

THE UNIVERSITY OF MANITOBA

CLAY MINERALOGY AND STRATIGRAPHY OF OFFSHORE LAKE AGASSIZ  
SEDIMENTS IN SOUTHERN MANITOBA

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES  
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE  
OF MASTER OF SCIENCE

DEPARTMENT OF EARTH SCIENCE

WINNIPEG, MANITOBA

FEBRUARY, 1974

## ABSTRACT

An experimental methodology study of five common mounting techniques and procedures and three calculation methods helped determine the specific X-ray techniques to be used in the semi-quantitative estimation of clay minerals in the study of offshore Lake Agassiz sediments. The aqueous pipette-on-glass slide technique with calculation by the direct comparison method was chosen because it offered best and most consistent results, ease and rapidity of obtaining results and best correlation possibilities.

Numerous attempts have been made at subdividing the offshore deposits of Lake Agassiz in southern Manitoba and adjacent parts of the United States. The results of detailed clay mineralogical and textural analyses of samples from the Red River basin suggest a three-fold stratigraphic subdivision. This subdivision is also supported by non-clay mineralogy differences within the sediment and by the limited soil engineering data available.

Unit 1, the lowermost offshore unit recognized, is defined primarily on the basis of its low montmorillonite:illite ratio, very fine average grain size and low Atterberg limits. Unit 2 is recognized by its high montmorillonite:illite ratio, very fine average grain size, and high Atterberg limits. Unit 3, the uppermost offshore unit recognized, is defined by its low montmorillonite:

illite ratio, relatively coarse grain size and low Atterberg limits. These three units can be identified throughout the sedimentary basin in Manitoba and roughly correlate with units in North Dakota.

Although various hypotheses can be suggested to explain the observed stratigraphic and lateral changes within the offshore sediments, probably the most reasonable explanation is that of differential settling of the clay particles caused by salinity changes in the lake and size difference of the various minerals.

## ACKNOWLEDGEMENTS

This study was supervised by Dr. James T. Teller who provided guidance and counsel during the laboratory research and preparation of the manuscript. Dr. Teller also made available a large number of samples collected as part of his subsurface auger drill program in southern Manitoba. Drs. R. Newbury and R. Harrison, both of whom were members of the thesis committee, also made helpful suggestions on the manuscript.

The writer is greatly indebted to Mr. John Little of the Water Resources Branch, Department of Mines, Natural Resources and Environmental Management, Manitoba government, for providing samples, drilling records and logs of test holes drilled during the summer of 1973. Mr. John Ledzarkawich of the Water Resources Branch supplied auger drill samples, core, drilling records and logs and unpublished engineering data of several holes in southern Manitoba.

Ms. Letty Last ably assisted the writer in field sample collection, sample analysis, drafting of the plates and figures and typing of the manuscript.

The writer also benefited greatly from discussions with Professors E. Leith, G. Russell, P. Cerny and Mr. Philip Kor. Mr. Kor also aided with field sample collection and sample analysis. Mr. Michael Arndt of the North Dakota Geological Survey supplied relevant information concerning sample preparation and X-ray interpretation.

Financial support during the study was provided by the Department of Earth Science and Dr. Teller.

The writer wishes to express his appreciation to the above and many others who provided assistance during this study.

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## CHAPTER 1

### INTRODUCTION

#### PURPOSE AND GENERAL DESCRIPTION OF THE INVESTIGATION

Glacial Lake Agassiz sediments occur within an area of 200,000 square miles in parts of Ontario, Manitoba, Saskatchewan, Minnesota, North Dakota and South Dakota. The Red River basin of North Dakota and Manitoba is the largest of Lake Agassiz' several sedimentary basins (Fig. 1). Despite a large amount of research done on the lake in such diverse areas as biology, archeology, soil science and general geology, relatively little work has been attempted in the area of stratigraphic subdivision and correlation of the offshore sediments on a regional basis. The main objectives of this thesis are to (1) determine the texture of these offshore sediments of Lake Agassiz in southern Manitoba; (2) qualitatively and semi-quantitatively examine the clay minerals of the offshore sediments; (3) develop a general overall stratigraphic picture of lake sedimentation by defining stratigraphic units based mainly on the above two criteria; (4) suggest an origin or source of these offshore clays by examining and using existing knowledge of the mineralogy of adjacent bedrock and drift; and (5) attempt to correlate the units recognized in this study with the results of other research throughout the basin.

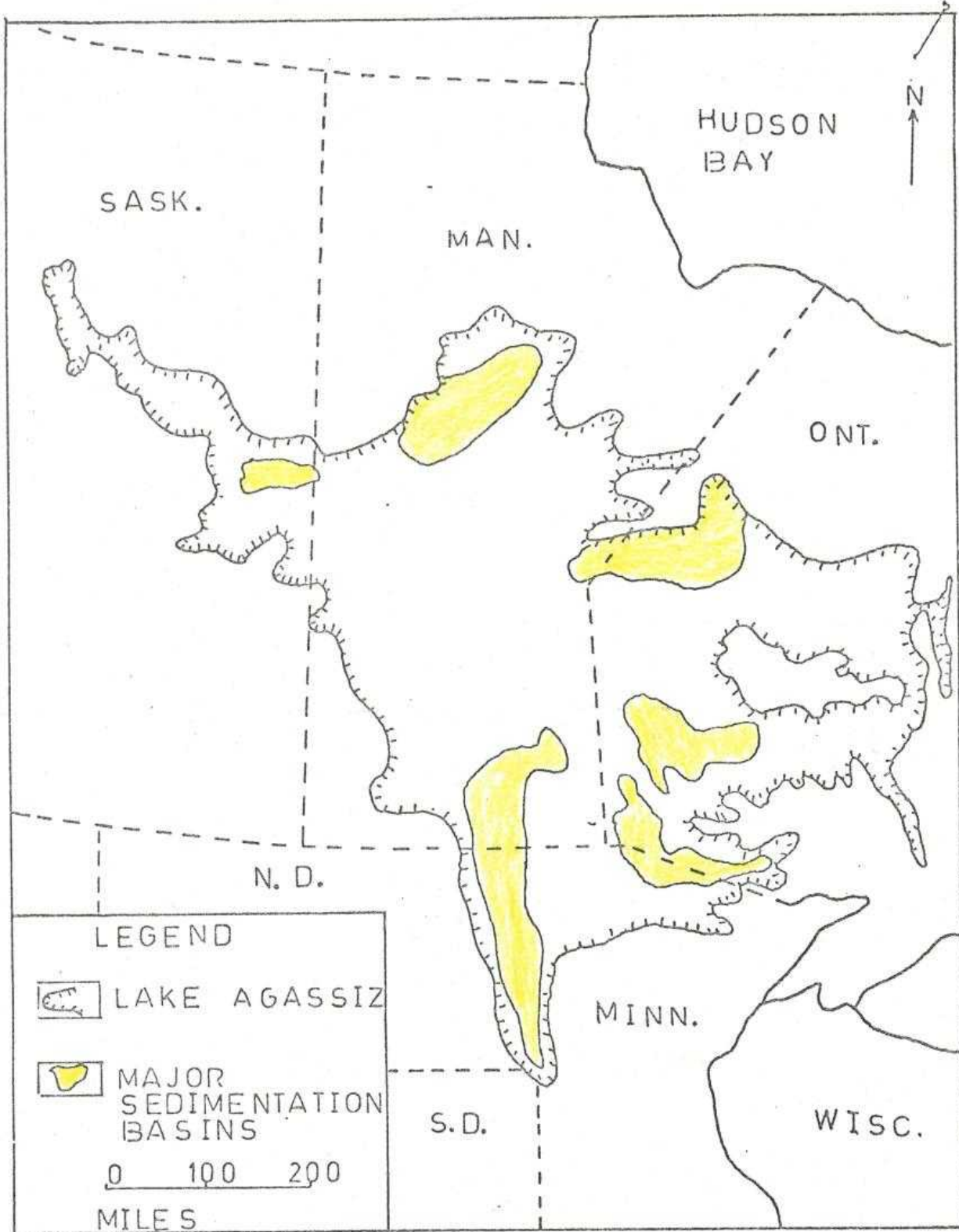


Fig. 1. Major Sedimentation Areas in Lake Agassiz (after Elson, 1967).



X-ray diffraction techniques were used to identify and evaluate the offshore clay-sized minerals. However, since the study of clay minerals by X-ray diffraction has not yet been standardized, a methodology study was also undertaken to determine if one or more specific techniques are particularly well suited for the study of offshore Lake Agassiz sediments, and to see if the use of a particular method would alter the stratigraphic units recognized.

#### PREVIOUS WORK

Numerous authors have previously given excellent and extensive reviews of the literature on the general study of Lake Agassiz (Elson, 1961; Wicks, 1965; Mayer-Oakes, 1966; Bannatyne, et al, 1970; McPherson, 1970; Fenton, 1970). The more important contributions will be useful in providing the necessary background information for the main part of this thesis.

Upham (1895), in undertaking the first comprehensive study of Lake Agassiz, recognized the lake as a product of meltwater from two main lobes of glacial ice. He estimated that the lake existed six to eight thousand years ago for a period of about 1000 years.

Tyrrell (1896) and Leverett (1912) generally expanded and refined Upham's ideas of lake formation. Johnston (1915, 1916, 1917, 1921, 1934, 1946) compiled several extensive surface and subsurface reports of Lake Agassiz in both Manitoba and Ontario. He recognized two separate ages of lakes. First, the fluctuating Keewatin ice sheet had its meltwater trapped between itself and highlands to the south. As it continued to retreat, early Lake Agassiz remained and eventually drained to the north. Then, an advancing Labradorean glacier sealed off the northern outlets

and the ponded meltwater formed true Lake Agassiz. Eventually, high water levels caused the formation of outlets to the south. Finally, the ice front retreated allowing northern outlets to be re-opened and the lake rapidly drained.

Elson (1957, 1961, 1962, 1967) has done most of the recent work on Lake Agassiz and has compiled a history which includes possibly four separate lake phases related to the fluctuations of the Wisconsin ice sheets. Wicks (1965) attempted an extensive and detailed mineralogical study of the glacial and lacustrine deposits in the Winnipeg area. His report emphasized the chemical and differential thermal analysis of the clays. McPherson (1968, 1970), Fenton (1970), McPherson et al (1971), and Fenton and Anderson (1971) studied and mapped the glacial deposits of the Winnipeg River-Beausejour area and the Portage la Prairie area. Wyder (1971) developed detailed cross-sections for the subsurface stratigraphy of a small portion of southern Manitoba.

The results of groundwater research and soil mapping have provided a large amount of sedimentological and stratigraphic information for this study. These include: Ellis and Schafer (1943); Ehrlich, et al (1953); Pratt, et al (1961); Charron (1961, 1964, 1965, 1967); Smith, et al (1967); Render (1970); and Michalyne, et al (1972).

The North Dakota Geological Survey is also doing extensive and detailed studies on offshore Lake Agassiz and related glacial sediments. Their most important and applicable reports include: Clayton (1966); Baker (1967); Ross and Karner (1967); Klausling (1968); Bluemle (1967, 1973); Hansen and Kume (1970); Moran (1972); and Harris, et al (in press).

## GENERAL DESCRIPTION AND GEOLOGIC SETTING OF LAKE AGASSIZ

Offshore sediments of glacial Lake Agassiz cover an area of about 6100 square miles in the Red River basin of southern Manitoba. The bedrock geology of this area consists of Precambrian granitic, metasedimentary and volcanic rocks in the east and a thick sequence of northwest trending Paleozoic, Mesozoic, and Cenozoic sediments in the central and west portion of the area (Davies, et al, 1962; Klassen, et al, 1970). The Paleozoic rock consists of limestones and dolostones with small amounts of sandstone and shale. The Mesozoic and Cenozoic rocks are predominantly shales and sands (Fig. 2). With the exception of a few isolated outcrops of limestone and granite on the north and northeastern edge of the area, all bedrock is covered by variable thicknesses of till and glaciofluvial deposits overlain by lake clays and recent alluvial deposits.

The offshore sediments of Lake Agassiz have been subdivided in a variety of ways by several authors (Table 1). In the Winnipeg area, Wicks (1965) recognized a massive bluish gray clay bed ("Blue-Gray Clay") and a rhythmically bedded (varved?) brown clay bed ("Brown Clay"). He called these two beds Lake Agassiz I Unit. Overlying this is a thin yellow silt bed, a "varved" silty clay bed (Greenish-Brown Clay Unit) and a very fine grained yellow sand bed of Lake Agassiz II Unit.

Most research since, however, has attempted to follow the general three unit stratigraphic sequence as recognized by Elson (1967) in the Red River Basin. In the Beausejour area, McPherson, et al (1971) reports a rhythmically bedded clay unit, a silty

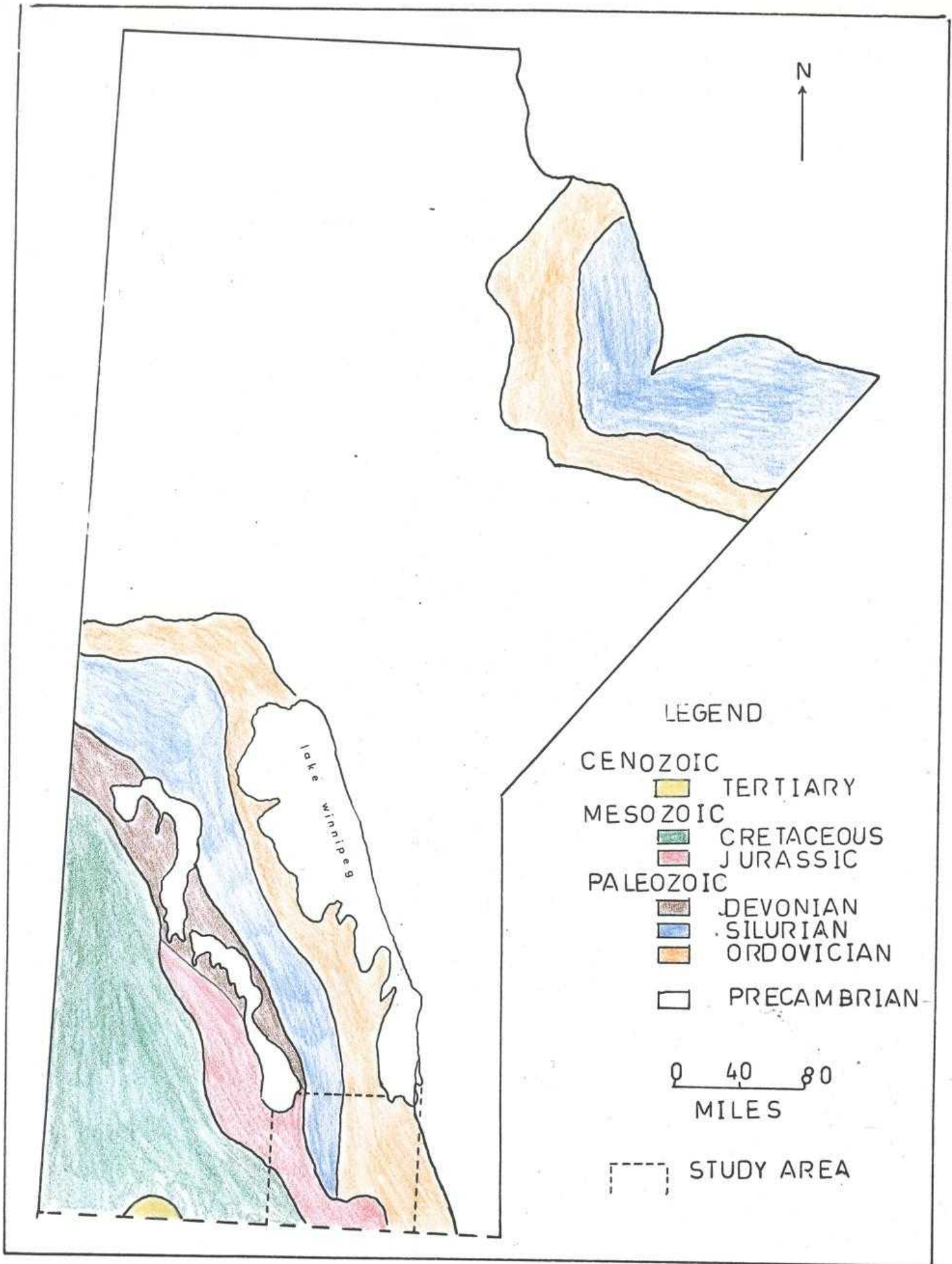


Fig. 2. Bedrock Geologic Map of Manitoba.

TABLE 1

THE SUBDIVISION OF LAKE AGASSIZ  
SEDIMENTS BY VARIOUS AUTHORS

Author	Tyrrell, 1896	Johnston, 1916, 1917
Area of Study	Southern Manitoba, North Dakota, Minnesota	Southern Manitoba
	Later Lake Agassiz Earlier Lake Agassiz	Early Lake Agassiz True Lake Agassiz
Author	Rominger and Rutledge, 1952	Wicks, 1965
Area of Study	Grand Forks, North Dakota	Winnipeg
	Unit 5 Unit 4 Unit 3 Unit 2 Unit 1	Lake Agassiz II Lake Agassiz I
Author	Elson, 1967	Groundwater and Hydrology Studies
Area of	Southern Manitoba	Southern Manitoba
	Lake Agassiz IV Lake Agassiz III Lake Agassiz IIa Lake Agassiz II Lake Agassiz I	Silt Unit also Brown Clay or Varved Unit  Clay Unit also Blue Clay or Gray Clay

(continued)

(Table 1 continued)

Author	McPherson, et al, 1971; and McPherson, 1970	Fenton and Anderson, 1971; and Fenton, 1970
Area of Study	Beausejour Area	South of Lake Manitoba
	Sandy Silt Unit  Mud Unit  Clay Unit	Silt Unit  Upper Lacustrine Unit also called Brown Clay  Lower Lacustrine also called Gray Clay
Author	Wyder, 1971	Harris, et al, in press
Area of Study	Morden-Carman Area	N. E. North Dakota - N. W. Minnesota
	Unit 9  Unit 7	Sherack Formation  Brenna Formation

clay bed (Mud Unit) and a sandy silt unit overlying till and outwash material. Fenton and Anderson (1971) developed a similar picture of Agassiz sedimentation in the Portage la Prairie area by dividing the sediments into a lower clay, an upper clay and an overlying silt unit.

The North Dakota Geologic Survey (e.g. Harris, et al, in press) also recognizes roughly similar units in North Dakota; however, partly due to the distance from other studies, many of their specific details of Lake Agassiz sedimentation are different from that of Manitoba.

## CHAPTER 2

### PROCEDURE FOR SAMPLE ANALYSIS

#### INTRODUCTION

Since a part of this study examines differences in methodology (Chapter 3), and because techniques of clay mineral study are so varied, it is important to include a brief outline and description of the general procedures and laboratory techniques used to obtain data for this report.

"Clay", generally referred to as a very fine-grained, naturally occurring end product of weathering, has several different connotations. Commonly it refers to a particular size of material. In this study clay-sized material is defined to be less than .0039 mm (3.9  $\mu$  or 8  $\phi$ ), and the following divisions and nomenclature are used:

very coarse to very fine sand	2 - .0625 mm
coarse to very fine silt	.0625 - .0039 mm
clay	<.0039 mm

A "clay" can also be defined on the basis of mineralogy; that is, a particle of any size which is composed of one or more of the minerals regarded as clay minerals (Carroll, 1970). Almost all clay minerals are phyllosilicates or, more commonly, layer-lattice silicates (Grim, 1968). In this thesis the major minerals studied were montmorillonite, illite, kaolinite and chlorite.



## FIELD METHODS

Samples analyzed in this study were obtained from several main sources: (1) auger drill samples and surface and shallow subsurface samples from Dr. J. T. Teller's continuing study of the surficial geology of southern Manitoba; (2) core and churn drill samples from the Water Resources Branch, Manitoba Department of Mines, Natural Resources and Environmental Management; (3) auger samples collected by R. McPherson and M. Fenton on their respective thesis studies; and (4) surface and shallow subsurface samples collected by the author (See Fig. 3). Approximately 310 samples were analyzed from 58 auger and churn drill holes and 20 natural exposures and shallow excavations.

The resulting stratigraphic subdivision presented in Chapter 4 is based on these analyses of samples which the author interpreted as offshore sediments of Lake Agassiz. That is, the samples were, in the depositional environment sense, already interpreted before analyses proceeded. In general, the criterion used for these environmental interpretations was texture (clay to silty clay).

## TEXTURAL ANALYSIS

Since most of the offshore sediments of Lake Agassiz are very fine grained (usually over 90% of the sediment is finer than 8  $\phi$ ), size analysis by the pipette method was used. Briefly this procedure is as follows:

- 1) Twelve to seventeen grams of sample were placed in a dispersant solution. Calgon was exclusively used for this purpose. Best results for the offshore Lake Agassiz material were obtained using three grams of Calgon per one liter of distilled water.

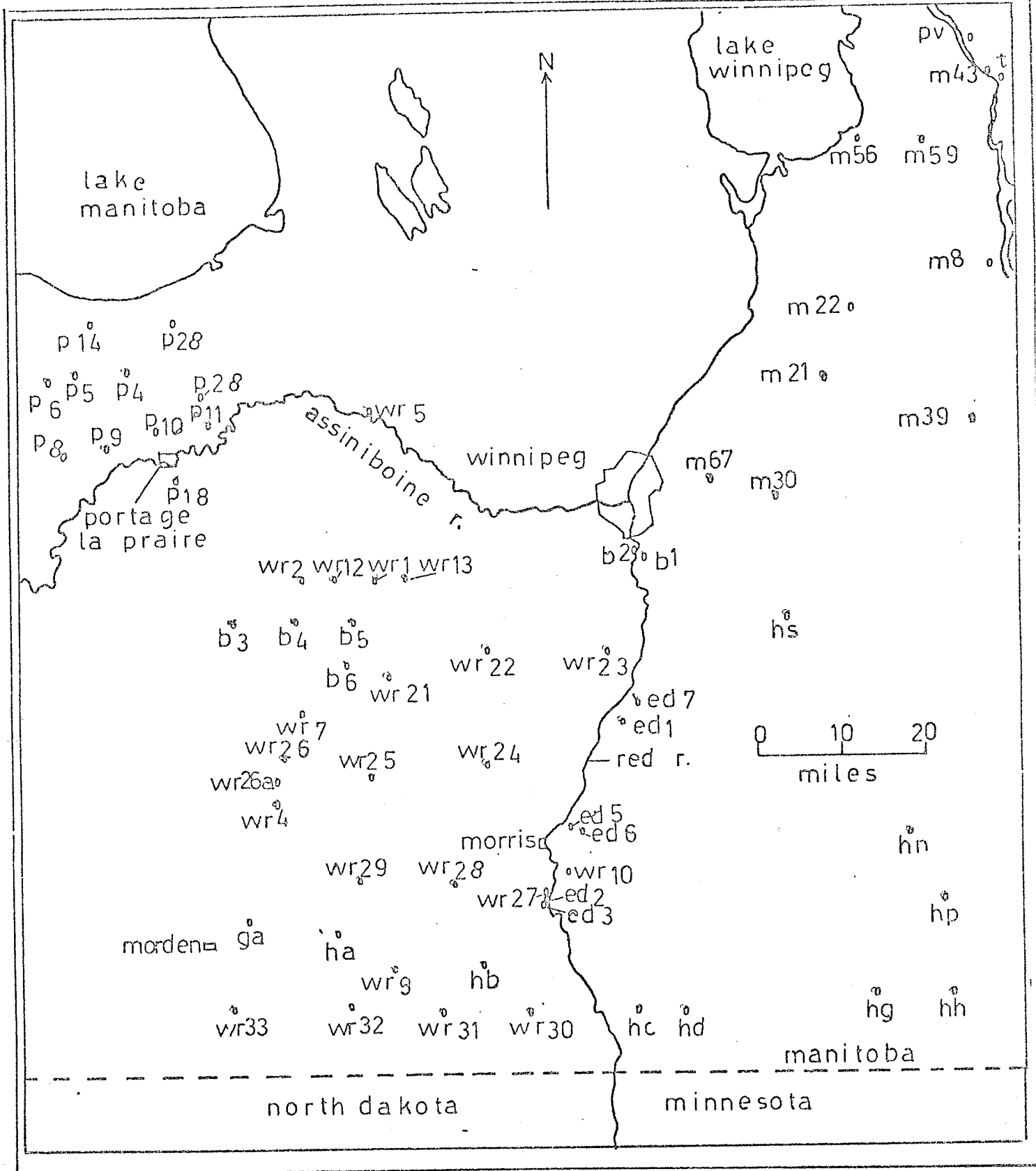


Fig. 3. Location of Sample Collection Sites (See also Appendix G).

2) The dispersed sample was then wet sieved through a 62  $\mu$  sieve using less than one liter of Calgon solution. All material less than 62  $\mu$  was placed in a 1000 ml graduated cylinder. The coarser fraction was weighed.

3) Pipetting was then done at times and depths as outlined by Folk (1968, p. 39). Details of the procedure are given in Appendix A and Folk (1968, pp. 37-40).

4) Weight percentages were determined for one half phi intervals from four phi to six phi, and one phi intervals from six phi to ten phi. Cumulative percentages were calculated, and a cumulative curve plotted.

5) At the same time that the nine phi and ten phi weight samples were being taken, an additional sixty ml portion was removed and put in a 125 ml (four ounces) polyethylene bottle for storage. From this storage reservoir, slides for X-ray analyses were later made. The storing of a relatively large amount of clay solution made it possible to return to the particular sample and size fraction and make additional slides.

