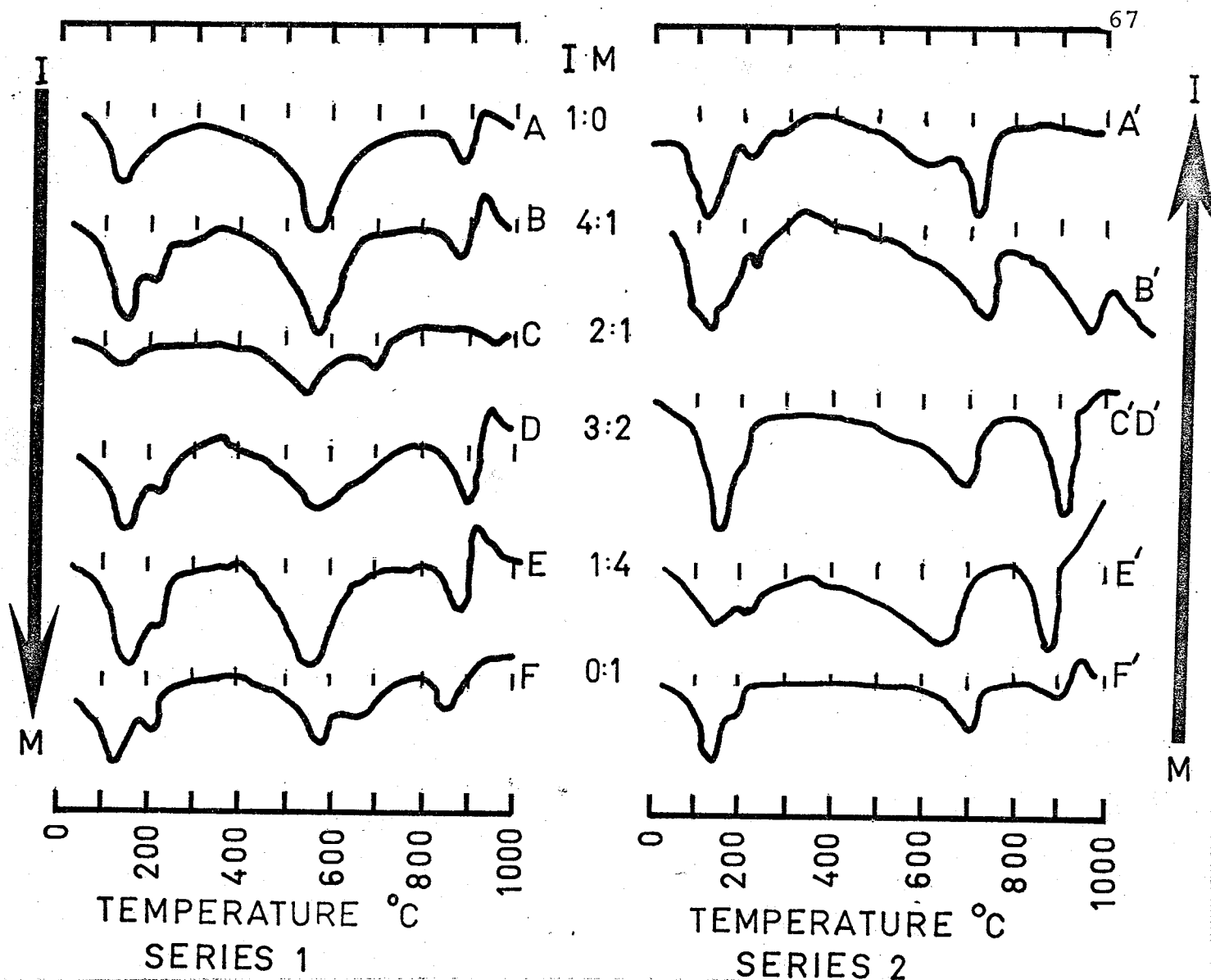


Fig. 19. Differential thermal curves for randomly-interstratified illite-montmorillonite minerals (approximate I:M ratio given on curves; probable direction of transformation indicated by arrows): A-illite, Fithian, Illinois, U.S.A.; B-mixed-layer mineral, Bear River, Wyoming, U.S.A.; C-sarospatakite, Sarospatak, Hungary; D-bravaisite, Noyant Allier, France; E-bentonite, Cameron, Arizona, U.S.A.; F-smectite, Dunning, Perthshire, Scotland; A'-illite, Ballater, Aberdeenshire, Scotland (redrawn with modified T scale to compare with other curves); B'-Ordovician bentonite, Pennsylvania, U.S.A. (redrawn with modified T scale to compare with other curves); C'D'-metabentonite, High Bridge, Kentucky, U.S.A.; E'-mixed-layer mineral, Decorah Shale, Wisconsin, U.S.A.; F'-montmorillonite, Wyoming, U.S.A. (Curves A, B, C, D, and E', after Grim, Bradley and Brown 1951; Curves C'D' and E, after Kerr, Kulp and Hamilton 1949; Curve F, unpublished curve of Professor R.E. Grim; Curve A', after Mackenzie, Walker and Hart 1949; Curve B', after Weaver 1953; Curve F', unpublished curve of A.R. Carthew.) (after Cole and Hosking, 1957)