#### MINERALOGICAL ANALYSIS

Qualitative and semi-quantitative clay mineral analyses were conducted on the basis of X-ray diffraction data on the ten phi and finer size fraction. Initial experiments showed that there were only minor differences in the diffractogram traces of the nine phi and finer and the ten phi and finer segments. The ten phi fraction was chosen for study because of less interference from non-clay minerals.

Diffractograms were run on a Philips powder diffractometer-generator using nickel filtered copper  $K\alpha$  radiation generated at forty kilowatts and twenty milliamperes. Further pertinent equipment settings included:  $1^\circ$  beam slit, 0.006 inch detector slit, 400 range counts per second and two seconds time constant with the zero suppressor at zero. Traces were run from  $2^\circ 2\theta$  to  $30^\circ 2\theta$ . The slides were scanned in one direction at a rate of  $1^\circ 2\theta$  per minute.

This combination of parameters was arrived at primarily by trial and error methods and should not be taken as a standard for all such sediment work. In particular, if few samples were to be analyzed and a greater accuracy was desired, the scanning speed can be cut to  $\frac{1}{2}^\circ$  to  $\frac{1}{4}^\circ 2\theta$  per minute. Also, depending on the suite of clay minerals present, the number of degrees scanned can be decreased or increased as necessary. Carroll (1970) suggests a range of  $2^\circ$  to  $37^\circ 2\theta$  for most general reconnaissance work while the North Dakota Geologic Survey scans  $3^\circ$  to  $15^\circ 2\theta$  for their Agassiz clay work (Arndt, 1973, written communication).

A "standard" slide of offshore clay was prepared and run every fifty samples to insure proper machine alignment and calibration. In addition, it was found that in samples from several localities (most notably Holes P-8 to P-18) pretreatment with hydrogen peroxide in order to remove organic material greatly enhanced the relative heights of the peaks, thereby making interpretation easier. Further aspects of slide preparation and oriented mounting techniques will be discussed in Chapter 3.

Three slides for each sample were prepared from the stored solution. Diffractograms were obtained from one which had been

glycolated (by placing in an ethylene glycol environment for at least forty-eight hours; Brunton, 1955) and one heated at 575°C for one hour (Carroll, 1970). The remaining slide was left untreated and kept for later use if necessary. Frosted petrographic slides were used throughout this project. Experiments confirmed the fact that the clay film will more readily curl and crack upon drying on unfrosted slides.

The above procedure (See Fig. 4) proved to work very well for analysis of offshore Lake Agassiz sediments. Once size analyses and slide preparation were completed, X-ray analysis proceeded rapidly. With the above conditions it was normal to run twenty samples per 8 hour day.

#### X-RAY INTERPRETATION

##### Non-Clay Minerals

As previously stated, it was not the purpose of this thesis to determine the presence or abundance of non-clay minerals (in the clay-sized fraction) in the Lake Agassiz sediments. However, several non-clay minerals were noted either because of their abundance as minor constituents or their possible importance to stratigraphic grouping and correlation. The quantitative analysis of carbonate minerals will be discussed later in this Chapter. Quartz was identified when present by its peak at  $4.26 \text{ \AA}$  ( $20.8^\circ$ ).<sup>1</sup> A much stronger peak for quartz exists at  $3.34 \text{ \AA}$  ( $26.6^\circ$ ), but this is usually masked by the 003 reflection of illite at  $3.33 \text{ \AA}$ . Feldspar was identified by its peaks at  $3.18 - 3.2 \text{ \AA}$  ( $28^\circ$ ) and

<sup>1</sup>All degree values given in this report are assumed to be  $2\theta$  using Cu K $\alpha$  radiation.

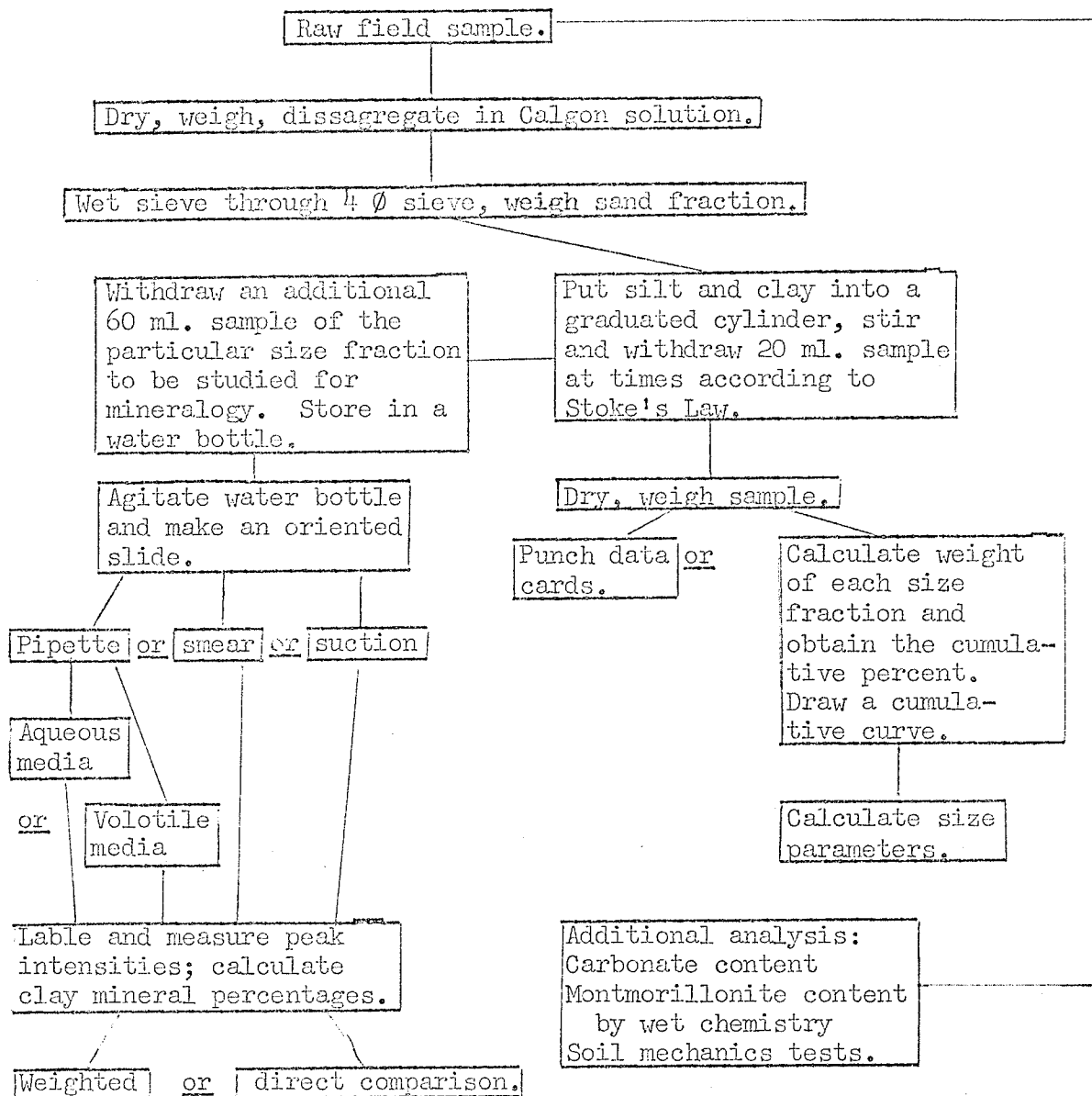


Fig. 4. Generalized Flow Sheet for Sample Analysis.

4.0 Å (22.2°). In most cases the diffraction patterns of these and other non-clay minerals were too poorly developed to conclude anything more than their presence.

#### Clay Minerals

Clay minerals identified in the samples are divided into four major groups: montmorillonite, illite, kaolinite and chlorite. These clay mineral groups constituted the bulk of the samples studied, and unless otherwise noted, are, for quantitative estimations, assumed to make up 100 percent of the sample. In combination, they produced a complex series of reflections in the 15 Å, 14 Å, 10 Å, 7 - 7.5 Å, 4.2 - 4.5 Å, 3.5 - 4.0 Å and 2.4 - 2.9 Å regions. The following criteria and heat and glycolation characteristics were used to identify and determine relative percentages of the clay minerals:

(1) The montmorillonite group is characterized by its expanding lattice. When dried it has a basal spacing of about 12.5 Å (7.05°). After glycolation the material expands to a 17 Å (5.19°) peak. Several problems arise, however, when this 17 Å peak is used for quantitative measurements. The peak is often very broad, and since it occurs at a low  $2\theta$  angle, accurate baseline positioning is very difficult. Differences of 100 percent were commonly observed simply by varying the baseline position beneath this 5.19° peak. For this and other reasons (See Chapter 3) the following technique of semi-quantitative analysis was used throughout the study: Heating at 575°C for one hour will cause a shift in the montmorillonite peak from 17 Å (5.19°) to 10 Å (8.8°) without having any effect on the

other mineral (illite) contributing to this  $10 \text{ \AA}$  ( $8.8^\circ$ ) peak (Carroll, 1970). Thus, the difference in intensities between the  $10 \text{ \AA}$  ( $8.8^\circ$ ) peak from the glycolated slide and the heated slide is the relative amount of montmorillonite in the sample.

An approximation of the degree of crystallinity of the montmorillonite was attempted using a method described by Biscaye (1965). Using the height of the  $17 \text{ \AA}$  ( $5.19^\circ$ ) peak above the background (p) and the depth of the valley on the low-angle side of the peak (v), the closer the ratio of p/v is to one the better is the crystallization of the montmorillonite material.

(2) Illite is a poorly defined term referring to a general group of mica-like clay minerals of indefinite structure (Grim, 1968). It is identified by a sharp peak at  $10 \text{ \AA}$  ( $8.8^\circ$ ) which is not affected by glycolation. Broad secondary peaks at  $5 \text{ \AA}$  ( $17.7^\circ$ ) and  $3.3 \text{ \AA}$  ( $26.7^\circ$ ) were also useful in identification, although the latter was often masked by the  $3.3 \text{ \AA}$  quartz reflection. Quantitatively, the amount of illite in the sample was assumed to be relative to the peak intensity of the  $10 \text{ \AA}$  ( $8.8^\circ$ ) reflection from the glycolated slide.

(3) The kaolinite and chlorite groups were identified by their combined, overlapping reflections at  $7 \text{ \AA}$  ( $12.4^\circ$ ) from the glycolated slide. Although various techniques do exist for the separation of the two components (notably that of Biscaye, 1964) the accuracy needed to quantitatively evaluate this separation was not achieved in this study. Instead, simply the presence of a large amount of either one of the components was indicated in the quantitative determination of the combined group. This was done by first determining if there



was a  $14 \text{ \AA}$  ( $6.3^\circ$ ) chlorite peak present. If not, most of the  $7 \text{ \AA}$  ( $12.4^\circ$ ) reflection could be attributed to kaolinite. After heating at  $575^\circ\text{C}$  for one hour, kaolinite will become amorphous, and its contribution to the  $7 \text{ \AA}$  ( $12.4^\circ$ ) peak will disappear. Chlorite upon heating, however, will show an increase in peak intensity (Carroll, 1970). Thus, if on the heated trace the  $7 \text{ \AA}$  ( $12.4^\circ$ ) and  $14 \text{ \AA}$  ( $6.3^\circ$ ) peaks were not reduced in amplitude, most of the reflection was coming from the chlorite.

Wicks (1965), in a differential thermal analysis of Lake Agassiz sediments in the Winnipeg area, reports a possible high amount of mixed-layer minerals and interstratification of the clays, particularly of the illite and montmorillonite groups. However, in the current X-ray study, less than 5% of the samples studied showed evidence of interstratification. When present, it is characterized by broad basal diffraction peaks in the  $17 \text{ \AA}$  ( $5.19^\circ$ ) and 10 to  $14 \text{ \AA}$  ( $8.8^\circ$  to  $6.3^\circ$ ) regions on the glycolated trace (Gjems, 1967; Carroll, 1970). The mixed-layer material was simply noted if present, and no semi-quantitative estimations were attempted. Its presence was not frequent enough to be considered in the total clay mineral calculations.

#### Percentage Calculations

The standard method used to obtain semi-quantitative figures for the clay minerals studied was as follows (Pierce and Siegal, 1969):

$$\% \text{ Montmorillonite group} = \frac{X}{X+Y+Z} \times 100$$

$$\% \text{ Kaolinite plus Chlorite Groups} = \frac{Y}{X+Y+Z} \times 100$$

$$\% \text{ Illite group} = \frac{Z}{X+Y+Z} \times 100$$

where X = 10 Å peak height after heating minus 10 Å peak height after glycolation.

Y = 7 Å peak height after glycolation.

Z = 10 Å peak height after glycolation.

#### CHEMICAL MINERALOGICAL ANALYSES

Chemical analyses were undertaken on selected samples to determine if "wet" chemical methods could be worked into a standard analytical procedure in the investigation and stratigraphic subdivision of Lake Agassiz sediments.

About twenty percent of the total number of samples studied were quantitatively analyzed for their carbonate content using an intercept gasometric method developed by Dreimanis (1962) and modified by Teller (1972, written communication). Basically, this process consists of adding a measured amount of hydrochloric acid to a 1 gram portion of finely ground (< 200 mesh) sample in a closed system. The gas generated by chemical reaction of the acid with the carbonates displaces a connected column of water. The measure of the amount of water displaced after 45 minutes, after corrected for temperature and pressure changes, can be used to calculate the calcite and dolomite percentages. A complete description of this procedure is given in Appendix B.

#### SOIL MECHANICS ANALYSES

The use of engineering and soil mechanics properties has been recognized as an important tool in subdividing offshore Lake Agassiz sediments (Rominger and Rutledge, 1952; Moran, 1972; Arndt, 1972,

written communication). However, geologists have not applied the data to the lake stratigraphy in Manitoba. Therefore, an attempt was made in this study to incorporate soil mechanics properties with the general textural and mineralogical findings. Most of the data was obtained from the Water Resources Branch of the Manitoba Government and, to some extent, from publications of the Manitoba Soil Survey. I also analyzed several samples for plastic limit and natural water content. Details of the procedures used are found in Appendix C. Following is a brief description of the properties and parameters measured and used.

#### Liquid Limit

As the moisture content of a clay deposit increases from a dry state, the material changes from a solid or semi-solid to a plastic state and with increased moisture eventually to a liquid state. The liquid limit is the moisture content, expressed as percent of dry weight, at which the clay changes from a plastic solid to a viscous liquid (Rominger and Rutledge, 1952; Michalyna, et al, 1972). It depends mainly on the mineral composition, types and amount of organic material and texture.

#### Plastic Limit

Plastic limit, like liquid limit, is also a water content measurement. It is the amount of moisture, expressed in percent dry weight, at which the clay will change from a plastic solid state to a friable or brittle solid state (Rominger and Rutledge, 1952). Practically speaking, it is the moisture necessary to allow the clay to be rolled into a small cylinder without breaking (Michalyna, et al, 1972).

The plasticity index is an associated parameter calculated as the difference between the liquid limit and plastic limit. It is a measure of the range of moisture content over which a clay can exist in the plastic state (Rominger and Rutledge, 1952).

#### Natural Water Content

An important parameter in stratigraphic division of Lake Agassiz clays is the natural water content of the material. It is expressed, in percent dry weight, as the ratio of the loss of weight sustained by a sample after heating at 105°C to the weight of the normal air dried sample (Rominger and Rutledge, 1952). It is affected not only by mineral composition and texture, but also by the depositional and post-depositional history of the sediment.

The relative water content is another associated parameter defined as the ratio of the difference between the natural water content and the plastic limit to the plasticity index (Rominger and Rutledge, 1952).

#### Preconsolidation Stress

The preconsolidated stress is a basic soil mechanics test used particularly in foundation and settlement work. It is a measure of the maximum stress that has affected the clay prior to sampling. It also is strongly affected by the sediments' loading history.

## CHAPTER 3

### COMPARATIVE METHODOLOGY STUDY

#### INTRODUCTION

A number of variables affect the final semi-quantitative estimation of the various clay mineral groups from an X-ray diffractogram. These included: (1) variations in the response of the X-ray diffractometer equipment due to inherent inconsistencies or outside factors, such as electrical power surges; (2) variations in selecting pieces of sample for analysis; (3) variations in thickness of clay film subject to irradiation; (4) variations in mounting techniques; and (5) variations in quantitative calculation techniques. With the exception of variations (1) and (2), each of these will be discussed in detail in the following sections.

Several sets of analyses were repeated in an attempt to establish the importance of each of these variations. Table 2 summarizes the results of rerunning three sets of three samples. Column 1 lists the quantitative arithmetic mean values of the clay mineral groups with the thickness factor (clay film thickness) being variable. Thickness variation was produced by using slides containing seven mg, fifteen mg, twenty mg, and thirty mg of a sample (dry net weight). Column 2 evaluates the mounting variable. Four slides were prepared using the aqueous media pipette method, the

TABLE 2  
 REPEATED X-RAY ANALYSES  
 OF THREE SAMPLES OF LAKE AGASSIZ SEDIMENT

Sample	Column 1*			Column 2*			Column 3*		
	Ill	Mont	K C	Ill	Mont	K C	Ill	Mont	K C
HB-2									
mean	28	37	35	30	33	37	29	41	29
$\sigma$	.36	.99	.44	.41	.68	.91	2.9	2.1	1.9
HB-4									
mean	20	42	37	24	40	35	29	46	28
$\sigma$	.16	.46	.95	1.1	1.6	1.2	2.9	3.5	2.1
HB-6									
mean	20	50	30	26	43	30	29	45	31
$\sigma$	.36	.46	.27	1.6	1.4	1.3	3.3	6.0	1.1

\*Column 1 -- Thickness variation (7 mg, 15 mg, 20 mg, 30 mg).  
 Column 2 -- Mount variation (aqueous pipette, acetone pipette, smear, suction).  
 Column 3 -- Computing variation (direct comparison, height and area; weighted, height and area).

$\sigma$  = arithmetic standard deviation.

Ill = percent illite group.

Mont = percent montmorillonite group.

K+C = percent kaolinite plus chlorite group.

acetone media pipette method, the smear method, and the suction method of mounting. Column 3 shows the results of varying the calculation techniques using the direct comparison and the weighted methods (See pp. 45-47) with intensities being calculated by peak area and peak height. The arithmetic standard deviations are given to help illustrate the overall trend. The actual computed quantitative values for each of the sets are shown in Appendix D.

Although each of the three variables introduces some degree of deviation, the magnitude of these deviations should be an indication of the relative influence of each of the variable factors. Table 2 shows that the thickness variation contributed the least amount of inconsistency, and the calculation variable contributed the greatest.

The main emphasis of this chapter will be on the results of various experiments conducted in two main areas of clay mineral investigation: (1) techniques used to obtain oriented mounts suitable for X-ray diffractometry; and (2) methods used to obtain semi-quantitative estimates from the resulting diffractograms. There is no standard method used to mount or calculate the amount of clay minerals in sediments using X-ray diffraction techniques.

Finally, it should be noted that the purpose of this part of the study was to investigate the various techniques and methods in light of their reproducibility. However, accuracy (closeness to some "true" value) was not being investigated, and no comparison should be attempted between the clay percentages in this report and a "true" percentage.

## MOUNTING EXPERIMENTS

### Introduction

There are basically two types of clay mineral mounts: oriented (that is, the morphologic surfaces of the clay particles are preferentially oriented parallel to the plane of the slide) and unoriented. Although the use of unoriented mounts is common (Barshad, 1953; McAtee, 1956; Klug and Alexander, 1962; Schultz, 1964; Bystrom-Ackland, 1966; and Fenton, 1970), the preparation and interpretation of oriented mounts is easier and probably less erroneous (Brindley, 1961).

### Clay Film Thickness

One of the first and most important aspects considered when producing an oriented mount was obtaining a proper thickness of the clay film to give the maximum intensity of diffraction from crystal lattice planes. This was basically a question of how much of the clay slurry concentrate or paste should be mounted on the slide. This question has been studied (Harward and Theisen, 1962; Carroll, 1970), and the general consensus is that the slide should contain between 5 and 90 mg of sediment (dry net weight). This value will change depending on the particular suite of clay minerals, type of sediment being analyzed and the concentration of clay minerals in the solution (Jarvis, et al, 1957). Experiments conducted with clay-rich offshore Lake Agassiz sediments (Fig. 5) indicated a desirable net sample weight of ten to twenty mg. Less than this amount produced a clay film too thin, and the principle spacings were weak and diffuse. If much more than this amount was used high background peaks were



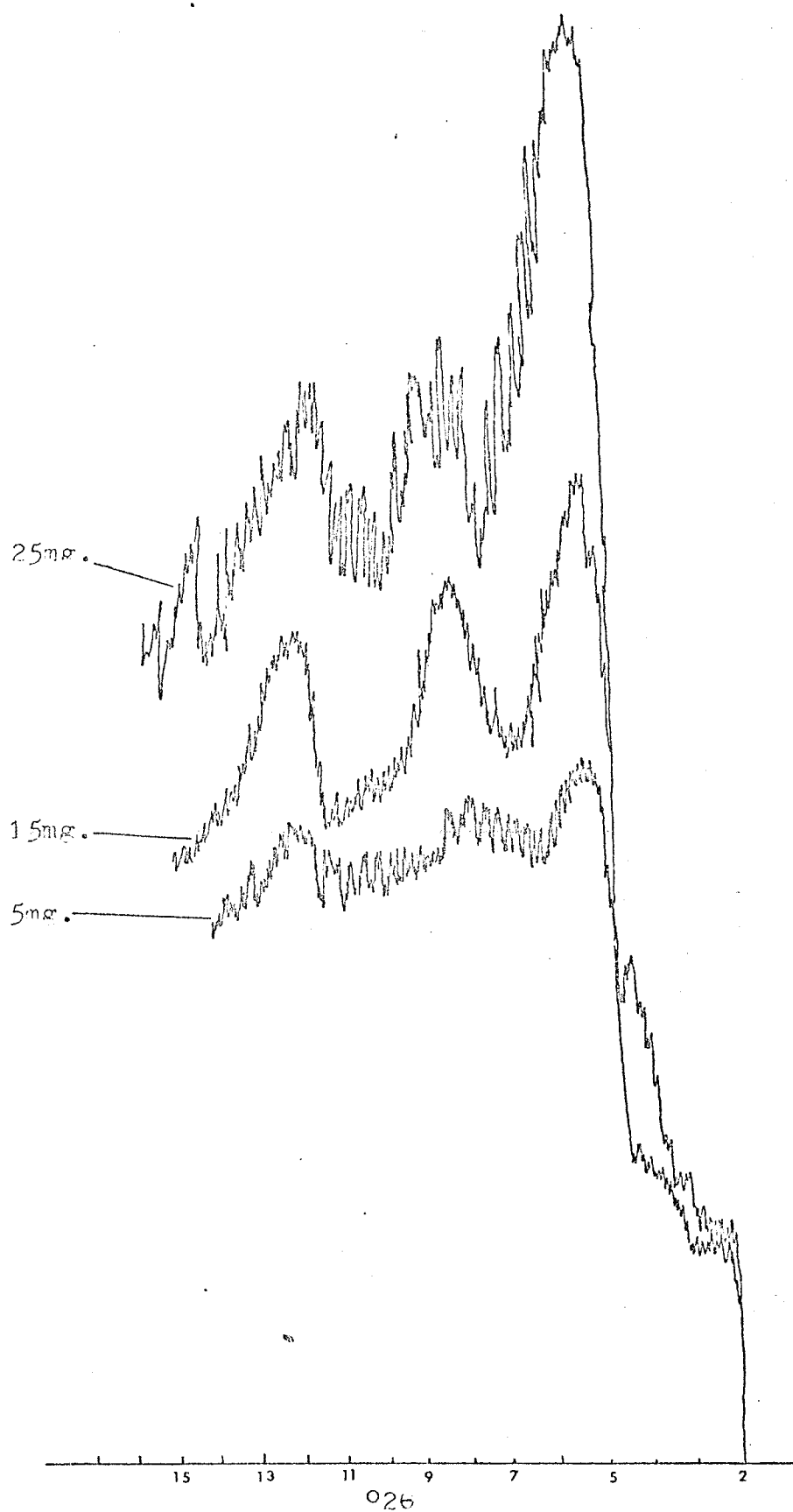


Fig. 5. Portions of X-ray Diffractograms of Sample HB-2 Using 5 mg, 15 mg and 25 mg of Sample.

produced which limited the quantitative aspect of the diffractogram. In addition to this, Stokke and Carson (1973) state that the thicker mount will produce an abnormally high reflection for montmorillonite due to segregation of the mineral nearer the top of the clay film. This is particularly pertinent when gravitational methods of mounting were used (See p. 29).

#### Pipette-On-Glass-Slide Technique

There are three basic types of clay mounting techniques referred to in the literature. Probably the most common method is that of depositing a given amount of clay solution on a glass slide and allowing the liquid portion to evaporate. This technique is referred to as the pipette-on-slide or sedimentation method. Since nearly all clay mineral particles are platy, the dispersed material should settle with a high degree of preferred orientation. However, several authors have recognized that this gravitational process leads to erroneous results, primarily due to segregation of the larger particles (with a greater settling velocity) in the lower part of the clay film and a corresponding concentration of the finer (slower settling particles) in the upper portion. Since the smaller clay particles are predominantly montmorillonite and the larger are kaolinite and illite (Schultz, 1955), this size segregation is also a mineral segregation. As 90 percent of the X-ray diffraction pattern originates in the upper five to ten percent of the mount (Gibbs, 1967), where the finer montmorillonite is concentrated, the amount of error in mineral percent calculations may be considerable (Stokke and Carson, 1973).

Gibbs (1965), Marvis, et al (1957), and others contend that the quality of the clay slide diffractogram (that is, the recognition and measurability of various peaks ) is a direct response to the amount of time allowed to let the clay particles settle and the solution media to evaporate. That is, a higher quality diffractogram should result if a greater amount of time is permitted for media evaporation. If the time for settling is increased, however, mineral segregation (as noted above) will also be increased. Conversely, it seems reasonable that if the time for evaporation is decreased, the factor of fine particle segregation will be curtailed. Parallel orientation should still be achieved by the platy clay particles as they settle through a liquid media. Thus, a comparative study was undertaken to note any differences in the pipette-on-slide method using water as a solution media and a more evaporative liquid (acetone or alcohol) which reduced the length of time allowed for particle settling and segregation.

The results (Table 3), based on fifteen samples, are inconclusive although a majority of the samples (53%) showed a lower montmorillonite content using the acetone and alcohol media mounts compared to the water media mounts. This decrease was usually in the range of ten to fifteen percent. However, thirty-three percent did not decrease but showed a large increase in montmorillonite, usually at greatest expense to the kaolinite plus chlorite group. Approximately thirteen percent of the samples showed less than three percent change in the values.

The decrease in percentage in the montmorillonite group using acetone and alcohol suggests that an increased evaporation rate

TABLE 3

VARIATION IN CLAY MINERAL PERCENTAGES RESULTING  
FROM PREPARATION IN VOLATILE VERSUS AQUEOUS MEDIA  
(Calculation by the Direct Comparison Method)

Sample	Aqueous Media			Acetone Media			Alcohol Media		
	Ill	Mont	K+C	Ill	Mont	K+C	Ill	Mont	K+C
HA-1	25	31	43	23	48	27			
5	35	7	61	45	10	45	47	7	46
7	27	27	44	38	21	40			
HB-2	28	36	36	31	31	38			
4	20	42	36	24	37	37	20	35	45
6	18	52	29	29	34	36	35	23	41
8	26	36	36	21	42	37			
P18-2	26	33	40	27	29	44			
4	27	27	45	19	53	26	19	50	29
6	33	25	41	37	20	42			
WR23-2	30	23	46	21	49	29			
4	33	26	40	41	14	45	40	12	48
8	37	31	31	50	45	25			
GA-7	35	45	20	32	44	24			
9	36	21	42	21	46	33			

caused by using a liquid media of higher volatile quality does result in a less vertically segregated clay mount. The increase in montmorillonite percentage cannot be explained.

Several attempts were made at decreasing the evaporation time even more by heating the slides just prior to applying the clay solution or by placing the freshly mounted slide on a warm surface. In almost all cases this procedure was unsuccessful. Increased temperature caused curling and cracking of the clay film or a general "bulbous" texture and appearance to the slide indicating a lack of parallel orientation.

Although it is probable that volatile liquid media mounts produce more accurate diffractograms (i.e., closer to "true" value), the aqueous media mount was chosen as the standard used in this study of Lake Agassiz sediments because of the following negative aspects involved in the former volatile liquid methods: (1) Slide preparation using the acetone and alcohol media required several additional steps, notably the longer centrifuge time necessary to remove the maximum amount of water possible before mixing with the volatile liquid (Appendix A). (2) Acetone and alcohol mounts were noticeably more susceptible to curling and cracking than were the aqueous mounts. (3) Volatile liquid mounts had a somewhat lower reproducibility (Table 4) indicating the process may be less precise. (4) The chemical effects, particularly any ion fixation process and its effect on the lattice structure of the clay mineral, have not been fully explored. (5) Acetone was observed to cause flocculation and gelation of the clay solution, a condition which is contrary to the parallel orientation concept. (6) The volatile liquids

TABLE 4

REPRODUCIBILITY OF CLAY MINERAL PERCENTAGES  
 USING ACETONE VERSUS AQUEOUS MEDIA MOUNTS  
 (Calculation by the Direct Comparison Method)

Sample	Aqueous Media			Acetone Media			
	Ill	Mont	K+C	Ill	Mont	K+C	
HB-2	1	28	30	42	31	31	38
	2	28	36	36	29	34	37
	3	30	33	37	42	25	32
	4	28	34	37	37	35	28
	5	29	40	30	29	20	51
	6	.20	.82	1.2	1.3	1.4	1.7
HB-6	1	20	42	36	24	37	37
	2	29	35	35	29	35	37
	3	13	41	40	42	20	37
	4	21	42	33	16	31	53
	5	20	37	33	25	40	33
	6	.96	.70	.60	2.9	1.8	1.7

were observed to set up circulation or flow patterns within the clay slurry. This also decreases the amount of preferred orientation achieved.

#### Smear Method

Although the pipette-on-slide technique is the more conventional method of specimen preparation (Carroll, 1970), the potential segregation problems warranted examination of other possible procedures. A second mounting procedure, the smear-on-glass-slide technique, involved making a thick clay paste and spreading this paste evenly over the slide (Appendix A; Theisen and Harward, 1962). In theory, this process should not only produce an oriented clay mount but also effectively eliminate any size segregation due to settling through a particular media, and consequently, give a lower quantitative estimation for montmorillonite. The results of a comparison between the smear mount and the pipette-on-slide mount (aqueous media) showed this to be true (Table 5). The calculated montmorillonite values were generally lower using the smear technique.

Once again, as in the case of the volatile liquid media pipette method, the smear technique probably gave more accurate results because of the elimination of the segregation problem. This method was not chosen as the main analysis technique for the Lake Agassiz sediment study, however, because of several negative aspects involved. Again, the smear method required several time consuming auxiliary steps in the general procedure, most notable being the evaporation of the clay concentrate to a thick paste (Appendix A). This paste must be at a very precise consistency. If it is too thin a partially "settled" slide will be produced; if too thick, the

TABLE 5

VARIATION IN CLAY MINERAL PERCENTAGES  
 RESULTING FROM PREPARATION BY THE SMEAR MOUNT  
 VERSUS THE PIPETTE-ON-SLIDE(AQUEOUS) MOUNTING TECHNIQUE  
 (Calculation by the Direct Comparison Method)

Sample	Pipette			Smear		
	Ill	Mont	K+C	Ill	Mont	K+C
HA-1	25	31	43	49	15	35
5	35	7	61	45	9	46
7	27	27	44	38	20	41
HB-2	28	36	36	30	32	37
4	20	42	36	21	46	31
6	18	52	29	29	45	25
8	26	36	36	18	57	24
P18-2	26	33	40	30	32	39
4	27	27	45	42	24	32
6	33	25	41	29	30	40
WR23-2	30	23	46	36	23	41
4	33	26	40	44	20	37
8	37	31	31	39	30	30
GA-7	35	45	20	27	27	46



clay will not smear on evenly and thus the particles will not assume an oriented arrangement. A much more important discrepancy was the lack of reproducibility using this procedure. Table 6 shows rather high standard deviations compared to the pipette technique for five mounts of the same samples. This high degree of variability is no doubt due to the inconsistency of the amount of parallel orientation achieved in producing the smear.

#### Suction Method

A final method of obtaining an oriented mount to be compared in this study consists of depositing an amount of clay solution on a porous slide and, by applying suction to the underside of the slide, removing all of the solution media. Although the original investigators of this method call for the slides to be made from plates of white, unglazed, nonvitreous ceramic tile (Kinter and Diamond, 1956), this particular material was not available for this study. Instead, flat plates were made from a type of semi-porous ceramic earthenware commonly used for flower pots (available from Jonasson Ceramic Supply, Winnipeg). This material allows reasonably rapid passage of the water through the slide and is inexpensive.

Several advantages were observed in using this procedure. First, slide preparation is very rapid (Appendix A). Since there were no evaporation or settling processes involved, the slides could be mounted and ready for irradiation within thirty minutes. The suction procedure, done by holding a length of rubber tubing (connected to a vacuum system) on the underside of the slide, usually took less than fifteen minutes. The remainder of the time was to allow the

TABLE 6

REPRODUCIBILITY OF CLAY MINERAL PERCENTAGES BY  
THE SMEAR METHOD VERSUS THE PIPETTE METHOD  
(Calculation by the Direct Comparison Method)

Sample	Pipette			Smear			
	Ill	Mont	K+C	Ill	Mont	K+C	
HB-2	1	28	30	42	30	32	37
	2	28	36	36	35	26	38
	3	30	33	37	42	31	28
	4	28	34	37	16	49	35
	5	29	40	30	41	24	35
	$\bar{x}$	.30	.77	.74	2.4	2.2	1.1
HB-6	1	20	42	36	29	45	25
	2	29	35	35	12	52	36
	3	18	41	40	28	41	30
	4	21	42	38	42	28	30
	5	20	37	33	35	34	31
	$\bar{x}$	.96	.92	.60	2.4	2.3	.87

clay to completely dry. Second, the suction mounts were noticeably more stable, that is, there was very little cracking or curling of the clay film. This was probably due to the porosity of the slide which allowed the clay particles to penetrate and get a "foothold" on the mount. Also, although not directly used in this study, Kinter and Diamond (1956) point out that by passing various solutions through the clay mount, it is possible to saturate the sample with one or more cations for ion exchange studies. This is particularly useful in soil clay mineralogy work and eliminates tedious processes of cation saturation while the material is still unmounted.

Finally, a higher degree of parallel orientation was probably achieved with the suction technique than with any other method studied. Kinter and Diamond (1956) compared peak intensities of the pipette-on-glass-slide and suction techniques and found that the suction method gave heights two to twelve times as great as those of the glass slide. A similar relationship was observed in the present study (Fig. 6). The problem of vertical size segregation was also again apparently largely avoided as suggested by consistently lower values of montmorillonite (Table 7). Also, in a limited reproducibility study, the suction technique proved to be slightly more precise than the pipette-on-slide technique (Table 8).

Despite the number of advantages and the fact that the suction-on-porous-plate method was probably a better (more precise) oriented clay mounting technique, there were several disadvantages which precluded it from being used in this study of Lake Agassiz sediments. The major problem involved obtaining the slide or porous plate. If available at all, porous ceramic material will probably not be of a

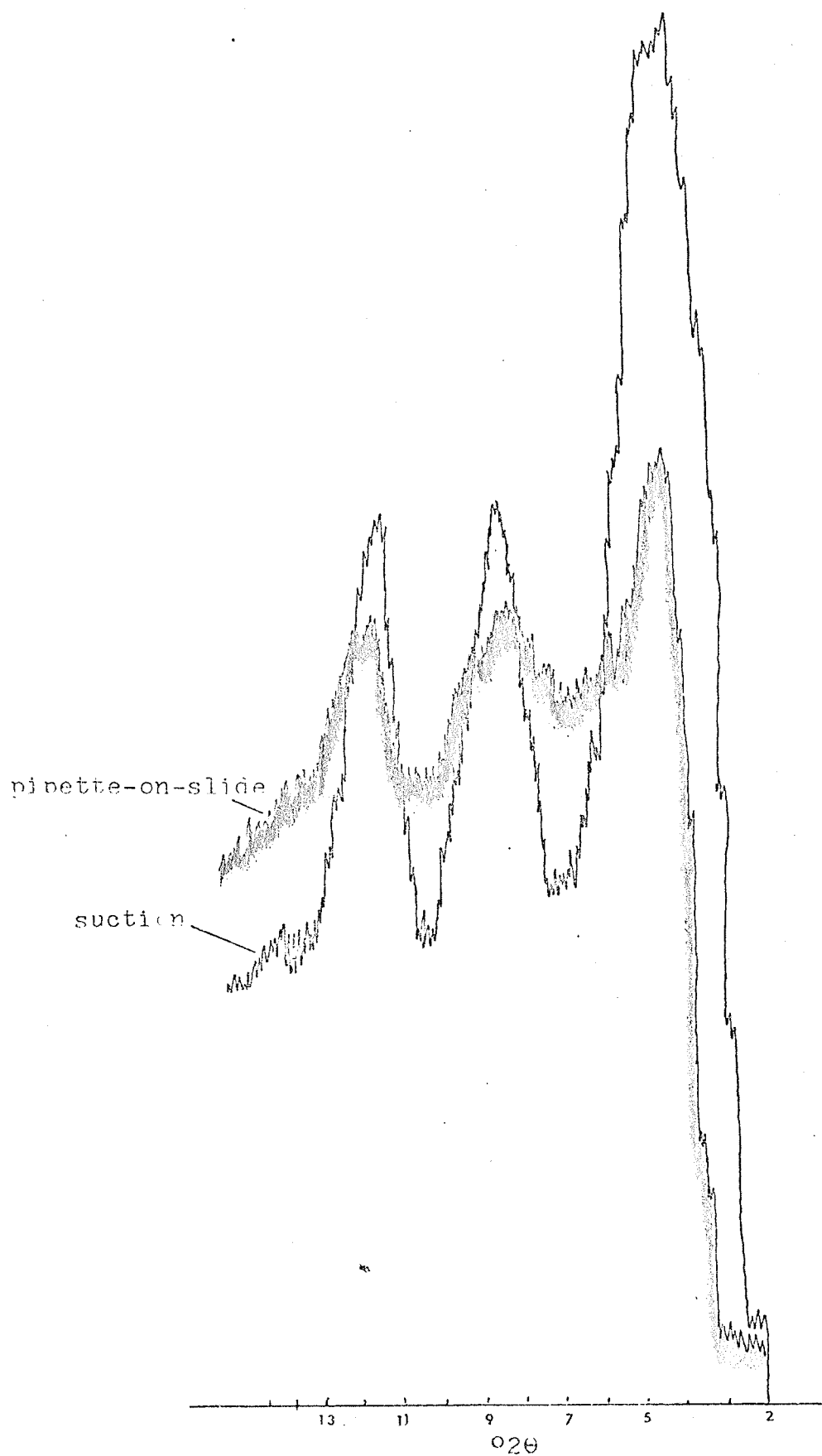


Fig. 6. Portions of X-ray Diffractograms of Sample HB-2 Using the Suction Technique and the Pipette-On-Glass Slide Technique.

TABLE 7

VARIATION OF CLAY MINERAL PERCENTAGES  
 RESULTING FROM PREPARATION BY THE SUCTION MOUNT  
 VERSUS PIPETTE-ON-SLIDE(AQUEOUS) MOUNT  
 (Calculation by the Direct Comparison Method)

Sample	Pipette			Suction		
	Ill	Mont	K+C	Ill	Mont	K+C
HB-2	28	36	36	31	31	38
4	20	42	36	29	36	34
6	18	52	29	29	41	30

TABLE 8

REPRODUCIBILITY OF CLAY MINERAL PERCENTAGES  
 BY THE SUCTION METHOD VERSUS THE PIPETTE METHOD  
 (Calculation by the Direct Comparison Method)

Sample	Pipette			Suction		
	Ill	Mont	K+C	Ill	Mont	K+C
HB-2 1	28	30	42	41	32	27
2	28	36	36	40	35	25
3	30	33	37	41	34	24
$\sigma$	.33	1.2	1.9	.24	.62	.62

usable size or shape and, therefore, must be cut and ground to approximately the dimensions of a petrographic slide. If actual flower pot ceramic is used, as was the case in this comparative study, the curved ceramic must also be ground to produce a flat uniformly thick slide. After irradiation, storage is a problem since the slabs are usually considerably bulkier than glass slides and do not fit into standard storage boxes.

An important aspect which must be considered if the suction method is to be used as a main analysis technique is that of the porosity of the ceramic material. The slide has to be porous enough to allow easy passage of water when suction is applied but cannot be so porous that size segregation, by withdrawing the finest material, can occur.

## CALCULATION EXPERIMENTS

### Introduction

A comparison of the methods used to compute the percent of clay minerals from X-ray diffractograms was undertaken primarily to investigate any significant differences that might exist due solely to the method of calculation.

It has been recognized since the 1930's, when the first work on making quantitative estimations from X-ray diffractograms of mixed powders was attempted, that these values are, at best, semi-quantitative approximations. Carroll (1970) points out that these semi-quantitative figures, based on comparisons of peak intensities, depend on many factors, including the orientation of the particles, thickness of the mount, evenness of spread on the slide, differences in crystal perfection, hydration and chemical composition. Many authors

(Johns, et al, 1954; Murray, 1954; Schultz, 1955; 1964; Weaver, 1958; Brindley, 1961; Klug and Alexander, 1962; van der Marel, 1966) have concluded that all schemes of clay mineral evaluation by X-ray diffraction techniques are only semi-quantitative.

However, in spite of the numerous and obvious limitations of the accuracy of the quantitative data, most authors agree that the results do give a clearer idea of the general distribution and variation in clay minerals within a particular study. The methods of arriving at these semi-quantitative values are extremely varied, and in many cases directly contradict each other. Pierce and Siegal (1968) give an excellent review and comparative study of five of the main calculation methods. A similar comparison of two methods was undertaken as part of this Lake Agassiz study.

#### Baseline Position

Schultz (1964), in an X-ray analysis of the Pierre Shale, contends that inconsistencies in baseline positioning could contribute a high amount of variation in calculated amounts of clay minerals, particularly if there are small amounts of the specific mineral. He proposes baseline positioning such that it marks where the diffractogram trace would be if the mineral producing the peak were absent. He furthermore suggests that the baseline be constructed by the use of a french curve. Others (Schoen, 1962; Gjems, 1967) propose the use of a baseline approximating a hyperbola. It seems, however, that if the very approximate nature of the resulting quantitative figures is accepted, variations produced by baseline locations will be negligible. Furthermore, experiments with Lake Agassiz sediments showed that variations caused by baseline positioning were generally

less than five percent (Table 9) indicating that it makes little difference where the baseline is placed as long as the positioning is consistent throughout the study. In this Lake Agassiz study the baseline was placed through the middle of the background trace.

#### Peak Area versus Peak Height

Another aspect to be evaluated is the method of obtaining the diffractogram peak intensity. Although rarely does an author indicate how he calculated the intensity, experiments showed that variations up to twenty percent can exist (Table 11).

Apparently the most commonly used method of evaluating the reflection intensity is to measure the area under the particular peak. This can be done using a polar planimeter (Pierce and Siegal, 1969) or an approximation technique developed by Schultz (1964).<sup>2</sup> There is little difference between the two techniques (Table 10).

The second method of evaluating the peak intensities is by measuring the height of the peak above the baseline. In a limited study comparing the height and area calculation methods (Table 11), half of the samples analyzed showed little difference (all within 3%) from one method to the other while the other half showed moderately large (10-25%) but inconsistent variation.

Johns, et al (1958), Schultz (1958, 1964) and Brindley (1961) conclude that the peak area method is probably more accurate, but also point out that many factors can influence the accuracy, most notable being the degree of crystallinity of the clay minerals, the amount and kind of material making up the clay mixture, and the

<sup>2</sup>Schultz' approximation method consists of using the sum of the height at the peak position, heights at  $\frac{1}{2}^{\circ}$  on either side of peak position, and heights at  $1^{\circ}$  on either side of peak position.



TABLE 9

VARIATIONS OF THE CLAY MINERAL PERCENTAGES  
 RESULTING FROM DIFFERENT BASELINE POSITIONING  
 (Calculation by the Direct Comparison Method)

Sample	Lower			Middle			Upper		
	Ill	Mont	K+C	Ill	Mont	K+C	Ill	Mont	K+C
HB-2	28	36	35	28	36	36	26	36	33
4	22	41	37	20	42	36	20	40	38
6	18	53	30	18	52	29	19	52	29
8	29	30	39	26	36	36	26	36	36
10	21	33	45	21	35	43	20	35	45

TABLE 10

VARIATION OF CLAY MINERAL PERCENTAGES RESULTING FROM  
 PEAK AREA BEING CALCULATED USING A POLAR PLANIMETER  
 VERSUS AN APPROXIMATION METHOD (SEE P. 42)  
 (Calculation by the Direct Comparison Method)

Sample	Polar Planimeter			Approximation Method		
	Ill	Mont	K+C	Ill	Mont	K+C
HB-1	35	29	35	40	22	37
2	31	42	26	24	46	22
3	15	68	27	22	74	26
4	24	55	21	18	60	21

TABLE 11

VARIATION OF CLAY MINERAL PERCENTAGES RESULTING  
 FROM INTENSITY MEASUREMENTS USING PEAK AREA VERSUS PEAK HEIGHT  
 (Calculation by the Direct Comparison  
 Method using Areas and Heights)

Sample	Area			Height		
	Ill	Mont	K+C	Ill	Mont	K+C
HB-1	40	22	37	39	21	39
2	24	46	22	28	36	36
3	22	51	26	20	51	27
4	18	60	21	20	42	36
5	23	51	25	17	52	30
6	38	30	32	18	52	29
7	21	46	33	25	33	41
9	29	30	40	29	29	42

amount of background noise on the diffractogram. However, the peak height method is much less time consuming and therefore was used in this thesis.

#### Weighted Calculations versus Direct Comparison

Perhaps the most variable factor involved in obtaining semi-quantitative information on the relative proportion of various clay mineral groups present in a sample is the method of computation. Basically there are two procedures: weighting the figures and direct comparison.

The more commonly used weighting method involves multiplying each of the peak intensities by a factor to relate one mineral to another. These factors, based on mass absorption and X-ray scattering coefficients, vary from one author to another (Johns, et al, 1954: on a glycolated trace, the  $17 \text{ \AA}$  area [montmorillonite] is equal to four times the  $10 \text{ \AA}$  peak area [illite] and twice the  $7 \text{ \AA}$  peak area [kaolinite plus chlorite]; Hathaway and Carroll, 1954:  $17 \text{ \AA}/10 \text{ \AA}/5 \times 7 \text{ \AA}$ ; Schultz, 1964:  $17 \text{ \AA}/4.5 \times 10 \text{ \AA}/\frac{7 \text{ \AA}}{4}$ ; Pierce and Siegal, 1969:  $17 \text{ \AA}/3 \times 10 \text{ \AA}/2 \times 7 \text{ \AA}$ ). The method of Johns, et al (1954) was selected for this comparative study.

The second method, direct comparison, involves calculating the relative amounts of clay minerals using both the glycolated and heated traces. The intensities of the  $10 \text{ \AA}$  and  $7 \text{ \AA}$  reflections on the glycolated traces are directly comparable to the relative amounts of illite and kaolinite plus chlorite respectively. The montmorillonite group content is the difference between the intensity of the  $10 \text{ \AA}$  peak on the heated trace and that on the glycolated trace. This method has the advantage of not having to work

with the 17 Å<sup>0</sup> peak which is usually erratic and difficult to evaluate.

The results of a comparison between these two methods were inconclusive (Table 12). Variations of up to 30% were calculated. The percentage of illite seemed to vary the most consistently, with 77% of the samples giving a higher content using the weighted method. Correspondingly, montmorillonite and kaolinite plus chlorite were both lower with this procedure. However, the conclusions reached by Pierce and Siegal (1969), that the direct comparison (by peak heights) method is of little value for comparative purposes was not substantiated in this study. Naturally any type of weighted value system, if adequately supported through chemical and X-ray determinations of mass absorption and crystallinity properties of the suite of minerals being studied, will no doubt improve the absolute quantitative estimations for that particular study. But, by simply noting the number of different factors introduced under the premise of weighting, it may be concluded that weighting is possibly an unnecessary refinement. It is not applicable to regional studies without further considerations.

#### CONCLUSIONS

Significantly different quantitative results have been obtained using a variety of methods and techniques of clay slide mounting and calculation reported in the literature. However, since all of these techniques lead only to semi-quantitative results, exacting and precise methods of mounting and calculating are probably unnecessary. The researcher's own preference, type of sediments being analyzed,

TABLE 12  
 VARIATIONS OF CLAY MINERAL PERCENTAGES  
 RESULTING FROM CALCULATION BY THE WEIGHTED METHOD  
 VERSUS THE DIRECT COMPARISON METHOD

Sample	Weighted Method			Direct Comparison Method		
	Ill	Mont	K+C	Ill	Mont	K+C
HB-1	27	51	21	39	21	39
2	36	32	31	28	36	36
3	38	38	24	20	51	27
4	40	31	29	20	42	36
5	32	38	29	17	52	30
6	38	26	36	18	52	29
7	27	43	29	25	33	41
8	45	34	21	26	36	36
9	39	33	27	29	29	42
10	27	47	25	21	35	43
HA-1	33	16	50	25	31	43
3	30	43	26	27	31	41
5	29	42	29	35	7	61
GA-1	29	40	29	6	50	43
3	53	20	26	25	25	50
5	36	40	24	29	33	37
7	30	59	10	35	45	20
9	33	40	26	36	21	42

suite of minerals expected, equipment and time available, and previous and concurrent work are most important in determining the combination of procedures to be used for a particular study.

Although quantitatively one method may be better than another, all of the techniques, if used singly and consistently, will show the variations and trends in clay mineral content of the stratigraphic sequence being studied. In light of the contradictory situation existing in the literature pertaining to many of these basic procedures it is of prime importance to list, in detail, all aspects of the methods being used in any study.

Specifically this comparative study showed:

(1) Size and mineral segregation is a definite problem in attempting to arrive at semi-quantitative estimates of clay minerals using X-ray diffraction techniques. Oriented slides of samples produced by the sedimentation method generally showed higher montmorillonite values than slides produced by the smear and suction methods for these same samples. However, the conclusion arrived at in this report is that, although the smear and suction techniques do perhaps give more accurate (closer to "true" value) semi-quantitative results, the sedimentation method was selected as the most useful mounting technique because of low reproducibilities and more complex and time consuming preparation steps involved with the other two methods. Also, since the sedimentation method is more commonly used, it offers greater correlation possibilities.

(2) The results of attempting to correct the segregation problem by using a more volatile liquid media in the sedimentation technique were generally inconclusive. The conclusion reached is

that possibly these volatile liquid mounts do give more accurate values than aqueous mounts but physical (possible lack of achieving parallel orientation) and chemical (possible ionic substitution and interference) factors as well as those listed in (1) above, are drawbacks to the use of volatile liquids.