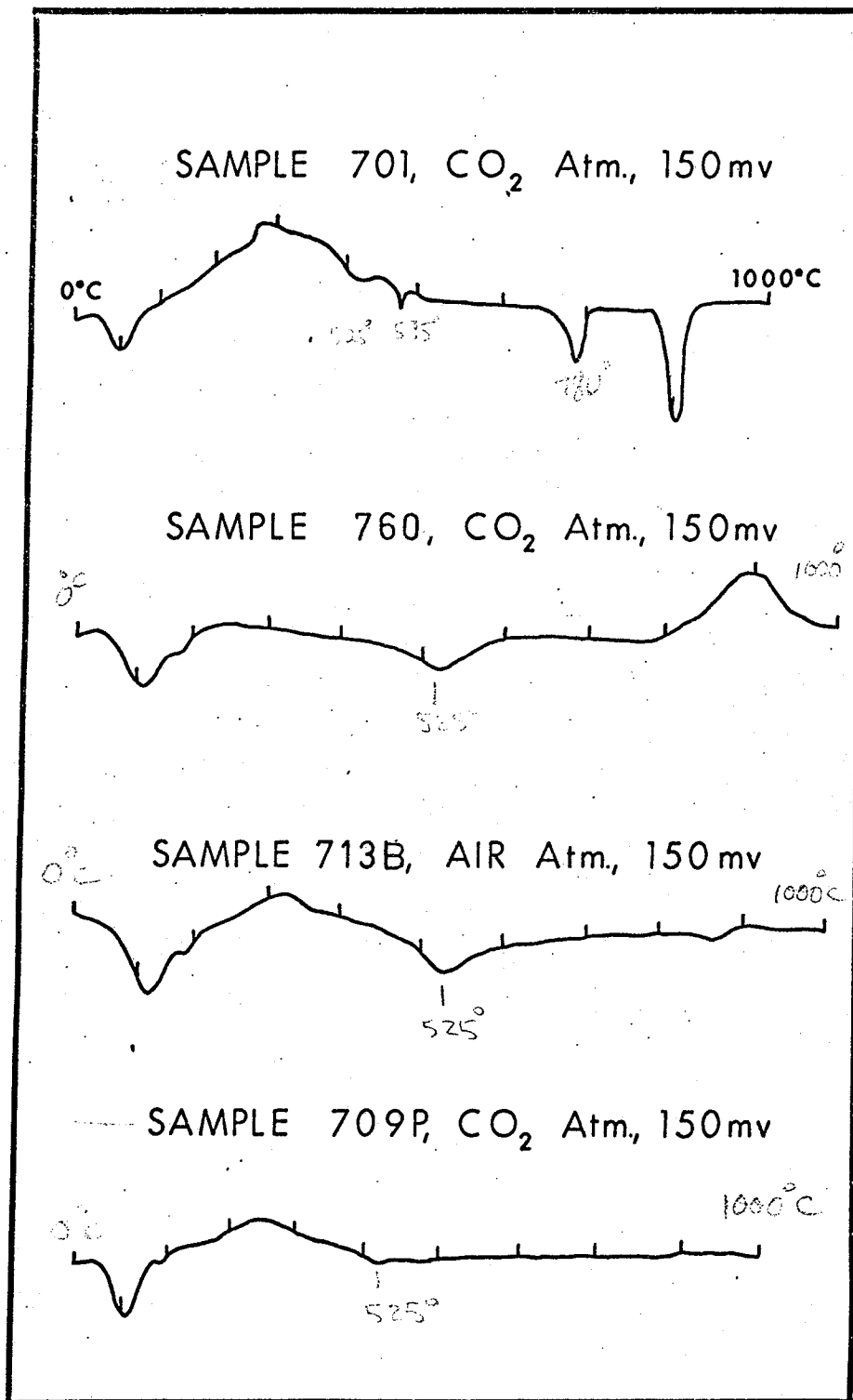


Fig. 20. Differential thermal curves for selected bottom samples of Lake Winnipeg

direction of transformation being from illite to montmorillonite. Wicks (1965) came to the same conclusion for the clays of Glacial Lake Agassiz as did Kodama and Brydon (1966).

Thermograms indicate that the dominant exchange ion on the montmorillonite is calcium as determined by the nature of the first endothermic peak.