(3) Differences in baseline positioning and the method used to evaluate peak intensities, in general, did not have much effect on the calculated clay values.

(4) The differences obtained by using two calculation methods were large. It was concluded, however, that the weighting method added unnecessary refinement to the semi-quantitative estimations.

(5) Clay film thickness differences in the pipette-on-glass-slide method produced little clay mineral percentage variation. However, considerable diffractogram quality differences were observed.

(6) In general, of the main variables affecting semi-quantitative clay mineral estimation by X-ray diffractometry, the calculation variable produces the greatest deviation, the mounting variable slightly less and the thickness variable the least deviation.

## CHAPTER 4

### RESULTS

#### INTRODUCTION

The main emphasis of stratigraphic data presented in this thesis is on the very fine grained offshore sediments deposited by glacial Lake Agassiz in the Red River basin of southern Manitoba. These offshore deposits do not cover the floor of the basin with equal thickness and in some areas constitute only a thin veneer on the surface (Fig. 7). The purpose of this section is to report my results of mineralogical, textural, and engineering work on these offshore sediments and to suggest stratigraphic subdivisions and correlations of the deposits.

#### NON-LACUSTRINE SEDIMENTS

In addition to describing the offshore sediments of the Lake Agassiz basin, Appendix G also reports the presence of non-lacustrine sediments, such as till and gravel. Although these non-lacustrine deposits were not studied for this report, the information presented in Appendix G and other subsurface data collected by Dr. J. Teller can be used to suggest a possible relationship of the tills and gravels to the lacustrine sediments.

In the central part of Manitoba's Lake Agassiz basin, offshore lacustrine clays and silty clays are present from the surface to a depth ranging from 50 to 160 feet.



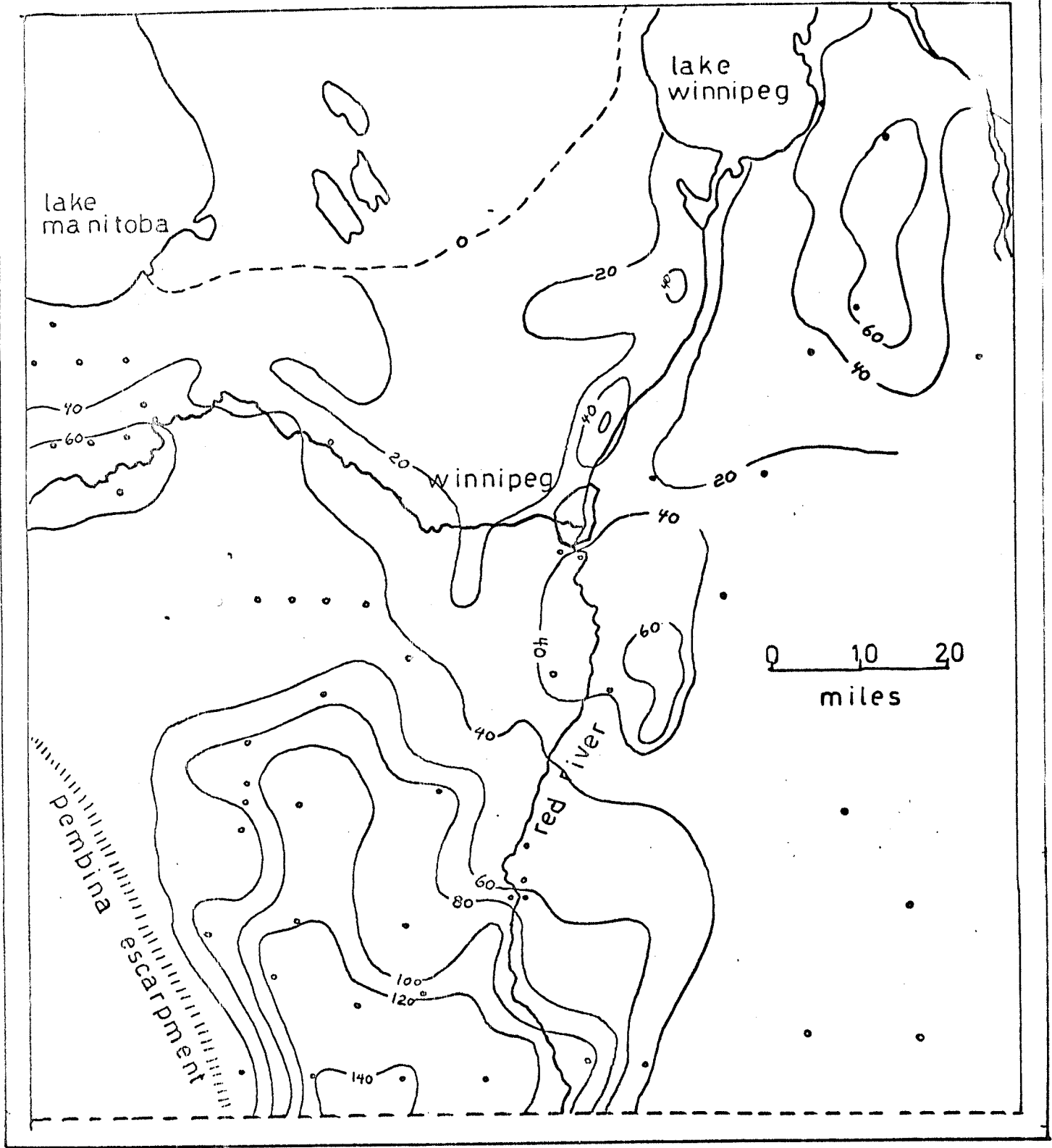


Fig. 7. Thickness of Offshore Lacustrine Sediment in the Red River Basin, Southern Manitoba. Contour interval is 20 feet. Control is based on the locations shown and on other water well data. The northern 0 line was estimated from Soil Survey reports.

Occasionally thin beds of sand and gravel can be found overlying and interbedded with the lacustrine clays (Charron, 1961).

In the central part of the basin this thick section of lacustrine clay usually rests directly on till or on a sandy gravel bed which is underlain by till. This till (or possibly tills) is interbedded with sands and gravels and extends to bedrock.

Farther east in the basin, however, a much thinner section (10-40 feet) of lacustrine sediments is found at the surface. Underlying this is till which, in turn, is underlain by lacustrine clay and finally till. Near the eastern margins of the central lake basin, till is found at the surface and is underlain by lacustrine clay and the basal till section.

#### STRATIGRAPHY OF OFFSHORE SEDIMENTS

##### Introduction

Chapter 1 summarized various attempts to divide the offshore Lake Agassiz sediments into units. However, several problems arise in attempting to work with these subdivisions:

(1) Many of the schemes are based on very localized studies, that is, a small number of sample locations in very close geographic proximity (For example, Wicks, [1965] based his mineralogical study on two, less than 60 foot, holes in the Winnipeg area; Ross and Karner [1967] on one hole in Grand Forks; Rominger and Rutledge 1952 on three holes in the Grand Forks-Fargo-Crookston area).

(2) The more comprehensive studies (i. e., those with a larger sampling base) of McPherson (1970) and Fenton (1970) are not primarily concerned with the areas of maximum sedimentation (i. e.,

the central Lake Agassiz basin). They have developed a stratigraphic picture based on the sediment record at the "margins" of the basin, which may or may not reflect the record in the "deeper water" portion of the lake. Also, the extensive work done in North Dakota and Minnesota, particularly in the Grand Forks-Crookston areas, was found to be of only limited applicability to this Manitoba study. Although this United States work is centrally located in the basin, its geographic distance from the Manitoba area and the lack of published information between the two areas (namely within Pembina and Walsh Counties, North Dakota) make for questionable correlations.

(3) Many of the stratigraphic schemes are based mainly on the color and the grain size of the sediment. Color, although often the most obvious and readily observed basis for subdivision, is a rather poor criteria due to its subjective character and the number of factors contributing to its variability. Grain size difference and variability remain important criteria for distinguishing between beach, nearshore, offshore, deltaic, and pre-lake and post-lake fluvial sediments. Within the offshore deposits, however, grain size alone has been shown by several authors (e. g., Rominger and Rutledge, 1952; Moran, 1972) to be a poor criterion on which to base a subdivision of the sediments.

Any study of offshore Lake Agassiz sediments in Manitoba is hampered by the almost total lack of natural exposures. The few exposures present (mainly in the Pine Falls-Winnipeg River area) have been studied and interpreted by Elson (1967) and McPherson (1970). Consequently, any further stratigraphic investigation must be done almost entirely on the basis of subsurface drilling.

This is not only costly but much important data, such as laminations, jointing, structure and the nature of the contacts, are either lost or difficult to assess.

#### Basis of Stratigraphic Subdivision

Many parameters were investigated as having the potential for subdividing and recognizing units within the offshore Lake Agassiz sediments. Some possible criteria, such as sedimentary structures, were eliminated because they are rarely preserved in samples retrieved from auger or rotary drill holes. Others which have been successfully used in subdivision schemes elsewhere (See Rominger and Rutledge, 1952; Moran, 1972) were not fully evaluated here because of the special engineering laboratory techniques and equipment required and the scarcity of existing data on samples collected in southern Manitoba.

Basically the following parameters were used in subdividing the fine-grained (offshore) Lake Agassiz sediments in southern Manitoba into three units: mineralogy, texture and soil mechanics data. Although color was very useful in developing the correlations presented in Chapter 5, it was of limited value in defining the units discussed here.

The offshore deposits studied were exposed in continuous section in cuts and drill holes from the surface to the first non-offshore lacustrine deposit ( i.e., till, gravel, or coarse sand) in the central part of the basin. Initially only the thickest sediment sequences (50-150 feet) encountered in drilling were used to establish the most important and usable parameters. As the

stratigraphic picture developed, data from near surface cuts, shallow drill holes and marginal basin holes were added. Figure 8 shows the fifteen holes used to make the initial parameter study.

### Mineralogy

Clay Minerals. -- As pointed out by Wicks (1965), McPherson (1970), and Quigley (1967a), qualitatively there is little vertical variation in the clay mineralogy of the offshore Lake Agassiz sediments. Illite, montmorillonite and other expandables, kaolinite and chlorite are the most important clay minerals.

In attempting to work with the semi-quantitative clay mineral data, it was apparent that patterns and units could not be easily recognized on the basis of the raw percentages. It was found that the montmorillonite to illite ratio greatly aided differentiation. The montmorillonite/illite value was chosen over the other possible ratios because it showed the largest variability and brought out the greatest differences.

Two significant breaks in the ratio values appear in many of the sections studied (Table 13). The changes are from a low (less than 2) montmorillonite/illite value in the lower 10 to 40 feet to a high value (greater than 2) in the overlying 10 to 100 feet. Stratigraphically above this there is a 10 to 70 foot section of low ratios (less than 2).

Carbonate Minerals. -- Based on a limited study of the carbonate content of the offshore Lake Agassiz sediments, a slight decrease in the amount of calcite and dolomite with depth can be seen (Appendix E). The upper one third to one half of most of the sections studied average about 5% calcite and 17% dolomite whereas the lower feet average only 2% calcite and 10% dolomite. Due to the high percentage variation, however, this decrease was not very useful in discerning the various units.

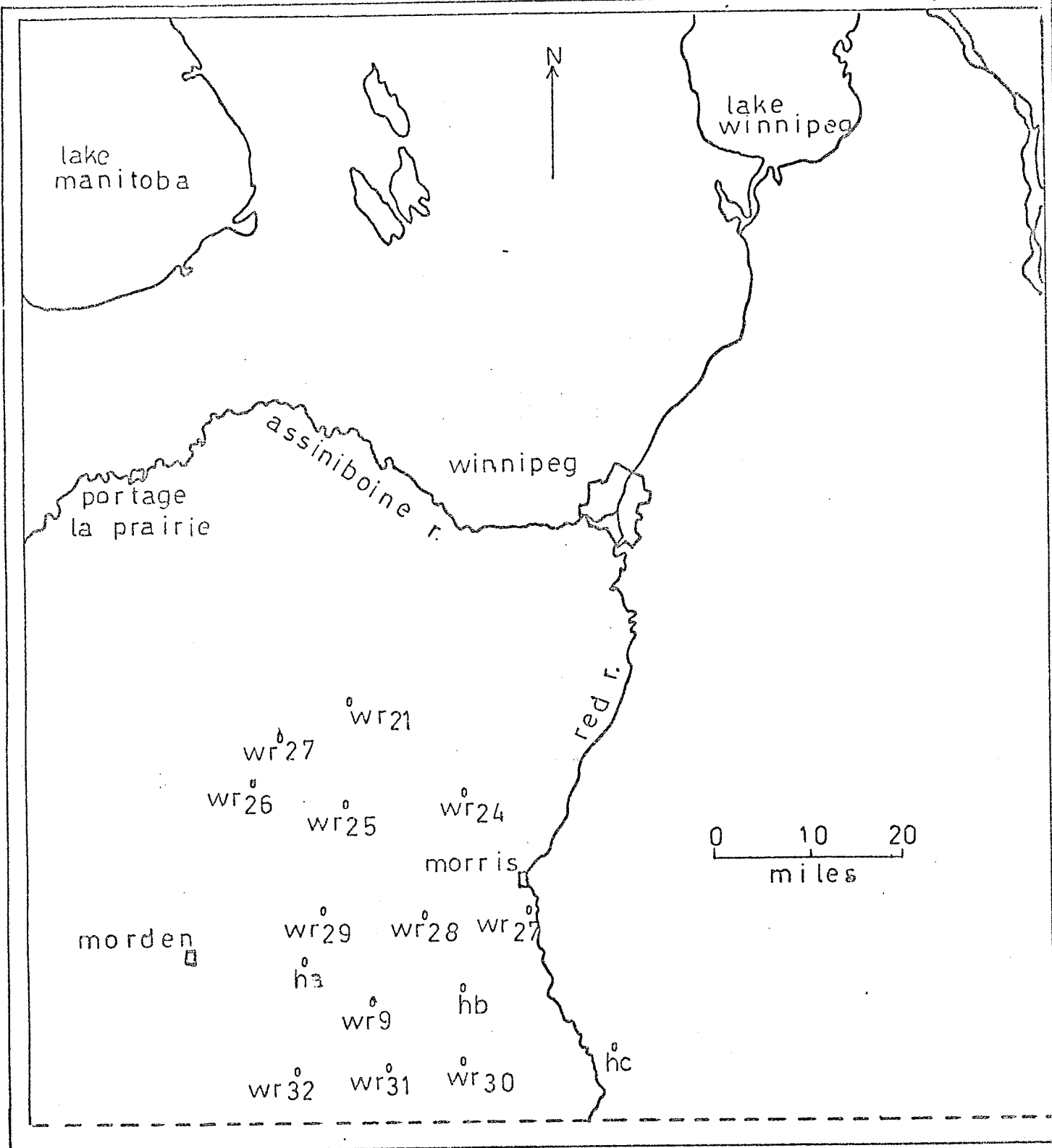


Fig. 8. Location Map Showing the Drill Holes used to Make Initial Parameter Study.

TABLE 13

VARIATION OF MONTMORILLONITE:ILLITE RATIO, TEXTURE, SOIL MECHANICS DATA AND COLOR IN SEDIMENTS FROM THE CENTRAL LAKE AGASSIZ BASIN

Hole & Sample	Depth <sup>1</sup>	M/I <sup>2</sup>	Texture <sup>3</sup>	Soil Mech. Data <sup>4</sup>	Color <sup>5</sup>	Unit <sup>6</sup>
HA-1	12	1.2	0/18/82	*-/27/-	10YR 4/2	3
2	26	1.2	TR/19/81	-/19/27	5YR 4/2	3
3	37	1.1	0/10/90	-/- /-	5Y 4/1	3
4	45	5.4	1/15/84	-/53/29	5Y 4/1	2
5	55	.2	2/13/85	-/29/36	5Y 2/1	1
6	36	.7	1/12/87	-/49/15	5YR 4/1	1
7	80	1	0/ 5/95	-/30/-	5YR 2/2	1
8	99	1.1	TR/17/83	-/ -/-	5YR 2/1	1?
HB-1	4	.5	10/42/48	-/ -/-	10YR 4/2	3
2	8	1.2	3/44/52	-/27/21	5YR 4/2	3
3	14	2.5	TR/18/82	-/ -/-	5Y 4/1	2
4	26	2.1	TR/11/89	-/34/20	5Y 4/1	2
5	36	3.0	TR/31/69	-/57/29	5YR 4/1	2
6	45	3.0	TR/13/87	-/68/25	5Y 4/1	2
7	55	1.3	0/ 5/95	-/49/41	5Y 2/1	1
9	80	1	TR/33/67	-/20/25?	5YR 4/1	1
10	89	1.6	TR/32/68	-/28/-	5YR 2/2	1
HC-1	4	.5	1/37/63	-/ -/-	5YR 4/2	3
2	8	0	TR/23/77	-/26/-	5YR 2/2	3
3	18	1.5	TR/ 6/94	-/31/17	5YR 3/2	3
4	28	4.5	TR/ 6/94	-/58/20	10YR 2/2	2

continued

<sup>1</sup>Approximate depth in feet from surface.

<sup>2</sup>Montmorillonite:Illite ratio

<sup>3</sup>% Sand/ % Silt/ % Clay

<sup>4</sup>Soil Mechanics Data:  
Liquid Limit (%) / Natural Water Content (%) / Plastic Limit (%)

<sup>5</sup>Rock Color Chart, Geological Society of America (1963).

<sup>6</sup>Author's interpretation and Unit designation based on all criteria investigated.

\*Data not available.

Hole & Sample	Depth	M/I	Texture	Soil Mech. Data	Color	Unit
HC-5	35	4.5	TR/11/89	-/42-21	5YR 4/2	2
6	45	3.5	TR/ 7/92	-/51/38	10YR 2/2	2
7	55	.5	TR/32/68	-/29/28	10YR 2/2	1
8	65	.5	TR/ 9/91	-/32/-	5YR 2/1	1
9	93	.6	TR/16/84	-/20/-	5YR 3/1	1
WR-7-1	10	.9	2/23/75	52/20/18	5YR 4/2	3
2	20	.7	TR/27/73	58/25/19	5YR 4/2	3
3	30	.9	TR/30/70	48/19/14	5YR 2/2	3
4	40	5.4	0/12/88	63/38/28	5YR 3/2	2
5	60	2.2	0/22/78	-/ -/-	5YR 3/1	2
6	65	2.3	TR/13/87	-/ -/-	5Y 3/1	2
7	75	.9	3/21/76	-/ -/-	5Y 3/1	1
WR-9-1	11	.5	TR/15/86	42/21/18	5YR 3/2	3
2	15	3.4	TR/15/85	61/42/34	5YR 3/2	2
3	25	3.2	0/10/90	74/41/29	5Y 4/2	2
4	30	3.5	1/18/82	45/43/28	5YR 3/2	2
5	35	3.3	0/ 9/91	-/ -/-	5Y 2/1	2
6	50	4	TR/13/87	44/40/30	5Y 4/3	2
7	65	.5	2/19/79	61/38/20	5YR 2/1	1
8	70	4	TR/19/81	-/ -/-	5YR 2/1	2
WR-21-1	10	.2	1/16/83		5YR 4/2	3
2	20	.3	TR/28/72		5YR 4/2	3
3	30	3.5	1/21/78	(Not Available)	5YR 2/1	2
4	40	.2	1/19/80		5YR 2/1	1
5	50	3.5	1/24/76		5YR 2/1	2
6	60	4.8	1/23/76		5YR 2/1	2
7	70	.5	1/17/82		5YR 2/1	1
WR-24-1	10	3.9	TR/ 7/93		5YR 3/2	2
2	20	2	1/ 6/93		5YR 3/2	2
3	25	3.3	TR/14/86		5Y 3/2	2
4	30	1.7	0/13/87		5YR 2/1	2
5	35	8.5	1/ 6/93	(Not Available)	5Y 3/1	2
6	40	6.6	TR/15/85		5Y 2/1	2
7	45	3	TR/18/82		5Y 2/1	2
8	50	3.2	1/17/82		5Y 2/1	2
9	60	1	1/21/78		5Y 2/1	1
10	70	.6	TR/42/58		5YR 2/1	1
11	80	.8	3/22/78		5YR 3/1	1
WR-25-1	10	3.4	3/26/71		5YR 4/2	2
2	20	2.2	1/17/82		5YR 3/2	2
3	30	3.9	TR/15/85		5Y 3/2	2
4	40	4.1	TR/26/74	(Not Available)	5Y 2/1	2
5	50	3.2	TR/17/83		5Y 2/1	2

continued



Hole & Sample	Depth	M/I	Texture	Soil Mech. Data	Color	Unit
WR-25-6	60	2.7	TR/23/77		5Y 3/1	2
7	70	.8	TR/15/85		5Y 3/1	1
8	80	2.2	1/11/88		5Y 3/1	2
9	90	1.9	1/20/79		5YR 2/1	1
10	100	1.3	1/21/78		5YR 3/1	1
WR-26-1	5	.8	4/21/75		5YR 4/2	3
2	10	.9	2/ 8/90		5YR 3/2	3
3	20	.6	TR/12/89		5YR 3/2	3
4	30	.7	4/18/77	(Not Available)	5YR 2/2	3
5	40	1.4	TR/ 8/92		5Y 3/1	3
6	50	2.9	1/12/87		5Y 2/1	2
7	60	3.4	TR/10/90		5Y 2/1	2
8	70	3.3	TR/13/88		5Y 2/2	2
9	80	2.5	TR/20/79		5Y 2/2	2
WR-27-1	5	.6	TR/28/72		5YR 3/1	3
2	10	1.1	TR/17/83		5YR 3/2	3
3	20	.7	1/10/89		5YR 3/4	3
4	30	1.2	TR/13/87		5Y 3/1	3
5	40	2.1	TR/17/83		5Y 2/1	2
6	50	2.9	0/10/90	(Not Available)	5Y 2/1	2
7	60	3.8	0/11/89		5Y 2/1	2
8	70	2.8	TR/11/89		5Y 2/1	2
9	80	1.4	2/16/82		5Y 2/1	1
10	90	2.4	1/ 9/90		5Y 2/1	2
11	100	.9	1/ 8/91		5Y 2/1	2
WR-28-1	10	.8	1/ 9/91		5Y 4/2	3
2	20	.6	TR/11/89		5YR 4/2	3
3	30	1.1	1/12/87		10YR 3/1	3
4	40	.7	TR/10/89	(Not Available)	10YR 2/1	3
5	50	2.4	TR/ 8/92		5Y 2/1	2
6	60	3.7	TR/17/83		5Y 2/1	2
7	70	1.9	TR/12/88		5Y 3/1	2
8	80	1.9	1/ 4/88		5YR 4/1	1
9	90	3.8	1/18/81		5Y 3/2	2
WR-29-1	10	.7	TR/29/71		5YR 4/2	3
4	40	.2	TR/52/48		5Y 4/2	3
5	50	4.7	TR/20/80	(Not Available)	5Y 4/2	2
7	70	1	TR/24/76		5Y 2/2	3
9	90	6	1/42/58		5Y 2/1	2
10	100	2.7	TR/ 4/96		5YR 2/1	2
11	110	.6	1/ 9/90		5YR 3/1	1
12	120	2.1	2/ 9/89		5Y 2/1	2

Hole & Sample	Depth	M/I	Texture	Soil Mech. Data	Color	Unit
WR-30-1	10	2	TR/16/84		5YR 3/2	3
3	30	2.5	1/21/79	(Not Available)	5YR 4/2	2
7	70	3.4	TR/18/83		10YR 2/2	2
10	100	3.6	0/ 3/97		5Y 2/1	2
12	120	.6	TR/ 8/91		5YR 2/1	1
WR-31-1	10	2.5	1/ 8/91		5YR 4/2	2
3	30	4.3	2/13/85	(Not Available)	5Y 3/1	2
7	70	3.5	TR/11/89		5Y 3/1	2
10	100	.6	1/20/80		5Y 3/1	1
13	130	.9	TR/ 9/90		5Y 3/1	1
WR-32-1	10	.8	1/28/71		5Y 4/2	3
3	30	2	0/12/88	(Not Available)	5YR 3/1	3
7	70	3.3	TR/17/83		5Y 3/1	2
10	100	2.9	TR/ 9/91		5Y 2/1	2
14	130	1.2	TR/ 13/87		5Y 2/1	1

Other Non-Clay Minerals. -- Quartz and feldspar were also identified in this study. Both minerals are present throughout the Lake Agassiz sediments and both have an erratic or random distribution (Appendix E). In approximately half of the samples analyzed, however, quartz does show a close relationship to texture: the coarser the sample is, the more intense the quartz peak is on the X-ray diffractogram. No quantitative estimates were made for either mineral.

#### Texture

Table 13 shows how the sand/silt/clay percentages vary in the drill holes studied. One significant break appears in the upper half of several of the sections. This textural change is from very fine grained sediment (averaging 82% clay, 17% silt and 1% sand) in the lower portions to coarser sediment (averaging 69% clay, 28% silt and 3% sand) in the upper 10-50 feet. In over half of the samples analyzed, this division coincides with the upper division based on the montmorillonite:illite ratio. In the remainder, however, there is no correspondence between the textural and mineralogical divisions.

#### Soil Mechanics Data

Table 13 shows how several Atterberg limits (liquid limit, natural water content and plastic limit) vary in the holes. Several of the sections show a basal zone of low natural water content and plastic limit, a middle section of higher (5-10%) limits and an upper portion of values similar to those of the basal zone. These groupings appear to coincide with the above mineralogy divisions.

### Color

Colors were determined for the samples using a Rock Color Chart.<sup>3</sup> Although many exceptions occur there seems to be at least a two-fold and possibly a three-fold subdivision in most cases: an upper light to pale brown or tan portion, and a lower light to medium gray and dark gray to grayish brown portion. However, these color divisions are, for the most part, completely independent of the above mineralogical and/or textural divisions (i.e., these color zones do not coincide with the mineralogical, textural or soil mechanics zones). For this reason color was not extensively used in subdividing the offshore sediments in this thesis. However, since many other Lake Agassiz studies do use this feature as a basis of subdivision the colors were noted and used in the correlations presented in Chapter 5.

### Definition and Description of Units

#### Unit 1

Definition. -- Unit 1, the lowermost offshore unit recognized in this study, overlies till, gravel, sand or other non-lacustrine material. It is defined primarily on the basis of its low montmorillonite/illite ratio coupled with its slightly lower natural water content. The montmorillonite/illite ratio is less than 2 with an average of 0.9. The natural moisture content ranges from 20% to 45% with an average of 27% (Table 13). The Atterberg limits are slightly less than that of the overlying unit.

<sup>3</sup>Prepared by the Rock-Color Chart Committee and distributed by the Geologic Society of America, New York, 1963.

Mineralogy. -- Qualitatively, the mineralogy of clay-sized particles in Unit 1 is similar to the rest of the offshore Lake Agassiz sediments. Illite, montmorillonite and other expandables, kaolinite and chlorite are the most important clay minerals. Quartz, feldspar, calcite and dolomite were the non-clay minerals identified.

Quantitatively, the clay minerals offer a good basis of differentiation. The low montmorillonite:illite ratio emphasizes the average clay mineral distribution of 33% illite, 26% montmorillonite and 40% kaolinite plus chlorite (Table 14, Fig. 9 and Appendix F).

The carbonate content of Unit 1 also helps distinguish it from the overlying units. The average calcite value is 2.5 and dolomite 9.9 percent, both of which are lower than in Units 2 and 3.

A measure of the relative crystallinity of the montmorillonite showed extreme variability with values ranging from .2 to .9. Nearly all of the kaolinite plus chlorite percentages were usually attributed to kaolinite in the semi-quantitative analyses (See Appendix F).

Texture. --- Most of the sediment in Unit 1 is composed of more than 80% clay-sized particles (Table 14, Fig. 9, and Appendix F). The average distribution is 1% sand, 17% silt, and 81% clay. This is slightly less clayey than the overlying Unit 2 and much finer grained than Unit 3. However, the textural similarity of Unit 1 to that of Unit 2 prohibited its use as a main criteria for recognition.

The upper several feet of Unit 1 sometimes contain angular, pebble-sized silt blebs which are more characteristic of parts of Unit 2. However, their distribution in Unit 1 throughout the basin is erratic.

TABLE 14

AVERAGE SAND-SILT-CLAY CONTENT AND  
SEMI-QUANTITATIVE CLAY MINERALOGY OF UNITS 1, 2, 3  
(Based on all samples analyzed)

Unit	N*	Illite			Montmor- illonite			Kaolinite & chlorite			Sand			Silt			Clay		
		L*	M*	H*	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
3	113	0	36	75	0	24	87	0	39	66	0	3.3	27	1	30	88	40	69	99
2	92	0	18	31	41	55	77	7	26	44	0	.9	10	1	16	67	60	84	99
1	46	20	33	46	6	26	46	29	39	61	0	1.4	5	1	18	42	58	81	97

N = number of samples

L, M, H = refer to Low, Arithmetic mean, and High values

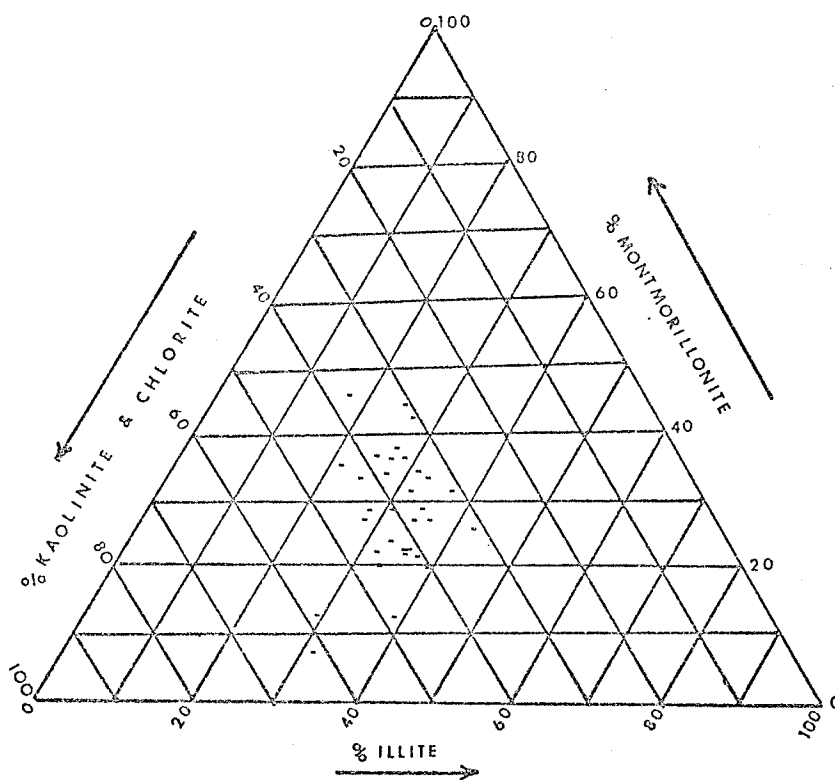
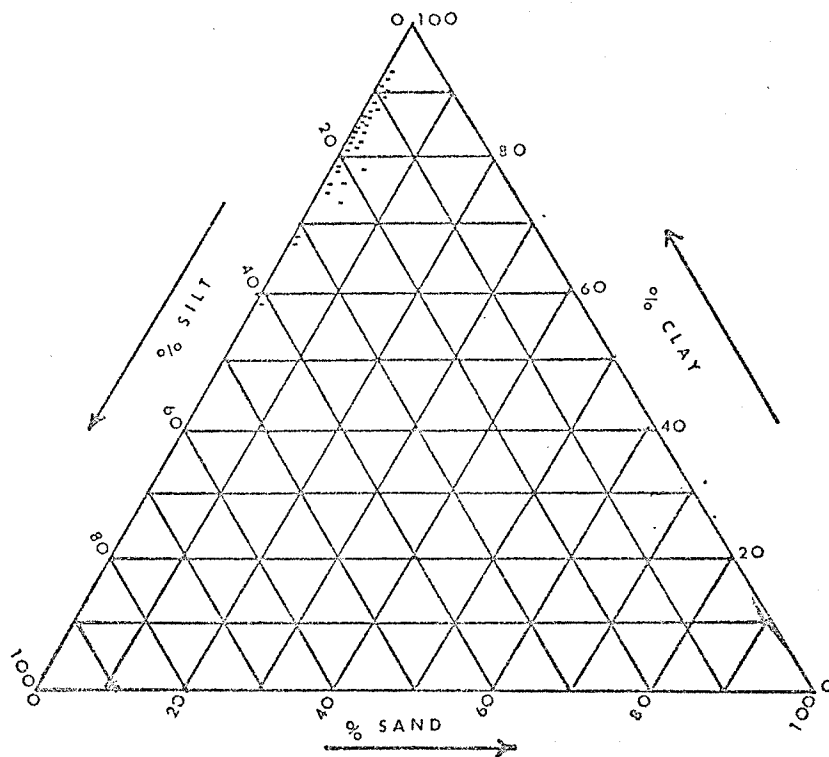


Fig. 9. Texture and Clay Mineralogy of Unit 1.

Soil Mechanics Data. -- The 5-10 percent lower natural water content is one of the main factors used in identifying Unit 1 (Table 13). This, however, is probably a response to the clay mineralogy change in Unit 1: the lower natural water being a function of the lower montmorillonite content.

Color. -- The color of Unit 1 ranges from a dark olive gray (5 Y 3/1) to dark brownish gray (5 YR 3/1) and is relatively constant.

Geographic Distribution, Variation and Thickness. -- Unit 1 was found exposed in surface cuts in only two localities (samples B-1-4b and c, and T-3). All other information was derived from 46 subsurface samples from 22 holes. The extent of Unit 1 in the studied area is shown in Figure 10.

There is only very slight lateral textural variation of Unit 1 throughout the basin (Fig. 10). A contour map of the average montmorillonite content (Fig. 11) shows that the montmorillonite mineralogy changes tend to correspond with the subtle textural changes. That is, the areas of coarser sediment generally have a lower montmorillonite content.

The average thickness of Unit 1 is 15-20 feet with extremes of 0-45 feet (Fig. 12).

## Unit 2

Definition. -- Unit 2 is primarily defined by its characteristic high montmorillonite:illite ratio. Other parameters useful in recognition are the slightly higher natural water content, higher carbonate content, and finer grain size than Units 1 and 3. The relatively high percentage of angular silt clasts, the medium to dark olive gray color, more distinct laminae and the stratigraphic



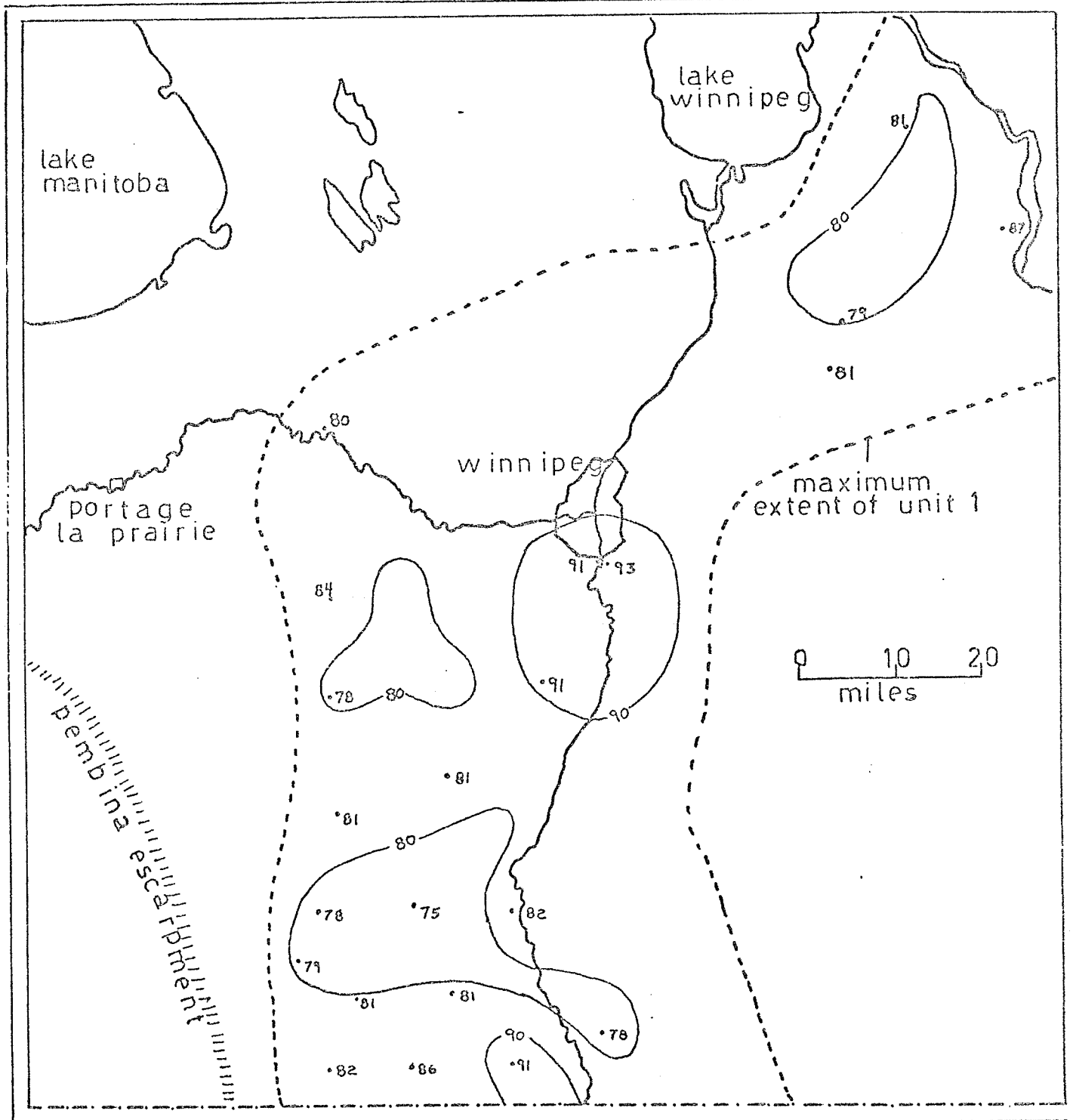


Fig. 10. Extent and Variation of Average Clay Content of Unit 1. Contour interval of 10%. Unit 1 was not identified in holes outside of the extent line.

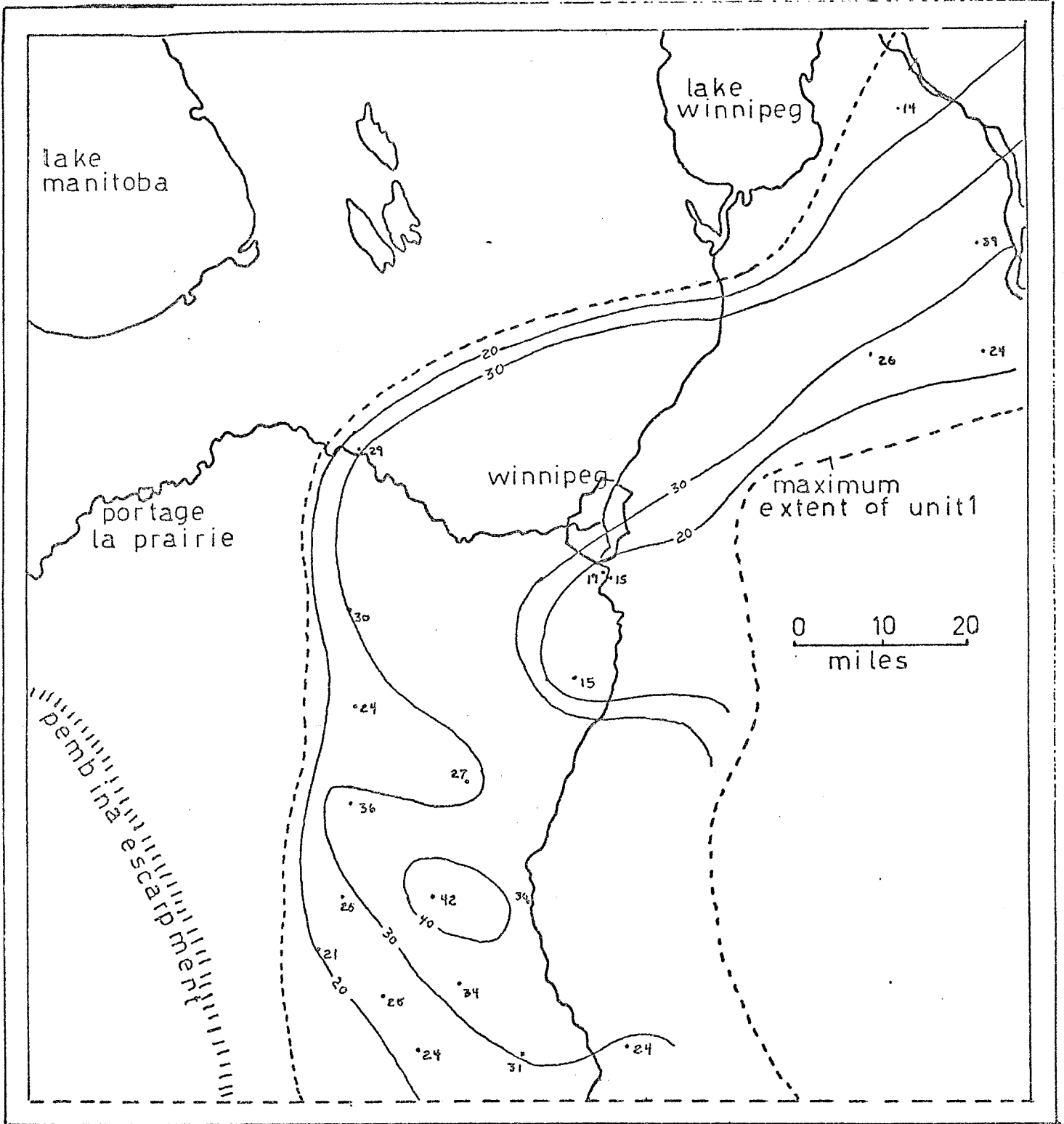


Fig. 11. Variation of Average Montmorillonite Content of Unit 1. Contour interval is 10%

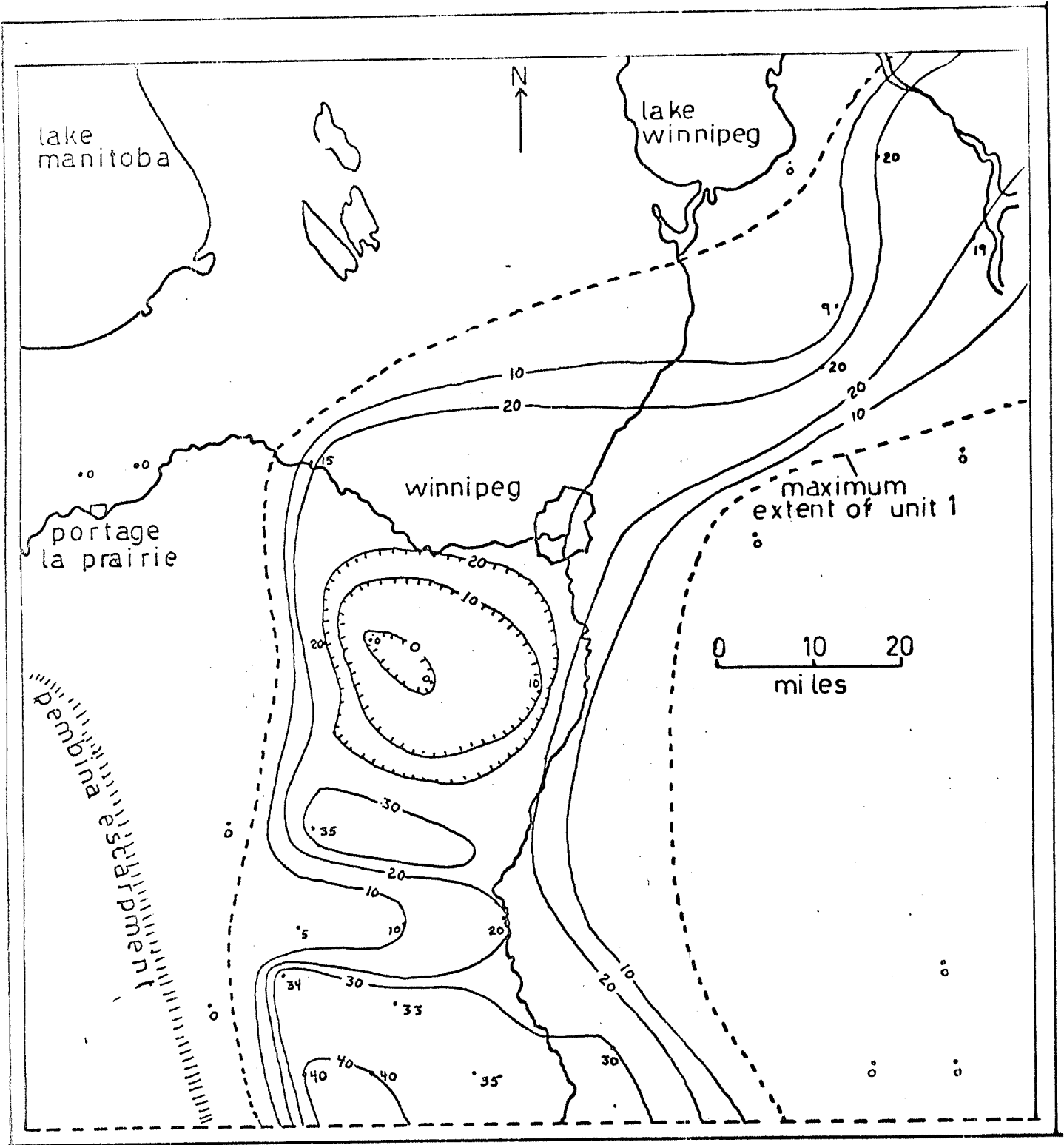


Fig. 12. Isopach Map of Unit 1. Contour interval is 10 feet.

position (i.e., Unit 2 directly overlying Unit 1 and underlying Unit 3) were also used as criteria for recognition in some instances; however, correlations based solely on these latter criteria remain doubtful.

Mineralogy. -- The basic clay-mineral components of Unit 2 are the same as that of the other two units: montmorillonite, illite and kaolinite and chlorite are the dominant clay minerals; quartz, feldspar, calcite and dolomite are the main non-clays.

Unit 2 is characterized by a higher montmorillonite content than the other units. The montmorillonite:illite ratios are greater than 2 with an average of 3.0. The average distribution is 18% illite, 55% montmorillonite, and 26% kaolinite plus chlorite (Table 14 and Fig. 13). Nearly all of the kaolinite plus chlorite figure was usually attributed to kaolinite. A measure of the crystallinity of the montmorillonite showed a range similar to that of Unit 1.

The average carbonate content of Unit 2 (calcite: 3%; dolomite: 12%) is greater than that of Unit 1.

Texture. -- Grain-size analysis shows that over 80% of the sediment of Unit 2 is composed of clay sized material. The average distribution is 1% sand, 16% silt and 84% clay which is much finer than the overlying Unit 3 but very similar to Unit 1 (Table 14 and Fig. 13).

Soil Mechanics Data. -- The natural water content, plastic limit and liquid limit values of Unit 2 all tend to be relatively higher than that of the other two units (Table 13).

Color. -- The color range of Unit 2 is much more variable than that of Unit 1. It is usually a medium to dark olive gray (5 Y 4/1) and in the lower parts is always this color. In the

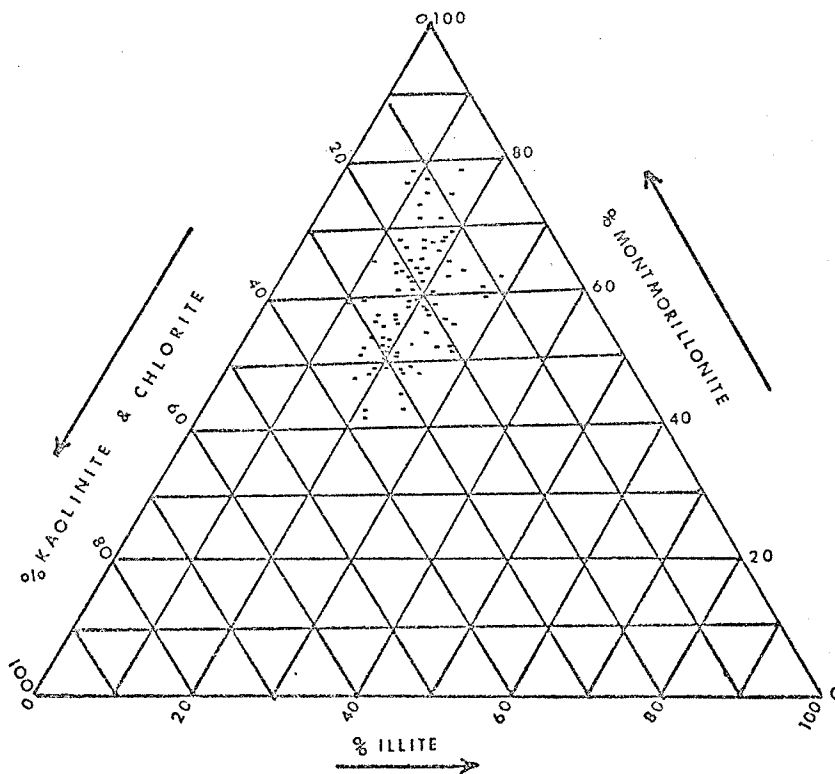
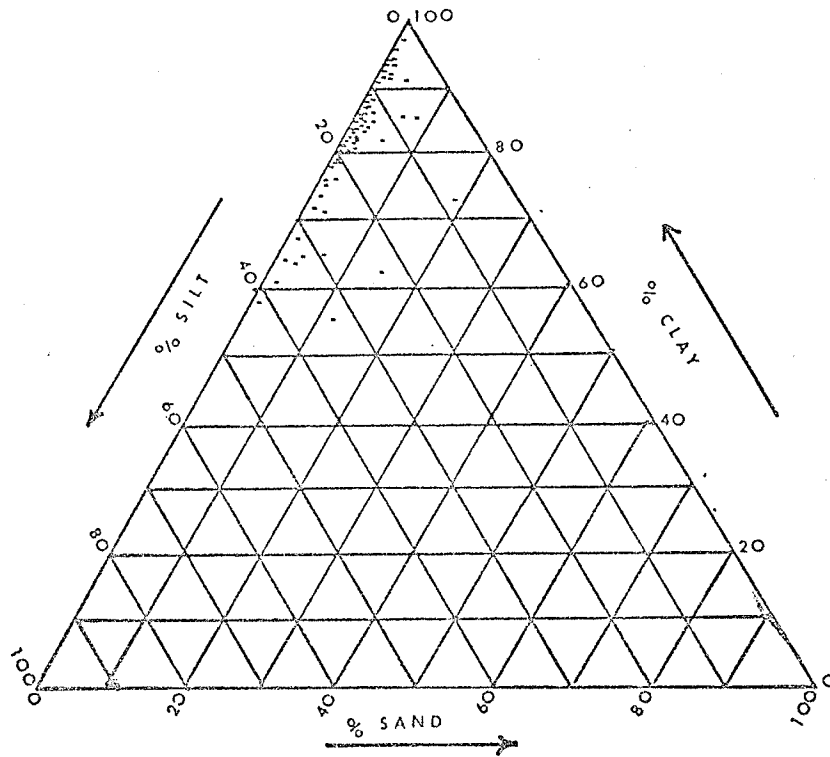


Fig. 13. Texture and Clay Mineralogy of Unit 2.

upper few feet of the unit, however, it often grades sharply to a chocolate brown to grayish brown (2.5 YR 4/2). This variability makes unit recognition by color nearly impossible. The analysis of some 200 samples showed no mineralogical or textural changes associated with this upper color change. This supports the earlier conclusion about the inadvisability of a subdivision scheme based on color.