Grim (1953) states that Hendrix, Nelson and Alexander (1940) studied the water adsorbed by montmorillonite saturated with various cations. For each cation they determined the amount of water adsorbed at various relative humidities, the resulting variation in the c-axis spacing of the mineral and the corresponding differential thermal curves. The endothermic curve in the 30 to 300°C temperature range is due to the energy necessary to drive off the adsorbed water from the montmorillonite. This endothermic peak due to loss of adsorbed water may take the form of a single, double or triple peak for montmorillonites containing certain cations at certain relative humidities (Figs. 21 and 22). In the case of dual peaks of samples prepared at comparatively low relative humidities, the larger of the maxima is attributed to the dehydration of the cation and the lesser of the maxima to the loss of water from the surface of the clay mineral away from the hydrating ion. At higher relative humidities the dual peaks become triple and the third maxima is attributed to the development of an additional layer of oriented water molecules.

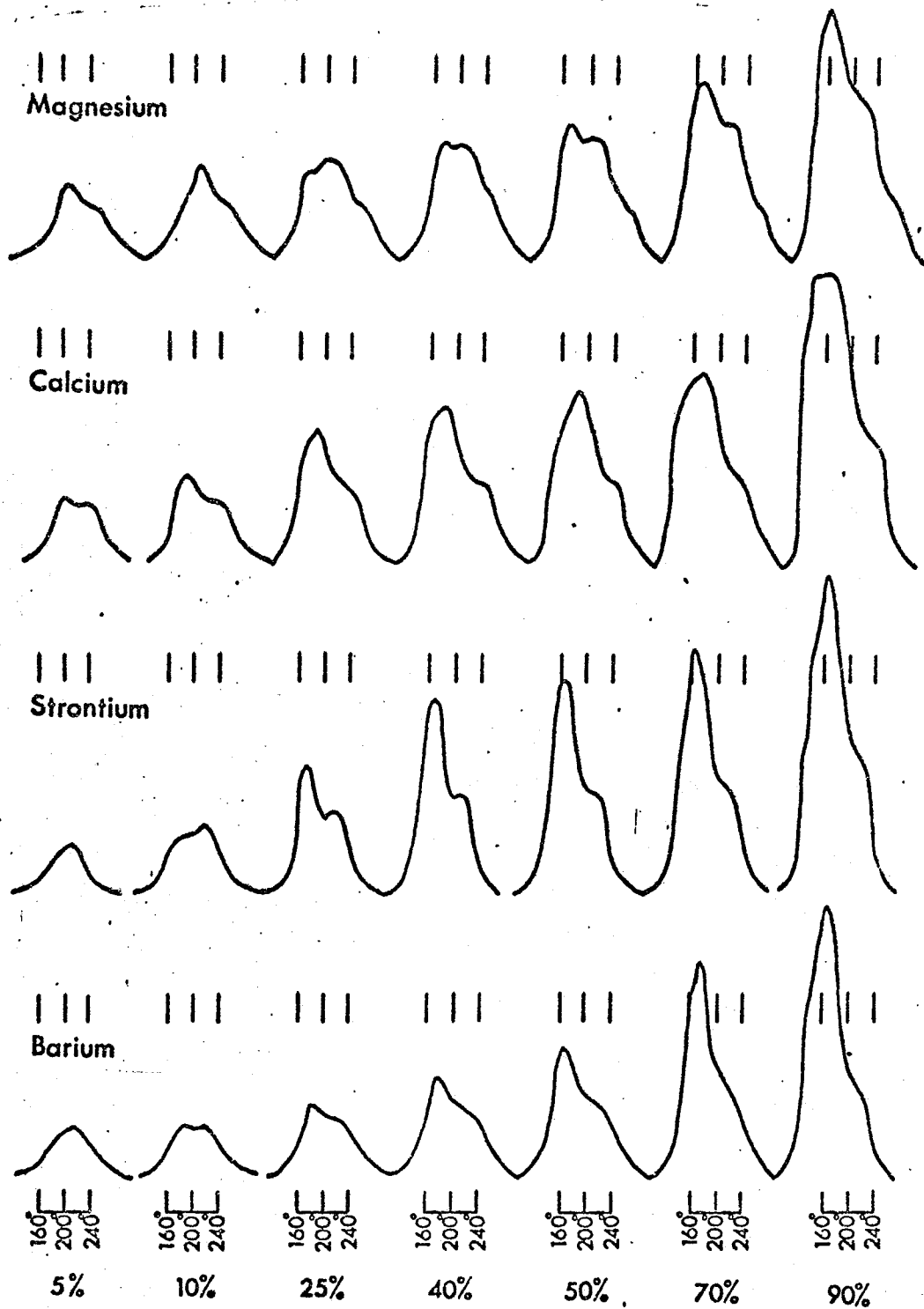


Fig. 21. Differential Thermal Analysis curves in static air, of Hendricks, Nelson and Alexander (1940) for Mississippi montmorillonite saturated with various divalent cations at different relative humidities. Note that the curves are pointing up rather than down the page (after Wicks, 1965).