Geographic Distribution, Variation, and Thickness. -- Subsurface data (93 samples from 36 holes) indicates Unit 2 covers most of the Red River basin and extends beyond the limits of Unit 1 (Fig. 14). Unit 2 directly overlies Unit 1 in the central part of the basin; but in the northeastern part and at the margins it directly overlies till, pre-Lake Agassiz sediment or Paleozoic bedrock. Thickness of the unit ranges from 5 feet at the margins to a maximum of over 100 feet near the International Border (Fig. 15). Other depositional centers of Unit 2 appear to be located about 30 miles northeast of Winnipeg and 45 miles southwest of Winnipeg.

Lateral textural variation is more apparent in Unit 2 than in the underlying unit. This variation ranges from less than 70% clay in the center of a trough-shaped area near the western margin to greater than 90% south of Winnipeg, north of Emerson and west of Lac du Bonnet (Fig. 14). There does not, however, appear to be any relationship between the textural variation and the thickness variations of Unit 2.

Individual clay minerals in Unit 2 also show considerable lateral variation. A map of the average montmorillonite values shows that the southern part of the basin generally has a higher

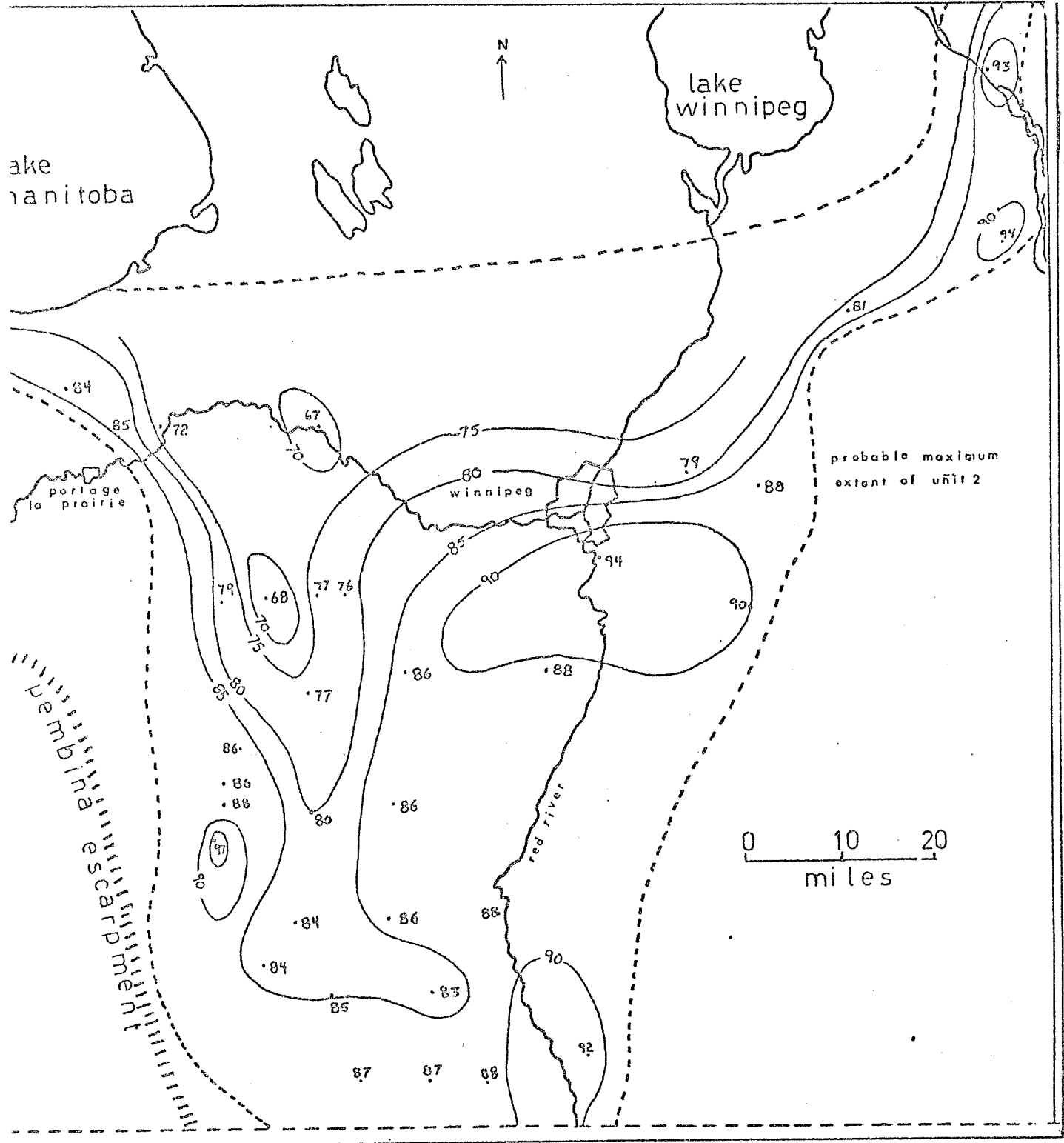


Fig. 14. Extent and Variation of Average Clay Content of Unit 2. Contour interval is 5%. Unit 2 was not identified in holes outside of the extent line.

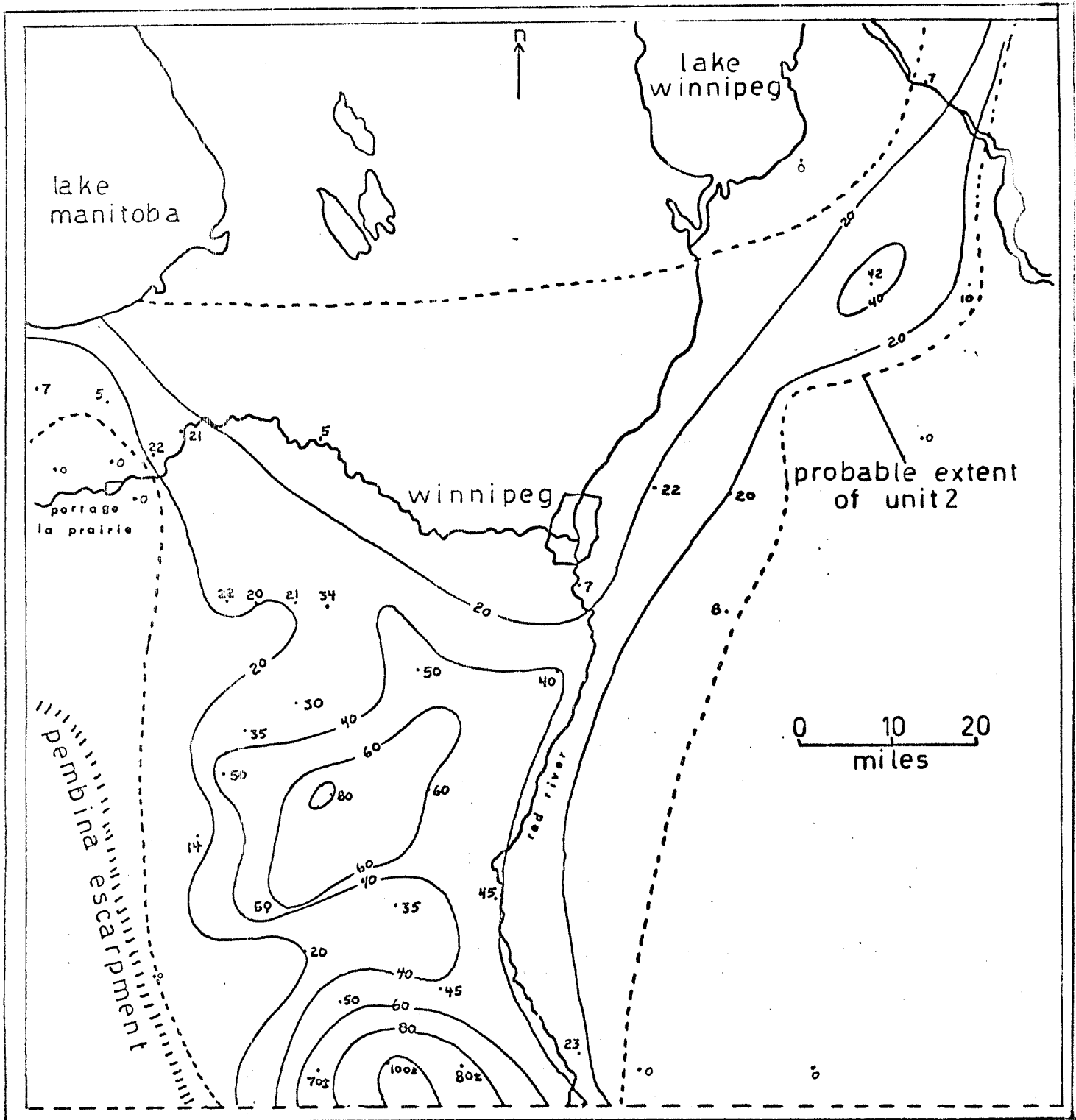


Fig. 15. Isopach Map of Unit 2. Contour interval is 20 feet.



content than the northern areas (Fig. 16). There does not appear to be a good relationship between mineralogy changes and size variation or thickness variation.

Silt Clasts. -- The presence of small, angular, buff to light gray, calcareous, silty fragments is more common in Unit 2 than in the other units. The underlying Unit 1 only contains a small amount of these clasts in its upper few feet. The overlying Unit 3 also sometimes contains widely scattered silt blebs.

These silty clasts have been reported by a number of authors (Wicks, 1965; Quigley, 1967a; Fenton, 1970; McPherson, 1970; Harris, et al, in press). An analysis of the silt clasts from 5 holes and cuts (summarized in Table 15) shows that they are composed predominantly of silt sized material (average distribution: 1% sand, 85% silt and 14% clay). Furthermore, chemical and X-ray diffraction analyses show that the clasts are primarily dolomite, calcite and quartz, which agrees with Quigley's (1967b) findings. The clay mineral fraction is characterized by a very low montmorillonite content (average distribution: 50% illite, 6% montmorillonite and 43% kaolinite plus chlorite).

The clasts, usually a pale orange (10 YR 8/2) to light yellowish gray (5 Y 8/2), range in size from less than 1 mm to over 30 mm in diameter, with the norm varying from hole to hole and with depth. They are angular to subrounded and usually are roughly tabular shaped. In some instances they can make up over 80% of the individual laminae.

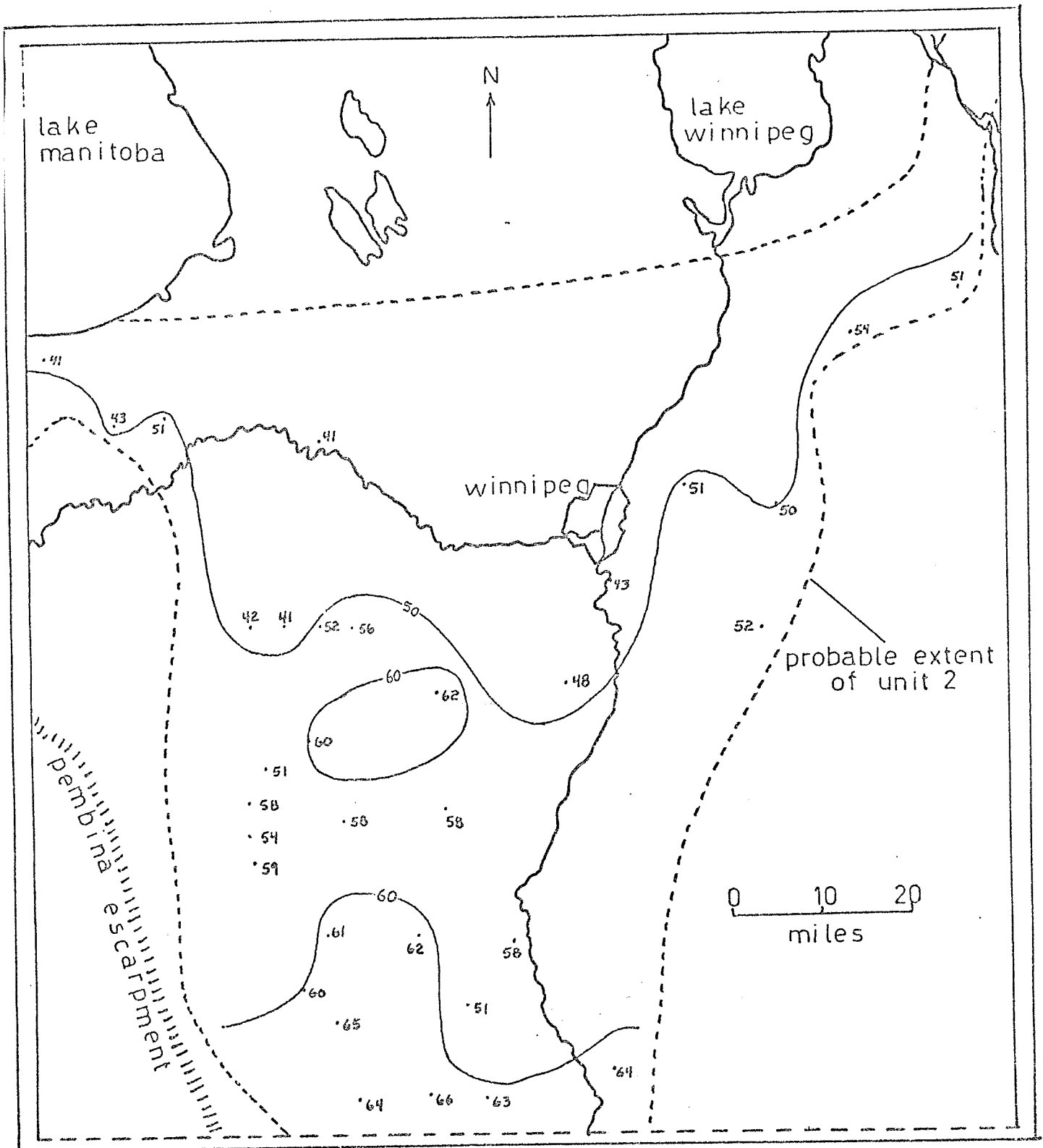


Fig. 16. Variation of Average Montmorillonite Content of Unit 2. Contour interval is 10%.

TABLE 15

## SUMMARY OF ANALYSES OF SILT CLASTS

Sample	Sand	Silt	Clay	Illite	Montmor- illonite	Kaolinite & chlorite	Calcite	Dolomite	Quartz	Feldspar
PV-1	TR	93	6	54	-	46	21	66	S	M
2	TR	86	14	46	7	46			VS	W
WR-13										
-3A	2	89	9	50	-	50	15	73	S	M
WR-1										
-4A	TR	85	14	47	14	39	10	52	S	M
B-1-4										
Ba	1	72	27	46	11	43	18	47	S	M
WR-10-										
-2A	2	82	16	59	5	36			VS	W
Average	.8	84	14	50	6	43	13	59		

TR = Trace

A dash (-) indicates 0 or nil.

A blank indicates no interpretation was attempted.

The letters VS, S, M, W represent Very Strong, Strong, Moderate and Weak and refer to the relative strength of the particular peak on the X-ray diffractogram.

### Unit 3

Definition. -- Unit 3 is recognized chiefly by its low montmorillonite:illite ratio. Other parameters useful in recognition are coarser grain size and higher carbonate content than Units 1 and 2. The stratigraphic position (i.e., overlying Units 1 and 2) was also useful in identifying this unit.

Mineralogy. -- The qualitative mineralogy of Unit 3 is similar to that of the other two units. Illite, montmorillonite and kaolinite plus chlorite are the main clay minerals. The non-clays included calcite, dolomite, quartz and feldspar.

The montmorillonite:illite ratio of Unit 3 is less than 2 with an average of 0.7. The average clay mineral distribution is 36% illite, 24% montmorillonite and 39% kaolinite plus chlorite (Table 14 and Fig. 17). Most of the kaolinite plus chlorite figure was found to be due to kaolinite. A measure of the crystallinity of the montmorillonite shows it to be predominantly poorly crystalline (average value of 0.3) in contrast to the high variability of Units 1 and 2.

The average carbonate content of Unit 3 (calcite: 4.9%; dolomite: 16.8%) is higher than that of Units 1 and 2.

Texture. -- Grain size analyses show that Unit 3 is much coarser than the underlying two units. The average distribution is 3% sand, 30% silt and 69% clay (Table 14 and Fig. 17).

Color. -- The color of Unit 3 ranges from pale brown (5 YR 5/2) to olive gray (5 Y 4/1). This variability greatly limited the use of color as a recognition tool.

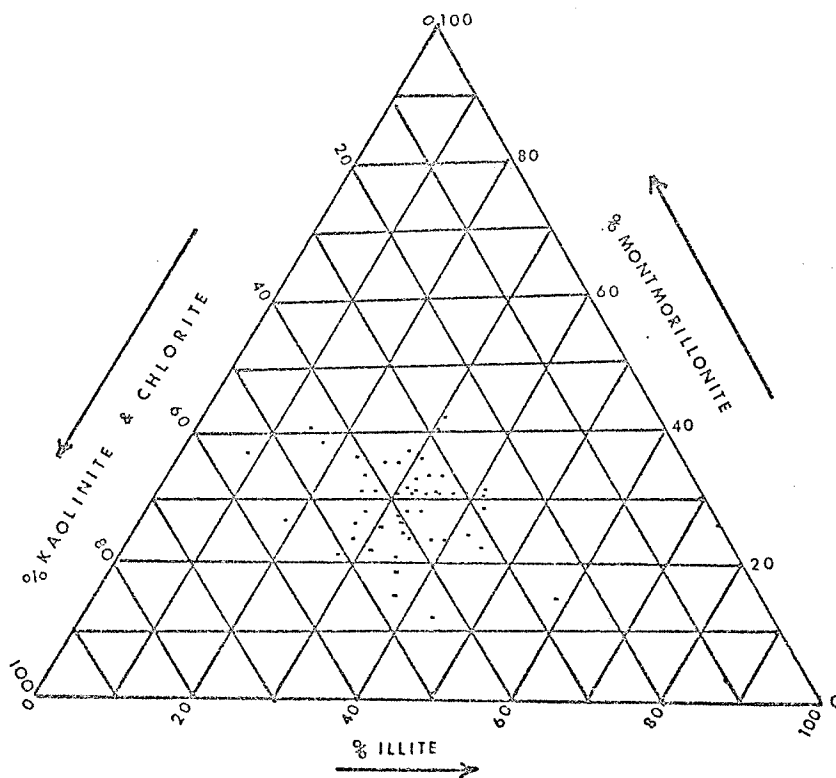
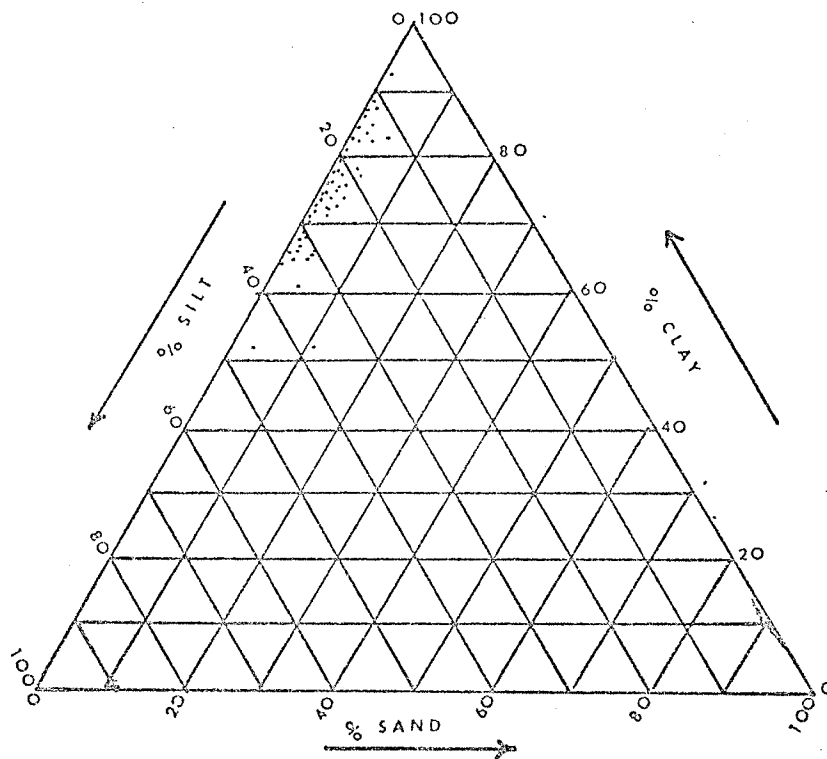


Fig. 17. Texture and Clay Mineralogy of Unit 3.

Soil Mechanics Data. -- The natural water content, plastic limit and liquid limit values all tend to be lower than that of Unit 2 and roughly similar to Unit 1 (Table 13).

Geographic Distribution, Variation and Thickness. -- Data from 43 holes indicates Unit 3 covers most of the Red River basin and Unit 2 (Fig. 18). A notable exception appears to be in the north central part of the basin where the unit seems to be absent. Thicknesses of Unit 3 are as much as 70 feet east of Morden with the average being 20-40 feet. Three centers of deposition are evident from Figure 19: north and east of Portage la Prairie, east of Lake Winnipeg and east of Morden.

Lateral textural variation shows an increase in grain size near to the margins of the basin (Fig. 18). There does not appear to be any relationship between the textural variation and the thickness variation of Unit 3.

The clay mineral content of Unit 3 shows lateral variation similar to that of Unit 2. Generally the montmorillonite content is greater in the southern parts of the basin (Fig. 20). However, there is no correspondence between clay mineralogy and size or thickness variation.

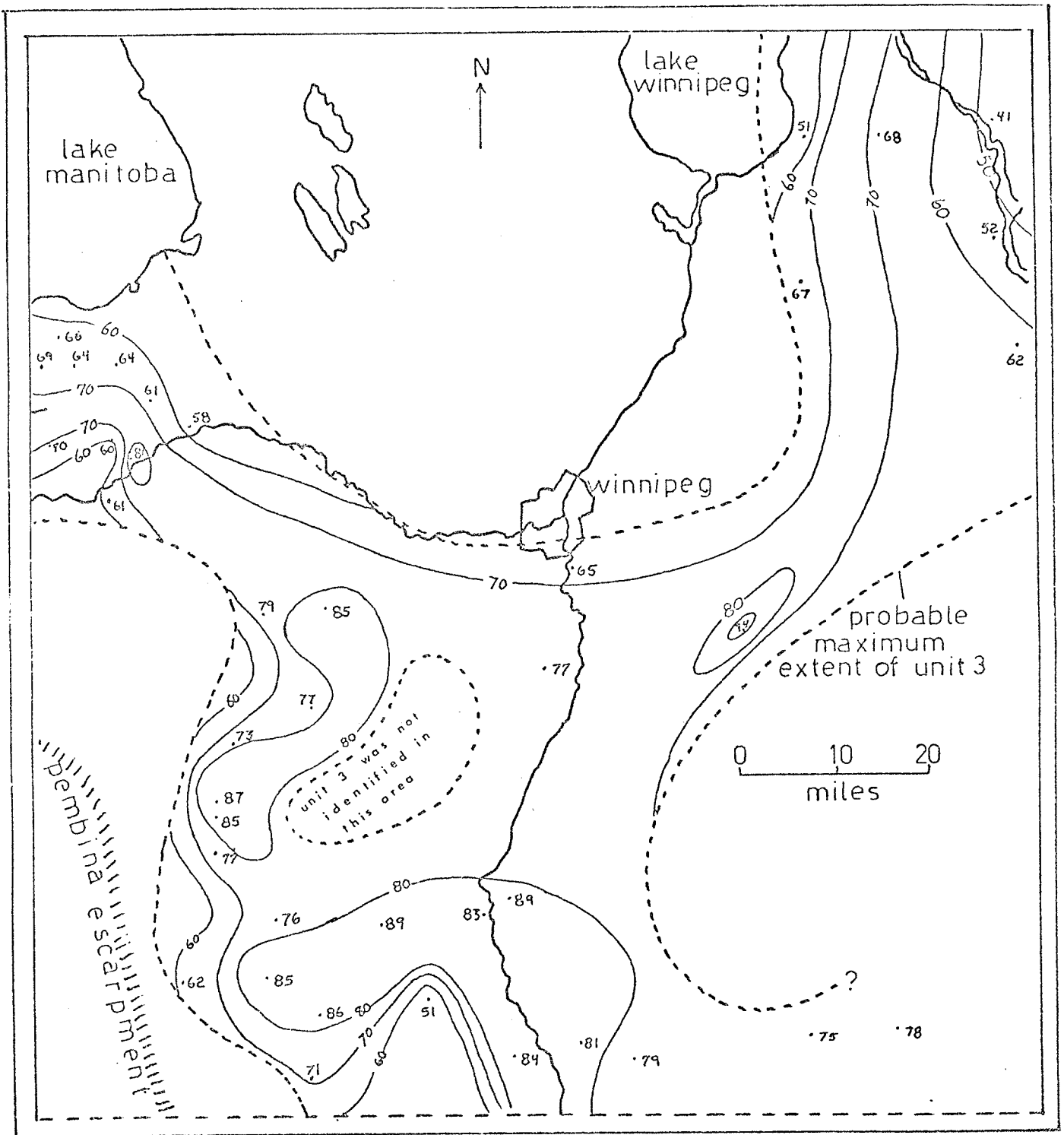


Fig. 18. Extent and Variation of Average Clay Content of Unit 3. Contour interval is 10%. Unit 3 was not identified in holes outside of the extent line.

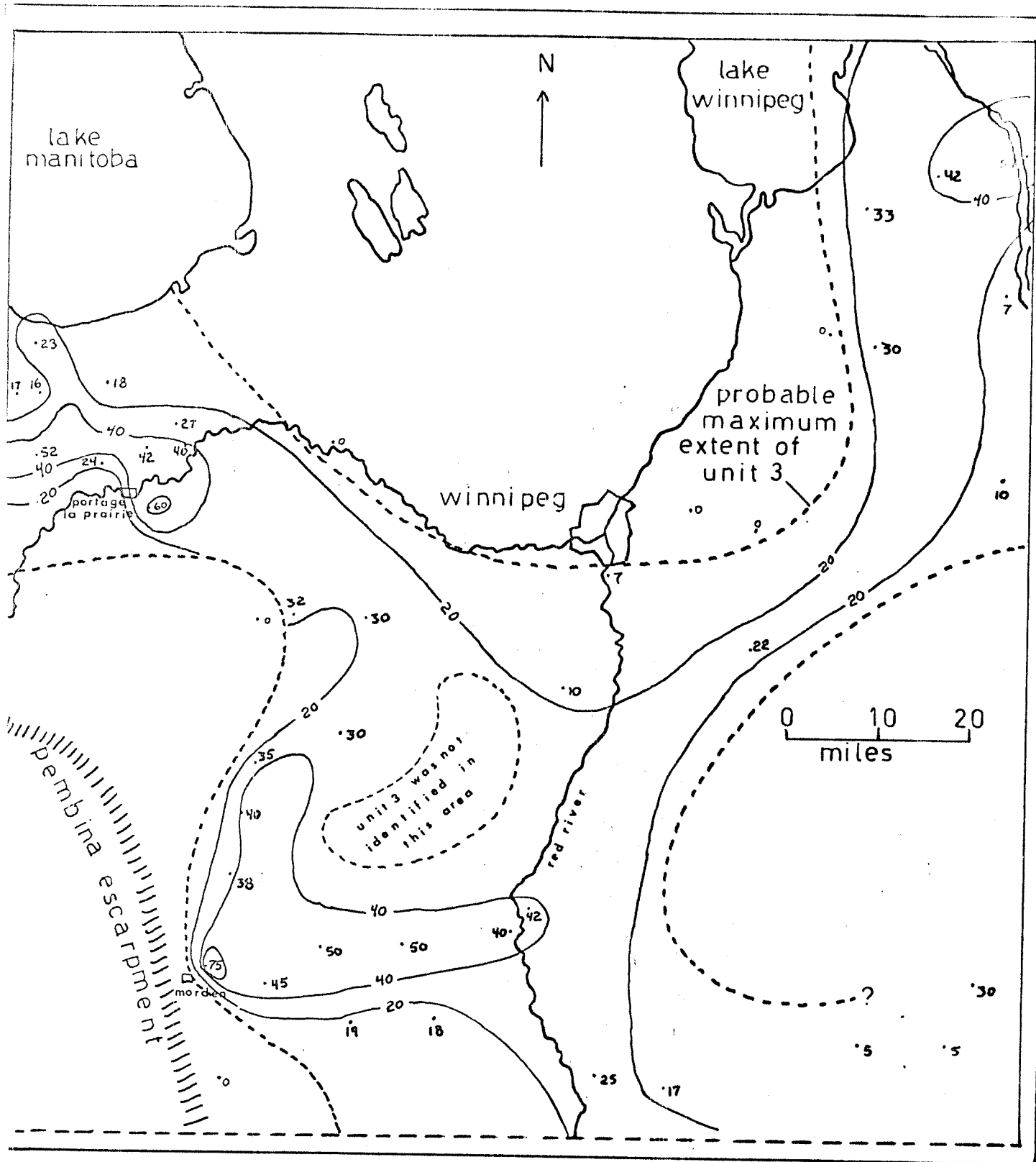


Fig. 19. Isopach Map of Unit 3. Contour interval is 20 feet.



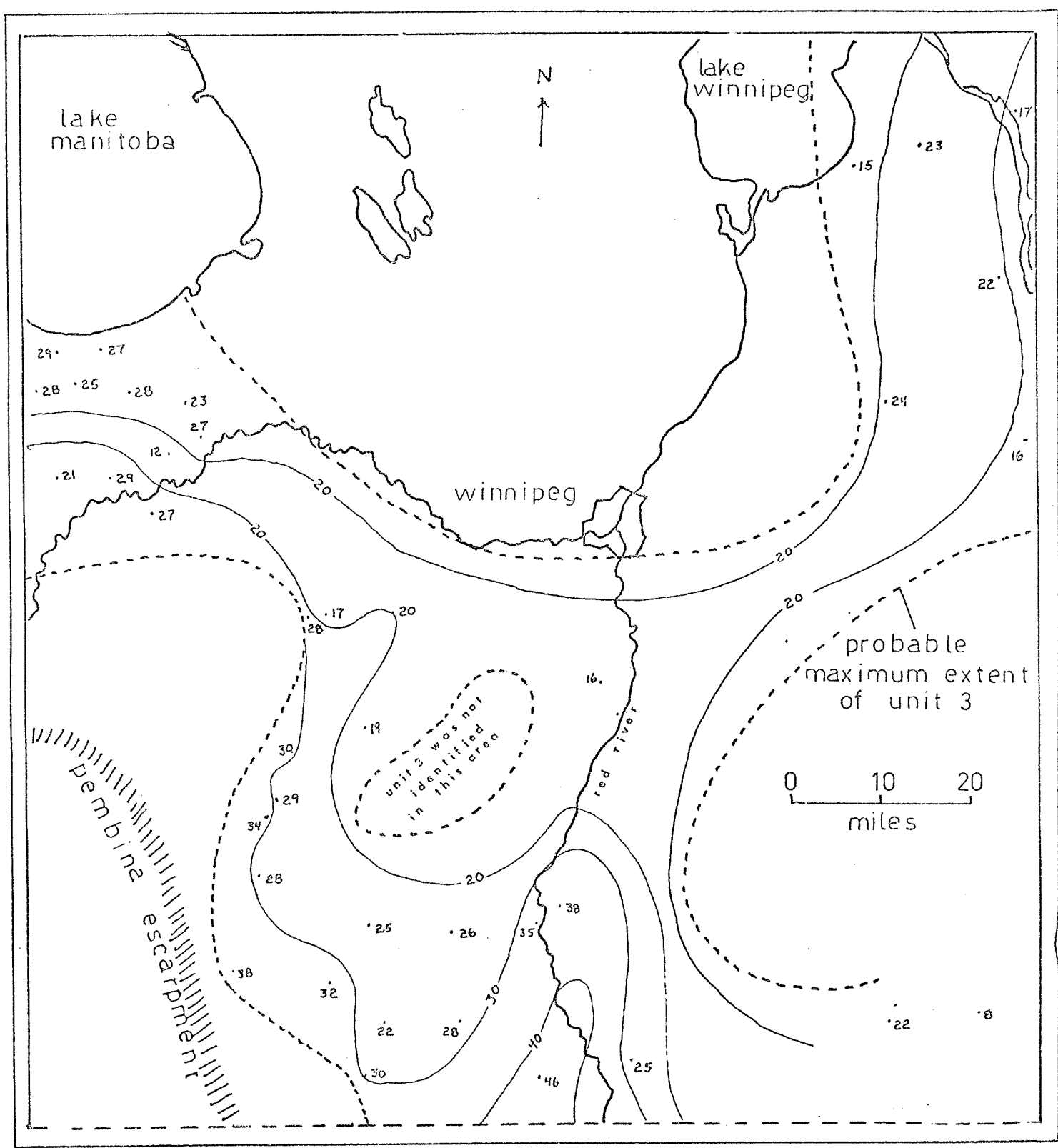


Fig. 20. Variation of Average Montmorillonite Content of Unit 3. Contour interval is 10%.

## CHAPTER 5

### DISCUSSION: INTERPRETATION, CORRELATION AND HISTORY

#### INTRODUCTION

One of the purposes of this research is to develop a better understanding of the history and characteristics of Lake Agassiz offshore deposition in southern Manitoba. Chapter 4 defined and discussed three stratigraphic units based on mineralogy, grain size and various other physical properties of the sediment. In the following section this data will be interpreted as to source and variations, and correlation on a regional basis will be attempted.

Lake Agassiz probably originally began in North Dakota as a superglacial lake and later changed to an ice-walled lake (Moran and Clayton, 1972). It is generally agreed that, although many fluctuations did occur, Lake Agassiz attained greatest depth during its early stages (first 1000-2000 years) and gradually decreased in depth throughout its history (Wicks, 1965). Drainage into the lake was not only from the fluctuating ice mass to the north, but also from streams draining the newly exposed glacial sediment to the south and west. Drainage out of the lake was initially through southern outlets, but as the margin of the ice fluctuated, eastern outlets were periodically opened and closed.

Various authors have recognized numerous lake stages through work on relict strandlines. In recent years, however, new evidence based on the offshore sediments suggests that the lake's history is much more complex than the strandline picture has developed (Elson, 1967).

Almost all previous research on Lake Agassiz sediments has attempted to develop the general sedimentation picture of the lake mainly on the basis of color and textural changes. This study has shown, however, that in the central part of the basin, neither color nor texture clearly define stratigraphic units. Also, almost all previous research on the clay mineralogy of the sediments has implied that there is neither vertical or lateral variation of the offshore deposits within the basin (Wicks, 1965; Quigley, 1967a, b; Fenton and Anderson, 1971; and McPherson et al, 1971).

#### ORIGIN OF OFFSHORE LAKE AGASSIZ DEPOSITS

##### Bedrock Sources

The material making up the offshore sediments was probably derived from two possible sources: bedrock and surficial deposits. Nearly all the research associated with Lake Agassiz in Manitoba concludes that the bulk of the clay-sized material (i. e., clay minerals) was ultimately derived from the Cretaceous shales of the Prairie region (Kodama and Brydon, 1965; Wicks, 1965).

The non-clay minerals in the offshore sediments probably had a greater variety of source areas. The quartz in the sediment could have been derived from the Precambrian granite to the north and east and from the sandstone of the Winnipeg Formation (Ordovician),

as well as from highly siliceous shales and sandstone within the Cretaceous (Bannatyne, 1970). Most of the calcite and dolomite no doubt came from Paleozoic sediments. The feldspars probably originated from igneous rocks of the Precambrian.

#### Surficial Deposit Sources

The questions of how much and what kind of material was derived from the pre-existing soils and glacial deposits, and what, if any, changes the clays have undergone since deposition in the basin are pertinent to this discussion since a portion of the sediment could have been derived from these sources.

An examination of all surficial deposits (till, glaciofluvial, glaciolacustrine) in the Prairies shows that, in general, the clay mineralogy is very similar regardless of origin or depositional environment (Wicks, 1965). Montmorillonite, illite and kaolinite are the dominant clay mineral groups. Quartz and feldspar are usually present in minor amounts (See Wicks, Table 2, 1965). Christiansen (1959, 1960), Rice, et al (1959), Wicks (1965), Kodama and Brydon (1965), and several others have all reached the conclusion that the Cretaceous shales are the source of the clay minerals in the glacial and glaciofluvial deposits of this area. Some also conclude that since there is such a striking similarity between the clay mineralogy of the shales and that of the glacial deposits, there has been very little diagenetic change during the erosion and redeposition of the material (Kodama and Brydon, 1965).

Recent glacial stratigraphy work (McPherson, et al, 1971; Teller, 1973, personal communication) indicates that the clay content of some of the tills in southern Manitoba exceeds 20-30

percent. Furthermore, the Huot and Falconer Formations recognized in North Dakota have clay contents of up to 85% (Harris, et al, in press). The liberation of this material, through not only the melting of the ice but also by streams and waves reworking the drift, would permit the tills of the area to be a favourable source of clay minerals for the offshore Lake Agassiz sediments.

#### CORRELATION AND RELATIONSHIP OF THIS STUDY TO OTHER REGIONAL AND LOCAL LAKE AGASSIZ STUDIES

A summary of probable correlations of the offshore units recognized in this study with other recent subdivision schemes throughout the basin is shown in Table 16. Several points should be noted in using this chart: (1) Only the most recently published stratigraphic subdivisions of a particular author or group are used. For example, Riddel (1950), Barocos and Bozozak (1958), Elson (1961, 1962), Laird (1964), Moran and Clayton (1970), and Moran, et al (1971) are not included because their work has largely been updated and refined or included in other reports; (2) In many of the areas the mineralogical units probably cannot be recognized because of variation over large geographic distances; (3) The chart is not intended to be a time correlation graph.

Correlations in Table 16 are based on the following factors:

(1) Clay mineralogy; (2) Particle size distribution; (3) Color; (4) Relative liquid and plastic limits and natural water contents; (5) Sedimentary structures and features; (6) Stratigraphic relationships and position. Not all of these criteria were used for any particular correlation nor do they have equal emphasis throughout this study. Where possible, samples of a particular

TABLE 16. - CORRELATION CHART

This  
report

Wicks (1965)  
South Winnipeg

Fine Sand and  
Sandy Clay Bed

---

Varved Silty Clay Bed

Unit 3

Lake Agassiz II

Yellow Silt Bed

---

Unit 2

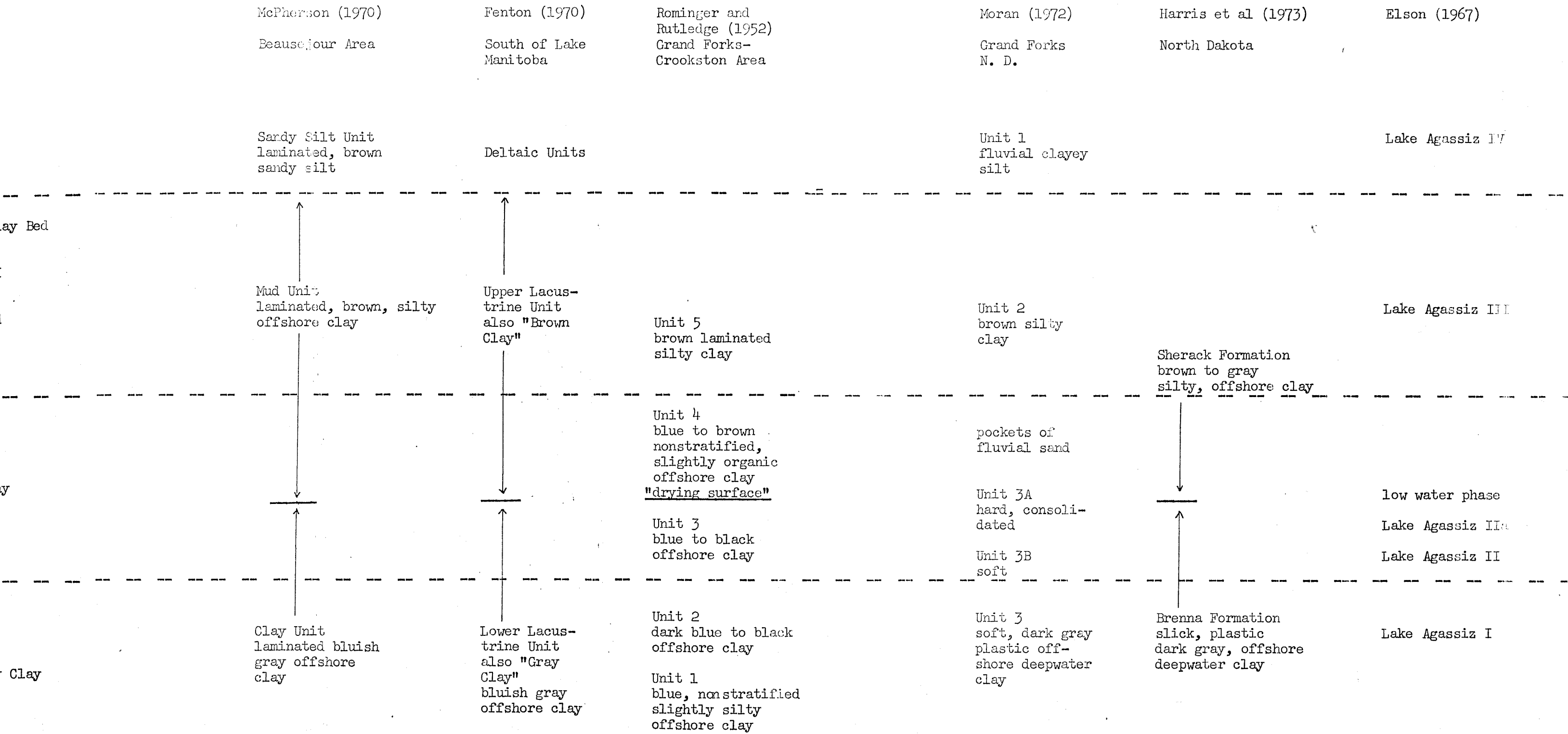
Upper Brown Clay

---

Lake Agassiz I

Unit 1

Lower Blue Gray Clay





research area were restudied as part of this thesis. This applies specifically to McPherson's (1970) and Fenton's (1970) thesis samples (See Appendix G).

Unit 1 of this study best corresponds to the lower 5 to 40 feet of McPherson's (1970) Clay Unit on the basis of clay mineralogy, color, and stratigraphic position. Samples of the lower part of the Clay Unit generally have a low (less than 2) montmorillonite:illite ratio, a dark gray color, and rest directly on till or bedrock. Based on stratigraphic position and color Unit 1 is correlable with Wicks' (1965) Blue-Gray Clay of his Lake Agassiz I.

Unit 1 was not recognized in the area directly south of Lake Manitoba, although Fenton (1970) does state (p. 63-66) that his Lower Lacustrine Unit was deposited between 10,500 and 12,500 years ago, and that this should (p. 70) "correspond to the Clay Unit of McPherson (1970)."

Unit 1 seems to be correlable with Unit 3 of Moran (1972) and the lower portion of the Brenna Formation of Harris, et al (in press), in North Dakota on the basis of grain size, color, engineering data, and stratigraphic position. The Brenna Formation (and Unit 3) is a dark gray, highly plastic clay that directly overlies a till. The liquid and plastic limits and the natural water content of Moran's Unit 3 (and Rominger and Rutledge's, 1952, Unit 1) show very roughly the same relationship with the overlying units as does Unit 1 with Unit 2 in this study.

On the basis of stratigraphic position Unit 1 is probably correlable to Elson's (1967) Lake Agassiz I Episode.

Unit 2 of this study best corresponds to the upper portion of the Clay Unit and the lower portion of the Mud Unit of McPherson (1970). Analysis of his samples in this interval show a high (greater than 2) montmorillonite:illite ratio. The unit also probably correlates to the Brown Clay of Wicks' (1965) Lake Agassiz I on the basis of stratigraphic position and the presence of silt clasts.

Unit 2 corresponds to the upper part of the Lower Lacustrine and the lower part of the Upper Lacustrine Units of Fenton (1970) in the Lake Manitoba area on the basis of similar clay mineralogy. Analysis of his samples from this interval show a high (greater than 2) montmorillonite:illite ratio.

Mainly on the basis of stratigraphic position Unit 2 probably correlates with the upper part of the Brenna Formation (Harris, et al, in press), and the upper part of Unit 3 and the lower part of Unit 2 of Moran (1972) in North Dakota. Moran (1972) also indicates that his Unit 2 is relatively higher in montmorillonite which corresponds to the high montmorillonite content of Unit 2 in this study.

Unit 3 of this study is best correlated with the upper Mud Unit of McPherson (1970) and the Upper Lacustrine Unit of Fenton (1970) on the basis of clay mineralogy, grain size and, to a limited extent, color. The two units are a brown, silty clay, and analyses show a comparatively low (less than 2) montmorillonite:illite ratio which corresponds with Unit 3.

Unit 3 probably corresponds to the Sherack Formation in North Dakota-Minnesota (Harris, et al, in press) on the basis of grain size,

stratigraphic position and color. The Sherack Formation is a brown to gray silty clay that directly underlies post-Lake Agassiz fluvial sands and gravels, and overlies a dark gray plastic clay. For the same reasons Unit 3 may be correlated to the upper portion of Moran's (1972) Unit 2 and Rominger and Rutledge's (1952) Unit 4 and 5.

### INTERPRETATIONS

#### Possible Factors Affecting the Mineralogical Differences

Basically, the units in this study can be recognized by their clay mineral differences: Units 1 and 3 have relatively low montmorillonite values and Unit 2 generally has a high montmorillonite content. The following factors could possibly explain this mineralogical difference.

#### Variation of Source Material

The most obvious hypothesis is that of a varying source for the clay minerals. A limited mineralogical study of one of the major deltas in the northwestern part of the lake (Assiniboine) showed a clay mineral suite that was conspicuously low in montmorillonite (Table 17). This suggests that relatively low montmorillonite sediment was being supplied to the lake basin in Manitoba. It seems possible that the rivers that formed major deltas in the western part of the basin were contributing sediment having a different clay mineral suite than that of the glacial meltwater from the north and east.

Also a measure of the relative degree of crystallinity of the montmorillonite for over 150 samples in this study (see Appendix F) showed that both Units 1 and 2 had a wide range of crystalline development, but that Unit 3 was predominantly poorly crystalline.

TABLE 17  
ANALYSIS OF ASSINIBOINE RIVER DELTA CUT

Sample	% Illite	% Montmor- illonite	% Kaolinite & chlorite	% Sand	% Silt	% Clay
SW-1-10	75	0	25	2	87	10
9	75	0	25	1	90	9
8	68	10	22	1	85	14
7	75	0	25	2	79	19
6	57	0	43	1	87	12
5	44	0	56	3	97	0
4	37	0	63	1	89	10
3	33	29	33	1	64	35
2	29	33	42	29	67	3
1	31	28	41	8	82	10

This would seem to be a strong indication of a change in source material.

However, since Kodama and Brydon (1965) found that all the Cretaceous shales and surficial deposits in the immediate vicinity of Lake Agassiz have a nearly uniform clay mineral assemblage as well as similar relative percentages, the observed Lake Agassiz clay mineral variations, if due to source variation, are likely the result of influx of material from a more distant source.

Source material variation can be used to explain much of the lateral variation evident within the units. Both Units 2 and 3 show a definite grading from relatively low montmorillonite in the north to high in the south (See Fig. 18 and 23). This trend probably continues south to the limits of the offshore sediments: Moran (1972) reports average montmorillonite contents of greater than 75% in the Grand Forks area. Differing source material, coupled with perhaps a different hydrologic regime in the southern part of the basin, could result in the laterally graded montmorillonite distribution seen in southern Manitoba.

#### Differential Settling

A second possible hypothesis involves the use of a differential settling and depositional mechanism. Since montmorillonite has a smaller diameter (0.01 $\mu$ ) than other clay mineral groups (kaolinite - 1 $\mu$ , illite - 0.3 $\mu$ ; Schultz, 1955), it should settle more slowly in a standing body of water.

Thus, if we assume the clay minerals of Unit 1 were deposited under a certain set of environmental and hydrologic conditions, the

deposition of the high montmorillonite of Unit 2 could be caused by a change in these conditions. Perhaps this change was from a rapidly flushed lake (low residence time) during the deposition of Unit 1 to a much higher residence time during the deposition of Unit 2. The low residence period would explain the relatively lower montmorillonite content, whereas during the high residence situation the montmorillonite would be given a greater time to "settle out" thereby increasing its concentration relative to the other clay minerals in the sediment. A return to the initial condition of low residence time would explain the decreased montmorillonite content of Unit 3.

Several questions and points need to be raised in connection with this second hypothesis:

(1) It is difficult to explain the lateral variations discussed in the previous section if this second hypothesis is fully accepted.

(2) What effect would a relatively shallow density or chemical barrier (thermocline or chemocline) have on the hydrologic conditions and changes necessary for the above differential settling? A barrier which prohibited intermingling of the upper, well mixed layer of water and lower, less turbulent water of the lake could effectively isolate clay minerals in suspension in the lower part, thereby increasing the residence time and consequently increasing the relative montmorillonite content of the sediment.

(3) What effect would a change in the average water depth have on the clay mineralogy of the sediments? A shallower lake would tend to have a greater amount of mixing and turbulence than a deeper lake, and this would decrease the amount of montmorillonite

allowed to settle. It is generally recognized (e. g. Elson, 1967) that the level of Lake Agassiz varied considerably throughout its history as drainage outlets opened and closed.

(4) Is it, in fact, possible to prohibit even the finest material (montmorillonite) from settling out year after year for at least several hundred years? That is, is it feasible to suggest that most of the finest material was actually being continually swept out of the basin? Confirmation or rejection of any hypothesis based on this argument, however, hinges on the development of a more complete hydrologic-physical limnologic picture of glacial Lake Agassiz.

#### Water Chemistry Changes

A third hypothesis which could possibly explain the mineralogical changes evident in the offshore Lake Agassiz sediments involves changing the chemical environment of the lake. If the mineralogy of Unit 1 is a result of a certain chemical balance within the entire basin for a given length of time, the deposition of Unit 2, with its slightly different clay mineral amount, can be explained by altering this chemical balance.