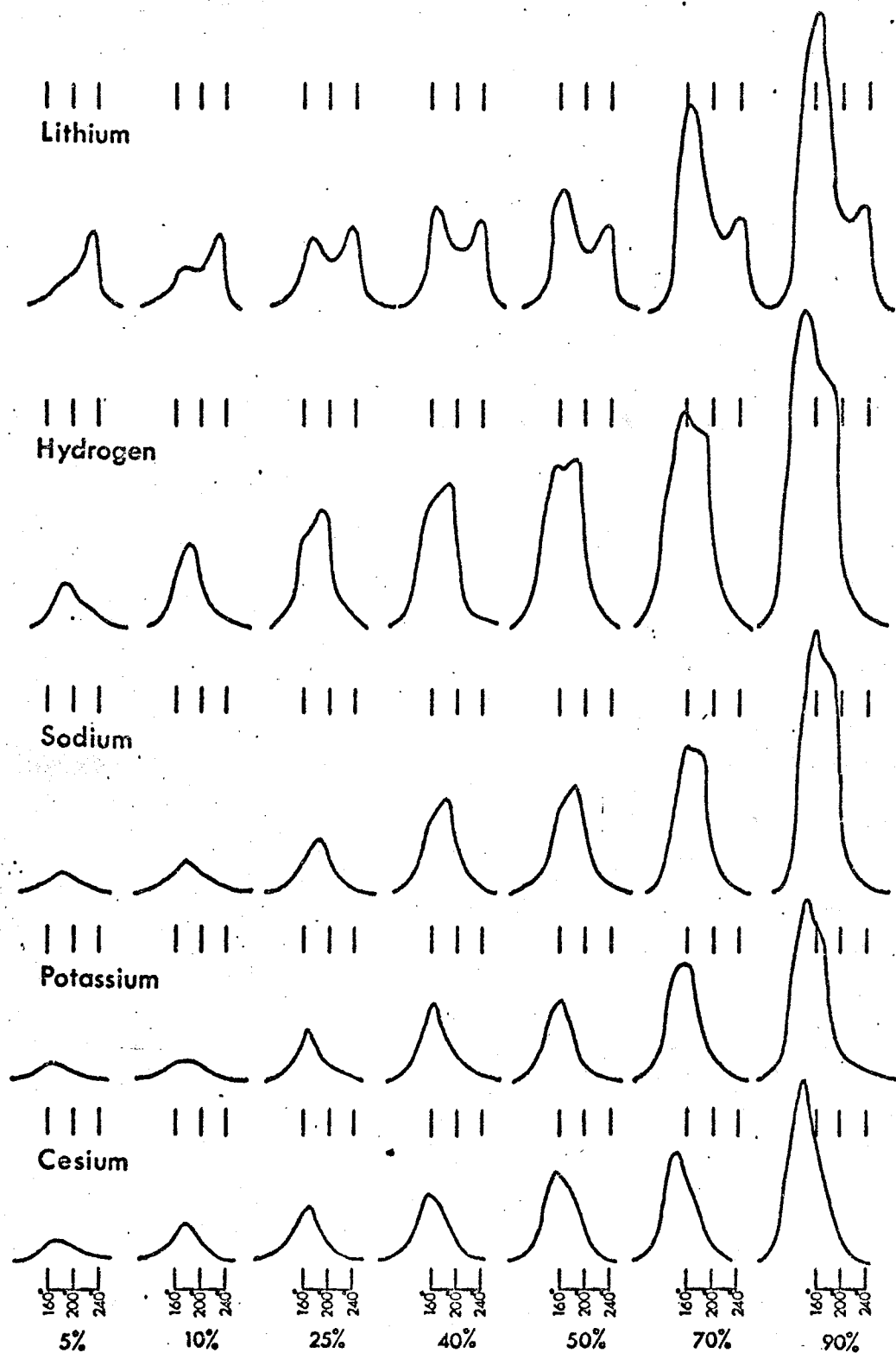


Fig. 22. Differential Thermal Analysis curves, in static air, of Hendricks, Nelson and Alexander (1940) for Mississippi montmorillonite saturated with various monovalent cations at different relative humidities. Note that the curves are pointing up rather than down the page (after Wicks, 1965).

Certain univalent ions show only a single peak at low relative humidities which is interpreted to mean that these ions are not hydrated. At higher relative humidities a layer of water is adsorbed which produces the second peak.

In the Lake Winnipeg clays (selected samples only) the samples analyzed, which were stored at 45 percent relative humidity, generally had two very distinct peaks. A main peak at approximately 100° to 110°C and a smaller shoulder at about 180°C . In a few samples a small peak at about 150°C was present. These peaks had the characteristic of calcium and strontium (Fig. 21) at 45 percent relative humidity. Strontium was deleted as a possibility because of the improbability of its existing in significant quantities in the lake, and calcium was considered to be the dominant exchange ion in the montmorillonite. Peak temperatures (Fig. 16) were 50° to 60°C lower because these Lake Winnipeg samples were run in dynamic gases which lowers the temperature of the peak (Wicks, 1965).

The dioctahedral nature of the clay minerals involved in the interstratification was indicated by a final endothermic couplet at approximately 900°C .

CHAPTER VI

SUMMARY OF CONCLUSIONS

1. Sediments in the basin may be divided into three more or less concentric units. A clay unit in the centre of the basin, a mud unit 'shoreward' of the clay unit and a nearshore undivided unit consisting of sand, gravel and Glacial Lake Agassiz deposits as well as minor amounts of silt and clay. The clay unit normally contains greater than 75 percent clay-sized (finer than 3.9 microns) particles but in places contains greater than 95 percent. Places where the clay-sized particle content is highest do not necessarily correlate with the deepest part of the south basin which is 40 feet in depth. The mud unit as defined by echograms is essentially a silty clay unit with fewer samples of clayey silt.

The undivided unit nearshore consists of (as determined from echograms, bottom samples and grain size analyses) sands and gravels which appear to be a lag deposit resulting from wave modification of glacial till; *in situ* 'outcrops' and loose water worked well-rounded clay clasts of Glacial Lake Agassiz origin 'varved' and massive clays, and recent deposits of silt and clay. Sands and

gravels in this unit consist of mainly quartz, feldspar, granite and sandstone, which occur predominantly on the eastern side of the lake, and dolostone and limestone which occur predominantly of the west side of the lake.

The clay unit has the largest areal distribution and covers approximately 50 percent of the south basin lake bottom. It has an apparent thickness of at least 25 feet (7.5 metres) at the center of the basin. The mud unit is next largest in size covering approximately 40 percent of the lake bottom and has an apparent thickness of at least 15 feet (4.5 metres).

2. The well-rounded tabular clay clasts are considered to have been formed by stream erosion of the Glacial Agassiz IV deposits after the lake drained. Many of these clasts (as well as many limestone and dolostone sands and gravels) are severely oxidized and have rust-coloured crusts on them suggesting very shallow water conditions or complete emergence which would be caused by the complete or nearly complete drainage of Glacial Lake Agassiz.

3. Three flat terrace-like features each approximately $\frac{1}{2}$ mile to 1 mile in size appear on the echograms in the space of 10 miles in the Narrows area of the lake. The level of these terraces is at approximately 684 feet above mean sea level (29 feet below the long term lake level datum of 713 feet above mean sea level). It is possible that these terraces reflect the level at which a previous

lower stage of early Lake Winnipeg stabilized. Unfortunately the exact water level which would produce these terraces is unknown.

4. Mineralogically, the Lake Winnipeg recent bottom sediments are quite homogeneous. The non-clay minerals are mainly quartz, dolomite and feldspar. Calcite is minor in the sediments and occurs mainly near the mouth of the Red River. The non-clay minerals are most abundant in the silt fraction of each sample (especially dolomite). The largest occurrence of dolomite is at the mouth of the Winnipeg River. This interpreted as being derived from the aeolian sandy silt unit which was deposited after Lake Agassiz IV drained and which is mainly composed of dolomite.

The clay minerals of the sediments consist of montmorillonite, illite and kaolinite plus chlorite. The average amounts of these minerals in the sediments (51 samples) are montmorillonite 54 percent, illite 32 percent and kaolinite plus chlorite 14 percent. These percentages are percent of total clay minerals not percent of the total sample. These percentages are representative of the clay to fine clay fraction of each sample.

Illite and montmorillonite occur as a randomly interstratified complex. The ratio of illite and montmorillonite in the interstratification is approximately one to one. Differential thermal data indicate that the nature of the illite and montmorillonite interstratification is 'normal'

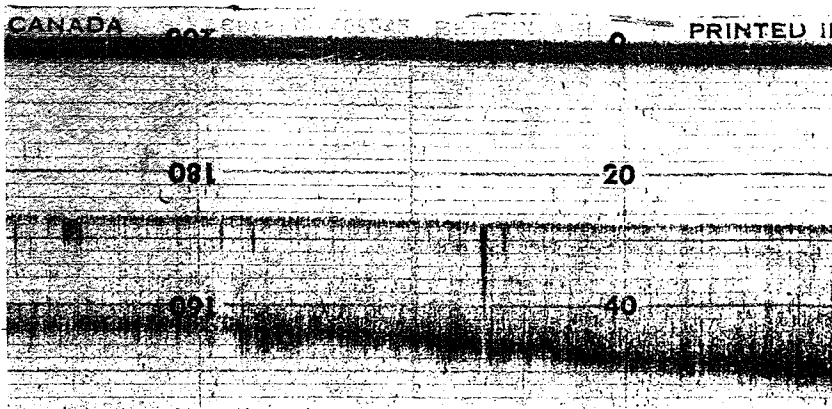
illite-'abnormal' montmorillonite with the direction of transformation being illite to montmorillonite. Both montmorillonite and illite are dioctahedral and the dominant exchange ion on the montmorillonite is calcium.

5. The clays of glacial till and Glacial Lake Agassiz which 'outcrop' on the lake bottom (nearshore in the undivided unit) are mineralogically different from the Recent clays in the basin. These Pleistocene clays have illite as the dominant mineral with minor to major amounts of kaolinite plus chlorite and generally minor amounts of montmorillonite. Till samples contained greater amounts of montmorillonite than glacio-lacustrine samples but both had less montmorillonite than the Recent clays of Lake Winnipeg. Because of the differences of the Pleistocene and Recent clays it seems unlikely that the source of the clays is directly from erosion of glacial till or glacio-lacustrine deposits within the lake itself.

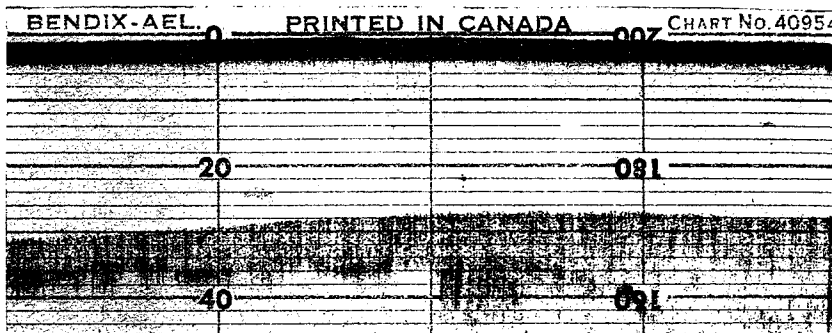
6. It appears that very little diagenetic change has occurred in the clay minerals from the Cretaceous Shale source, through the sequence of glacial erosion and redeposition as tills and glacio-lacustrine clays, pedogenic processes of soil formation, erosion of the soil and finally to deposition in Lake Winnipeg. The Pleistocene clays which subcrop in the lake appear to be an exception to the above conclusion.

7. A sedimentation rate calculated by suspended load of the Red River was found to be approximately 0.5 millimetres per year. Assuming this rate for each year since 7300 B.P. when Lake Agassiz drained (this age for Lake Winnipeg is actually not correct since Lake Agassiz drained almost completely leaving very little or no water behind for sediments to be deposited in; Lake Winnipeg developed at a later and unknown date) the total thickness of sediment deposited in the south basin by the Red River is in the order of 10 to 12 feet over the entire area of the south basin considered to be approximately 1000 square miles.

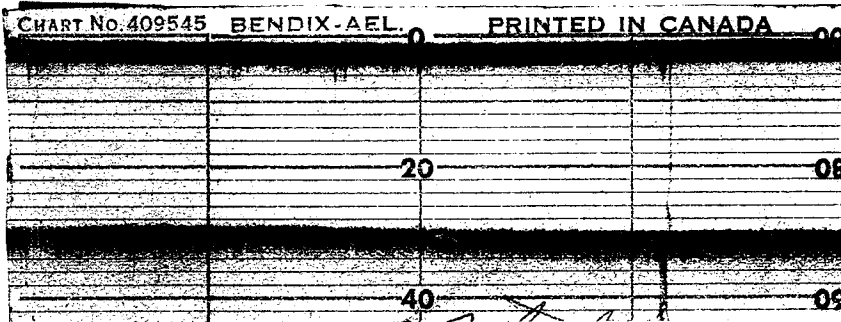
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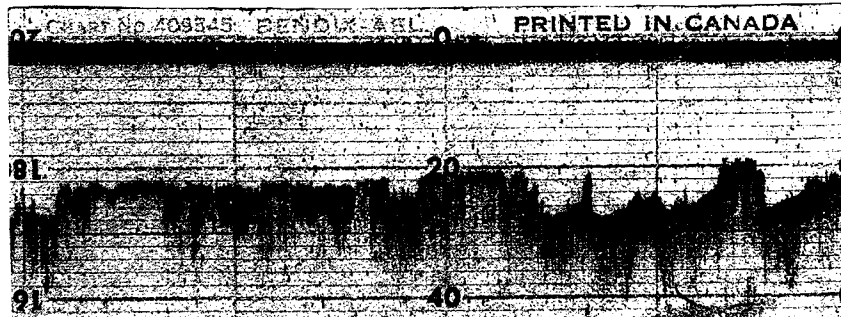
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TYPE III



TYPE IV



TYPE V

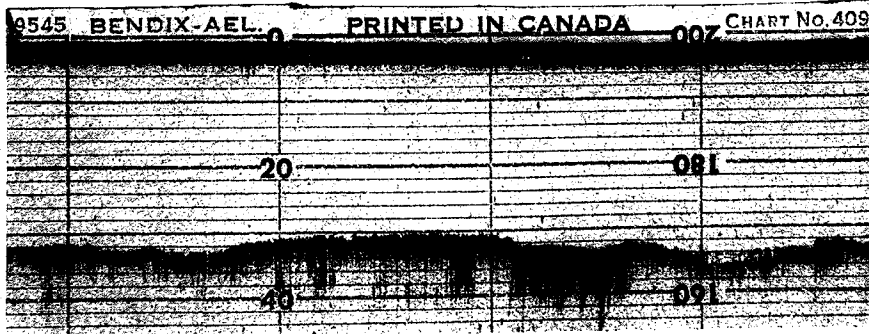


Fig. 23. Classification of echograms.

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APPENDIX A

LABORATORY ANALYSIS OF SAMPLES

Textural Analysis of Sediments

Samples collected in the field were homogenized and stored in plastic bags to prevent drying. As a consequence, disaggregation of samples was unnecessary.

Grain size analyses to determine the percent sand, silt and clay of each sample were performed in the manner recommended by Folk (1968).

Several samples were dispersed with various amounts of calgon (sodium metahexaphosphate) to determine the amount of calgon (calgon acts as a dispersant and prevents flocculation) which would best prevent flocculation of the clays. This concentration was determined to be 25 grams per litre.

Approximately 20 to 25 grams of wet sample were added to about 250 millilitres of distilled water (with calgon added) and beaten in a milkshake mixer for 15 minutes. The suspension was sieved through a 4 phi (62.5 microns) screen into a one litre graduated cylinder. Sediment retained on the screen was washed into a beaker, dried, and placed in a vial for future reference. The suspension in the

cylinder was increased to one litre by the addition of more distilled water. The sand and silt grain size analysis was determined by pipette method (Folk, 1968). Twenty millilitre aliquots were removed (at predetermined times) from the suspension, placed into weighed beakers and dried. The dried sediment was allowed to equilibrate with room atmospheric humidity for one day, was weighed and the amount of calgon was subtracted from the weight of the sample. Only the percent of sand, silt, and clay for each sample were determined. The limitations of the pipette method and the extremely fine-grained nature of most samples resulted in rather open-ended particle size frequency distributions which precluded calculation of the usual distribution parameters.

Mineralogical Analyses of Sediments

Mineralogical analyses were performed mainly with a Philips diffractometer using cobalt radiation (Ca K α : $\lambda = 1.78890 \overset{\circ}{\text{A}}$) and a graphite monochromator. Additional information was derived from Differential Thermal Analysis of selected samples performed on a Differential Thermal Analysis 13M unit (Robert L. Stone Company, Austin, Texas).

X-ray analysis was carried out using three separate techniques (Fig. 17); air dried unoriented bulk powder sample (approximately 100 mesh size); oriented aggregate (pipette on glass slide method) untreated slides of both

the silt and clay fractions of each sample, and finally unoriented, magnesium saturated, glycerol-treated ceramic slides of the minus 2 micron clay.

The air dry bulk powder samples gave very poor clay mineral peaks (Fig. 17, curve 4). This was probably due to masking by non-clay minerals. For the dry powder method to produce better peaks, separation of the fine clay fractions is necessary. This was not done and in general, this method was used very sparingly in the present study.

Oriented aggregates of the silt¹ and clay fractions gave excellent peaks for clay minerals (Fig. 17, curves 2 and 3). These oriented slides were prepared by pipetting suspensions of silt and clay onto glass slides. These slides were used to obtain the relative amounts of non-clay minerals in the samples but were not used to determine quantitative clay minerals results. According to Gibbs (1965) the pipette-on-glass slide method gives results for montmorillonite which are 33 to 68 percent higher than the true value for the minus 2 micron size fraction. This is the result of surface segregation of montmorillonite due to its smaller size and therefore lower (1/100) settling

¹ Silt is here defined as material in the 3.9 to 62.5 micron size range and clay is that material finer than 3.9 microns. However, the silt fraction does contain clay; this is a consequence of the fact that when performing grain size analyses the first aliquot (20 millilitres) is representative of the entire sample and is 1/50 of the total sample. Thus, the silt fraction is really silt and clay, and the clay fraction is entirely composed of only clay-sized particles.

velocity than kaolinite or illite. Also another factor in the error is that the degree of orientation is not the same for different samples.

The methods which were found to be acceptable by Gibbs (1965) for quantitative clay mineralogical results were smear-on-glass slide, powder press and suction of ceramic slide techniques.

In this study, slides for the quantification of clay minerals were prepared by placing an aliquot of suspension onto a ceramic slide with an eye dropper. Suction is unnecessary as capillary forces draw the water into the plate within a few seconds leaving a homogeneous clay film on the ceramic plate. The method of preparation of the clay suspension is that of Rex (1968) with several modifications. One or two grams of dry sediment were ground to approximately 0.5 millimetres in size. The sediment was placed in a disposable 10 millilitre test tube and a few millilitres of distilled water and one or two drops of non-ionic detergent (0.1 percent Aerosol OT non-ionic detergent) were added. Approximately one millilitre of mixed bed H^+ and OH^- ion exchange resin (Bio-RAD AG-501-X8, 20 to 50 mesh) beads were added to deionize the dispersion solution. The mixed bed resin beads quickly settle to the bottom of the test tube where they do not interfere with the withdrawal of an aliquot of the clay suspension. The resin dissolves any carbonates present in the sample. Hydrazine (one or two

drops of 32 percent Hydrazine) is added to assist the dispersing effect of the non-ionic detergent. The test tube suspension was then made up to 7 millilitres volume with distilled water and then dispersed with a sonifier (Branson Sonic Power, Melville L.I., New York). The test tube was then allowed to stand long enough to permit the silt to settle and an aliquot of clay dispersion was withdrawn with an eye dropper. The aliquot (approximately 1 millilitre) was spread on a $3/4$ " x $1\frac{1}{2}$ " and $\frac{1}{4}$ " ceramic plate. Capillary forces draw the water into the ceramic plate within a few seconds leaving a homogeneous clay film coating the surface. Two to three drops of 5 percent magnesium chloride in 50 percent water and 50 percent glycerol solution were added to saturate the exchange sites and expand the lattice of montmorillonite. Selected porcelain slides were heated to 550°C to distinguish between kaolinite and chlorite. The parameters of measurement used in X-ray diffraction analysis are presented in Table IX as well as the principal peak position of the common minerals which were found in the sediment samples.

Differential Thermal Analysis was used to augment information determined by X-ray analysis and no mineral identifications per se were determined from thermograms. Samples were prepared for Differential Thermal Analysis by grinding in a mortar and pestle to pass a 60 mesh screen and storing at 45 ± 5 percent relative humidity for at least

TABLE IX

Parameters of Measurement Used in X-ray Analysis and
Principal Peak Positions of Common Minerals

Parameters: Philips X-ray diffractometer and monochromator
Co K α radiation, Fe filter, KV = 40, ma = 20.
200 counts per second, Time constant = 2 seconds

Mineral	Peak (\AA)	Peak ($^{\circ}2\theta$)	Peak (hkl)
Calcite	3.04	34.25	104
Chlorite	14 and 7	7.3 and 14.7	001 and 001
Dolomite	2.89	36.1	104
Plagioclase Feldspar	3.20	32.5	040
Potassic Feldspar	3.24	32.1	220
Quartz	3.34	31.1	101
Kaolinite	7.2	14.3	001
Illite	10	10.3	001
Montmorillonite	17.7	5.8	001
Mixed-layer Montmorillonite- illite	9.35	11.0	002/001

24 hours prior to analysis.

To load the sample holder the material was poured into the sample cavity and packed, initially by tapping the holder with a finger and finally with the static load of an 8 inch long $\frac{1}{4}$ inch diameter glass rod. The holder was filled to the same point on each loading. On occasion material had to be added or discarded to keep the sample size constant. According to Wicks (1965) sample weights are reproducible to within 0.02 grams if the method is followed carefully. This eliminated the necessity of using weighed samples for each analysis.

APPENDIX B

ECHOGRAM INTERPRETATION

Echograms were used in the study to delineate the Lake Winnipeg sedimentary units. Figure 23 shows a representative echogram of each sedimentary unit. Type I represents the clay facies. The echogram shows a thin dark line at the sediment-water interface while the area below this interface is relatively clear or acoustically transparent, except where structure or an impermeable sub-bottom is encountered. Type II represents the mud facies. Sound does not penetrate the bottom as easily as in Type I and a grey sub-bottom is produced. The sediment-water interface is not clearly defined by a thin dark line; instead this area of the record blends uniformly with the grey sub-bottom record. Type III represents a sand bottom which is generally hard and smooth. The record is a relatively thin black line as sound does not penetrate well into this type of bottom. Type IV represents compact Lake Agassiz clays. The pronounced jagged surface is characteristic and seems to indicate an erosional surface. The bottom is dark on the echogram because of the compact nature of the clay. Type V represents glacial drift; a semicompacted to compacted.

bottom with an undulating surface which is characteristic.

The thicknesses of sediment shown on echograms are not true but apparent thicknesses. Sound travels through the water with a certain velocity and when the sound meets the water-sediment interface a change of velocity takes place.

Because the velocity of the sound in these sediments is unknown, the depth of sediment cannot be determined.

However, for most very fine clays the sound velocity will be close to that of water as these clays may contain up to 80 percent water by volume.