Brooks and Farrell (1970), in a study of a small, brackish, southern United States lake, showed that there is a definite correlation between the degree of salinity (i. e., total dissolved solids) of the water through which the clay is settling and the clay mineralogy. An increase in total dissolved solids in the lake water corresponded to an increase in the relative montmorillonite content and generally to a decrease in the other clay mineral groups. They

attributed this phenomena to differential settling characteristics brought out and emphasized by a slower flocculation rate of the montmorillonite.

In transport from their source area, clays, as well as other colloids which are negatively charged, will adsorb water molecules on their surfaces in a way that prohibits the particles from further colliding.

However, when these particles come in contact with saline conditions, the electrolytic action of the water will attract the adsorbed water molecules thus freeing the surface of the clay particle and allowing it to flocculate (Neiheisel and Weaver, 1967). It has been estimated that the salinity of the water need not exceed 1 ppt (much less than the salinity of some ground and surface water in southern Manitoba today) to initiate this flocculation (Krone, 1962, in Neiheisel and Weaver, 1967). In estuary studies the rate of flocculation of clays has been shown to be dependent on a variety of factors, most important of which is the type of clay mineral and its concentration relative to the non-clay minerals (Neiheisel and Weaver, 1967). Illitic and kaolinitic material is flocculated more rapidly than montmorillonitic clay (Brooks and Farrell, 1970).

Thus, the mineralogy of the units could be explained by invoking a low salinity (i.e., very fresh) condition during the deposition of Units 1 and 3 and a slightly higher salt content during the deposition of Unit 2.

The main requirements for this third hypothesis are, of course, to (1) find a mechanism responsible for the increased salinity and (2) find evidence, possibly through paleontological studies, to support the premise that the lake environment was actually slightly saline



during at least part of its history. Neither of these requirements has been resolved completely. Most of the limited paleontological evidence suggests that the lake was "fresh" (Tuthill, 1962, 1967; Moran, Clayton and Cvancara, 1971). Bickley, et al (1971) conclude, through the interpretation of a section in North Dakota particularly high in fossil content, that the lake was oligotrophic, with high sedimentation rates, in its early stages, and eutrophic, with abundant life, later in its development. During its final stages the lake approached the general ecology of a shallow slough. However, this tells us very little about the amount of total dissolved solids in the water. Also, since only 1 ppt can initiate flocculation and mineralogy changes, it is not possible to exclude this hypothesis on the basis of the nature of the fossils alone.

The dissolved salts, if present, could have several possible sources: (1) groundwater and (2) an influx of oceanic waters from Hudson Bay (Teller, 1973, personal communication). The high salinity of the groundwater west of the Red River today is well known (Charron, 1962). Charron (1961) gives averages of up to 3.2 ppt dissolved salts in the Plum Coulee area of southern Manitoba. In addition, Lakes Manitoba, Winnipegosis, Dauphin, Swan, Pelican and Red Deer in west central Manitoba show high concentrations of  $\text{Na}^+$  and  $\text{Cl}^-$ . In most cases these lakes are fed by brine springs whose total dissolved solid concentrations can reach more than 70 ppt (Thomas, 1959). If Lake Agassiz was receiving a large contribution, either via groundwater or surface water, from these highly saline sources, the flocculation hypothesis would seem to be possible. However, it must be kept in mind that the flow and chemistry of today's ground and surface water regime was not necessarily the same during the time of Lake Agassiz.

Another possible source of the salt water could be from the ocean itself. This would require the ice mass to have sufficiently downwarped the earth's crust between Lake Agassiz and Hudson Bay to allow a gradient to be set up in the direction of the lake. Andrews (1970), however, fails to indicate that the necessary gradient did exist.

#### Clay Mineral Changes

A final possible explanation is that the clay minerals of one or more of the units could have undergone post-depositional changes; that is, Unit 2 could have a higher montmorillonite content than Units 1 or 3 because some of the illite of Unit 2 has "weathered" to a montmorillonite structure. Although this illite-montmorillonite weathering sequence is well documented in clay mineral alteration work (see Jackson et al, 1948 and Novak et al, 1970), most research on the glacial sediments and the Cretaceous shales of the Prairies (see p. 86-87) suggests that it is not applicable to Lake Agassiz studies. However, it seems that more detailed research should be attempted along this line before the post-depositional change explanation is discarded.

#### Conclusion

The above discussion has pointed out only the more obvious possibilities concerning the cause of the clay mineral regime of offshore Lake Agassiz sediment and some of the observed or expected phenomena which help to support or refute the various hypotheses. The most likely conclusion that can be reached is that the particular stratigraphy was caused by some type of differential settling brought about by a chemical and/or hydrologic change in the lake.

## HISTORY

The history presented in this section is intended only to give the reader a better general understanding of the glacial events during the time of Lake Agassiz' formation and existence. It is based entirely on the correlation presented on pages 87-91. With the exception of the points noted in that section, this research did not find any firm evidence to contradict or add to Elson's (1967) detailed history from which much of the following is derived.

(1) Numerous tills were deposited in the Lake Agassiz basin by late Wisconsinan ice. As yet it is not known how many glacial advances and retreats are represented by these tills.

An ancestor of "classical" Lake Agassiz formed in the southern Lake Agassiz basin about 13,000 years B.P. and extensive offshore sediments were deposited in North Dakota. It is uncertain whether there is evidence of this early phase of the lake in Manitoba. Possibly the northern part of Manitoba's sedimentary basin was continuously ice covered while the fluctuating southern ice margin controlled lacustrine deposition in North Dakota and Minnesota.

(2) Following a brief ice re-advance (which deposited a very clay-rich till in North Dakota), Lake Agassiz began to form probably first as a superglacial lake and then as an ice walled lake (Moran and Clayton, 1970). Unit 1 and a part of Unit 2 were deposited during this time (12,500 to ~10,000 B.P.; Elson's Lake Agassiz Episodes I and II) as deep water, offshore sediment. Most of the major deltas on the western edge of the basin were also deposited at this time.

Numerous water level fluctuations occurred during this span of time (12,500 - 10,000 B.P.) corresponding to the ice sheet

opening and closing eastern outlets (See Elson, 1967). Elson (1967), on the basis of textural differences, suggests that there was a major low water phase about 10,500 B.P. with drainage into glacial Lake Barlow-Ojibway in Ontario. Soil engineering work in North Dakota (Rominger and Rutledge, 1952; Moran, 1972) identified a sharp change in physical properties resulting from dessication during subaerial erosion about 11,000 to 10,500 B.P. However, this type of change has not yet been recognized in southern Manitoba.

In North Dakota, rivers flowed across much of the exposed lake plain depositing isolated pockets of sand and gravel (Moran, 1972). The absence of Unit 1 from an area immediately south of Lake Manitoba suggests that the unit was either not deposited there or that erosion during the "low water" phase destroyed much of the sediment record.

(3) During another ice advance that blocked eastern outlets (10,000 B.P.), the lake level rose (Elson's Episode III) and Unit 2 and Unit 3 were deposited as offshore sediment between about 10,000 and 9,000 years B.P. The relatively higher number of silt clasts found in Unit 2 may indicate a closer ice front than during the deposition of Unit 1. Along the eastern edge of the basin the fluctuating ice mass caused interfingering of till with Units 2 and 3 which also indicates a close ice margin. This interfingering of lacustrine and glacial sediment is not recorded in the central part of the basin.

(4) Further ice retreat after about 8,500 to 7,700 years B.P. reduced Lake Agassiz to a very shallow lake in which fine lacustrine sands and silts and finally fluvial sands were deposited. These lacustrine and fluvial sediments were rarely deposited in the central part of the depositional basin and were not studied within this thesis.

## CHAPTER 6

### SUMMARY OF CONCLUSIONS

#### INTRODUCTION

This study tended to fall into two distinct areas of research:

(1) A comparative methodology study of X-ray analysis of clay minerals, and (2) A study of the clay mineralogy and stratigraphy of the offshore sediments of glacial Lake Agassiz in southern Manitoba. The results and conclusions reached in (1) helped to formulate a general procedure followed in the analysis of the clay samples from (2).

#### RESULTS OF METHODOLOGY STUDY

(1) The difference in the average size of montmorillonite compared to the other clay mineral groups does introduce error into quantitative determinations of the minerals by X-ray diffraction. This is attributed to the different settling velocities of the minerals, which tend to segregate the smaller montmorillonite particles near the top of the clay film when using the aqueous pipette-on-slide mounting technique.

(2) Attempts to correct this size and mineralogical segregation by introducing a more volatile liquid media were generally not successful. Also, chemical and crystallinity changes in the clays that might occur as a result of this introduction could not be evaluated.

(3) The use of the smear-on-slide and suction methods of mounting, which do not employ gravitational settling, showed consistently lower montmorillonite values. This suggests that these techniques do give more accurate results by eliminating the differential settling problem. However, low reproducibilities and more complicated, time consuming procedural steps eliminated these methods from use in this study.

(4) The thickness of the clay film being X-rayed affects the quality of the diffractogram. Experiments conducted with offshore Lake Agassiz clays indicated a desirable net, dry sample weight of ten to twenty mg per slide.

(5) A comparative study of two calculation procedures used in determining relative clay mineral percentages showed variations of up to 30%. It was concluded that the weighting method added unnecessary refinement to the semi-quantitative estimation.

(6) The following specific techniques and procedures were used in this study of offshore Lake Agassiz sediment:

(a) Aqueous pipette-on-glass slide method.

(b) Calculation by the direct comparison method using peak heights as indicators of intensity and baseline positioning through the middle of the background trace.

This set of procedures was decided on through a combination of best and most consistent results, ease and rapidity of obtaining results, and best correlation possibilities.

(7) In light of the approximate and semi-quantitative nature of clay mineral X-ray diffraction, it is most important to maintain consistency throughout a particular study and, if possible, a study region.

RESULTS OF STRATIGRAPHIC STUDY OF OFFSHORE LAKE AGASSIZ SEDIMENTS

(1) Using the results of analyses of about 350 samples of offshore Lake Agassiz sediment from 58 drill holes and major cuts in southern Manitoba, a three-fold stratigraphic subdivision based primarily on clay mineralogy, and secondly on carbonate content, engineering data and textural criteria, is proposed.

Unit 1 is characterized by montmorillonite:illite ratios less than 2, high clay values (generally greater than 75%), low carbonate values and low Atterberg limits. Unit 2 is characterized by montmorillonite:illite ratios greater than 2, high clay values (generally greater than 75%), and high Atterberg limits. Unit 3 is characterized by montmorillonite:illite ratios less than 2, low clay values (generally less than 70%), high carbonate values and low Atterberg limits.

(2) The cause of these mineralogical and textural differences, as well as lateral variations, can probably best be explained by taking into account two possible hypotheses:

- (a) Variable source material.
- (b) Differential settling of the clay minerals due to residence time variation and emphasized by size and flocculation differences.

The conclusion reached in this thesis is that differential settling caused primarily by salinity changes and secondly by size differences resulted in the observed vertical and lateral mineralogical variations.

(3) Correlations based on clay mineralogy, texture, color, engineering data, and stratigraphic position resulted in (Table 16) Unit 1 being equated to the lower part of the Brenna Formation in North



Dakota and the lower part of the Wicks' (1965) Gray and McPherson's (1970) Clay Unit in southern Manitoba. Unit 2 is equivalent to the middle and upper part of the Brenna, and the lower part of the Sherack Formation. In southern Manitoba it corresponds best to the upper part of the Clay Unit and part of the Mud or Brown Unit. Unit 3 is probably equivalent mainly to the middle and upper part of the Sherack in North Dakota and the Mud Unit in southern Manitoba.

(4) The glacial history arrived at in this thesis was based entirely on the results of the correlation. Basically, as the late Wisconsinan ice retreated, Lake Agassiz came into existence and Unit 1 and possibly a part of Unit 2 were deposited about 12,500 to 10,000 years B.P. There is evidence of a major low water phase about 10,500 to 10,000 years B.P. Most of Unit 2 and Unit 3 were deposited after this (10,000 - ~9,000 years B.P.). The lake drained (~7,500 years B.P.) after depositing silts and sands over the offshore clays.

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## APPENDIX A

### ROUTINE PROCEDURE FOR THE PROCESSING AND IDENTIFICATION OF CLAY MINERALS IN LAKE AGASSIZ OFFSHORE SEDIMENTS

Textural Analysis (modified from Folk, 1968; and Teller, 1972, written communication.)

The grain size distribution was determined for material of the finer than sand size fraction for 256 samples of offshore Lake Agassiz sediment from southern Manitoba. Samples were mainly derived from auger and rotary drill holes, but several shallow, near-surface samples were also analyzed. In the case of auger and surface samples, a twenty gram portion to be analyzed was taken directly from the field sample. Best results were obtained if the field samples had not been allowed to dry.

Chip samples from rotary drilling required more careful pretreatment. If possible, a chip approximately two inches square was selected from the field sample. This piece, usually dry, was thoroughly washed and "trimmed" to eliminate contamination from drillers mud and surface accumulations. Trimming consisted of cutting or scraping away an approximately one-half inch layer from the surface of the chip. The resulting piece was then used for further processing as follows:

1. Air dry a 20 g portion of the field sample. Generally this portion is cut into numerous small pieces and placed in a dust free cabinet. Drying is completed in 48 to 72 hours.
2. Place a weighed amount(12-17 g) of the sample into a 100 ml beaker or flask and add about 20 ml Calgon solution (for this study the Calgon solution was made up of 3 g Calgon per 1 liter distilled water). Slight disaggregation with mortar and pestil greatly aids in the dispersion

process; however, care must be taken not to break down any coarse material in the sample. Allow the sample to set overnight.

3. Wet sieve the slurry through a  $62\mu$  (4.0  $\phi$ ) sieve using less than 1 liter of Calgon solution. Retain both portions of the sample. Transfer all coarser than 4.0  $\phi$  material (sand) into an evaporating dish, dry and weigh.

4. Transfer the finer than 4.0  $\phi$  material into a 1000 ml graduated cylinder, add Calgon solution to bring the volume to exactly 1 liter, stir, and let stand for at least 12 hours to see if any flocculation occurs. If flocculation does occur vary the amount of Calgon in the cylinder. In this study less than one percent of the samples analyzed showed any flocculation.

5. Stir the solution and withdraw with a pipette 20 ml at the following times and depths (Folk, 1968):

times of withdrawal	depth (cm)	phi value
20 seconds	20	4.0
1 minute, 45 sec.	20	4.5
1 minute, 45 sec. (this and each successive time is after a second stirring.)	10	5.0
3 min., 28 sec.	10	5.5
6 min., 58 sec.	10	6.0
28 min.	10	7.0
1 hour, 51 min.	10	8.0
7 hr., 24 min.	10	9.0
14 hr., 50 min.	5	10.0

To give a better approximation of the cumulative curve 11 phi and 12 phi intervals were taken for sixteen samples. The times and depths are as follows: 11 phi - 59 hours, 20 minutes at 5 cm; 12 phi - 118 hours, 25 minutes at 2.5 cm.

6. Place the twenty ml sample into a pre-weighed 50 ml beaker. Wash the pipette once with distilled water adding the liquid to the

50 ml beaker. Evaporate to dryness in an oven at less than 90°C, weigh and obtain the net weight of the sample.

7. Calculate the total weight of the sediment in the cylinder, the weight of each size fraction, and the cumulative percent according to the following:

$$F = \text{total weight of sediment in cylinder} \\ = (\text{weight of } 4.0 \phi \text{ fraction} - 0.06) \times 50$$

$$\text{Cumulative \% coarser for a particular size fraction} = \frac{100 (S + F - P)}{S + F};$$

where S = weight of sand;

$$P = (\text{weight of particular size interval} - 0.06) \times 50$$

8. Plot a cumulative curve. Folk (1968) contends that if there is still a large amount of sediment finer than the last pipette interval, as is the case with most of the Lake Agassiz sediments, the cumulative curve past 10 phi can be approximated by extending a straight line from the curve to 14 phi at 100%. This was substantiated by experiment (Fig. A-1).

9. Compute the graphic mean, standard deviation, skewness and kurtosis.

#### Mineralogical Analysis

10. At the same time that the 20 ml of 9 and 10 phi size fractions are being taken, withdraw a 60 ml sample and place in a 125 ml (four ounce) polyethelene water bottle for storage.

11. Make an oriented clay mount by one of the following methods:

Pipette-on-glass slide (aqueous media) technique

- (a) Thoroughly agitate bottle containing sample. Be sure all clay material is completely disaggregated and in suspension. Best results were obtained using

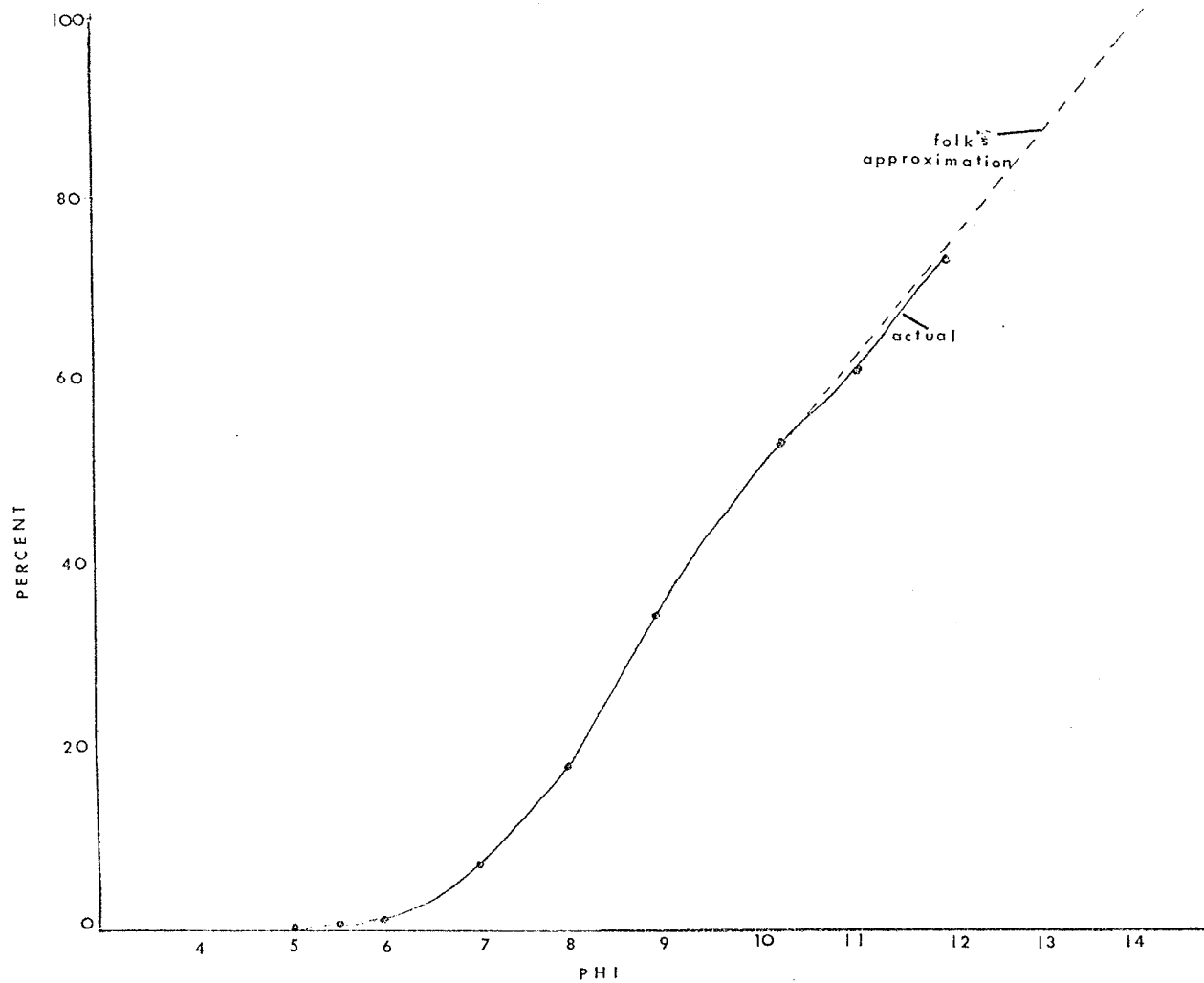


Fig. A-1. Cumulative Curve of Sample HA-1.  
Sixteen samples were analyzed for the additional 11 phi and 12 phi sizes to substantiate Folk's (1968) suggestion for cumulative curve approximation. All samples fell within four percent of the approximation line up to 12 phi.

a mechanical test tube shaker.

- (b) Using an eye-dropper place 12 to 25 drops (approximately one to two ml) on a frosted petrographic slide.
- (c) Air dry the slides in a dust free cabinet, making sure they are resting horizontally. Drying is completed in 8 to 12 hours. Experiments showed that the slide can be placed on a warm (less than 45°C) hot plate or oven to speed the evaporation process with no apparent effect on the resulting diffractogram.

Pipette-on-glass slide (acetone media) technique.

- (a) Proceed as in (a) above.
- (b) Concentrate the solution by placing approximately 35 ml in a ten cm centrifuge test tube and centrifuge for 30 to 45 minutes. Decant off all of the clear supernate liquid. Add 5 to 10 ml of acetone to the residue in the test tube, agitate, and, using an eye-dropper, place 12 to 24 drops of solution on a frosted petrographic slide. Although it is conceivable that this centrifuging and concentration step could be a source of possible error through selective settling, experiments showed there was very little difference, between a concentrated solution diffractogram and a non-centrifuged one. Also experiments showed that placing the slides on a warm (greater than 40°C) surface caused cracking and curling of the clay film.



Pipette-on-glass-slide (alcohol media) technique.

Proceed as above (acetone media) except add five to ten ml alcohol instead of acetone.

Smear-on-glass slide technique (Gibbs, 1965).

- (a) Thoroughly agitate bottle containing sample as in the pipette methods.
- (b) Concentrate the solution by placing thirty-five ml of solution in a centrifuge test tube and centrifuge 5-10 minutes. Decant all but ten ml of the solution and agitate.
- (c) Place the ten ml in a small watch glass and evaporate until the solution forms a thick paste. This usually takes eighteen to twenty-four hours. Experiments showed that there was no effect on the resulting diffractogram if the watch glass was placed in a warm oven (less than 50°C) to speed the evaporation process. However, care must be taken to prevent the paste from becoming completely dehydrated.
- (d) Using a small plastic spatula (or knife) spread the clay paste across a frosted slide in a thin, even layer.
- (e) Drying is completed in seven to fourteen hours.

Suction-on-ceramic-tile technique (Kinter and Diamond, 1956).

Follow (a) and (b) as in the pipette - aqueous media procedure, except in this method a porous ceramic tile

should be used in place of a petrographic slide. For this study the prescribed ceramic tile was not readily available so a semi-porous unglazed piece of pottery ("flower pot" ceramic) was used. The pieces had to be cut and ground to the appropriate size and thickness of a petrographic slide. Also, a larger amount of clay solution (three to five ml) is needed to develop an adequate slide. The solution is placed on the porous ceramic slide and suction is applied to the underside of it using a rubber tube connected to a vacuum system. The process is completed within fifteen to twenty minutes depending on the degree of porosity and thickness of the slide.

12. Place one of the prepared slides in a desiccator or other large sealed container with about 100 ml of ethylene glycol (Brunton, 1955). By constructing several cardboard stages, the desiccator is capable of holding up to 100 slides. Allow the slide to remain in the saturated environment for at least 48 hours.

13. Make a diffractogram of each glycolated sample. Keep slides in the desiccator until required. Begin interpretation of the diffractogram by labeling and measuring major peaks (See text).

14. Heat another slide in a muffle furnace at 575°C for one hour (Carroll, 1970). The standard muffle furnace can accommodate up to thirty slides at once. Diffractograms should be obtained from slides within twenty-four hours after heating because of possible re-hydration (van der Marel, 1966).

15. Begin interpretation of the diffractograms by measuring and labeling the major peaks.

APPENDIX B

PROCEDURE FOR DETERMINING CALCITE AND DOLOMITE CONTENT BY EVOLUTION OF CO<sub>2</sub> (Dreimanis, 1962; modified by Teller)

(See Fig. B-1)

1. Grind and sieve sample through 200 mesh sieve.
2. To flask I add exactly 1 gram of sample that has passed through sieve.
3. Add exactly 20 ml 2:1 HCl to funnel C.
4. Insert stopper F, and thermometer B, making sure all joints are pressure tight (do not use stop-cock grease on rubber stoppers). Make sure that valve E is in open position.
5. Equalize water levels using flask H and record an initial reading on buret D.
6. Record initial temperature reading and the room barometric pressure.
7. Turn on magnetic stirrer A, open stop-cock on funnel C and start timer.
8. Take readings of water level in buret D after leveling with the water in H, every 5 seconds for the first minute and every 10 seconds for the second minute. After 45 minutes take a final temperature reading and a final barometer reading. Note: do not replace leveling flask to its original elevated position after experiment has started.
9. Plot the ml values read from the graduated buret D versus the time at which they were read.
10. Determine the amount of CO<sub>2</sub> gas derived from calcite and the amount from dolomite by extrapolating from the break in the curve (See Fig. B-2). Convert temperature readings to °K.
11. Calculate the percent calcite in sample using:  
 % Calcite = volume of CO<sub>2</sub> gas derived from calcite X

$$\frac{273^{\circ}\text{K}}{760\text{mm}} \times \frac{\text{initial pressure}}{\text{initial temperature}} \times \frac{\text{molecular weight of calcite}}{\text{cc gas from 1 mole calcite}}$$

$$\times 100 = (\text{CalVol}) \times (0.3592 \frac{P_i}{T_i}) \times (0.00447) \times (100)$$

$$= (\text{Calvol}) \times (0.1606) \times (\frac{P_i}{T_i})$$

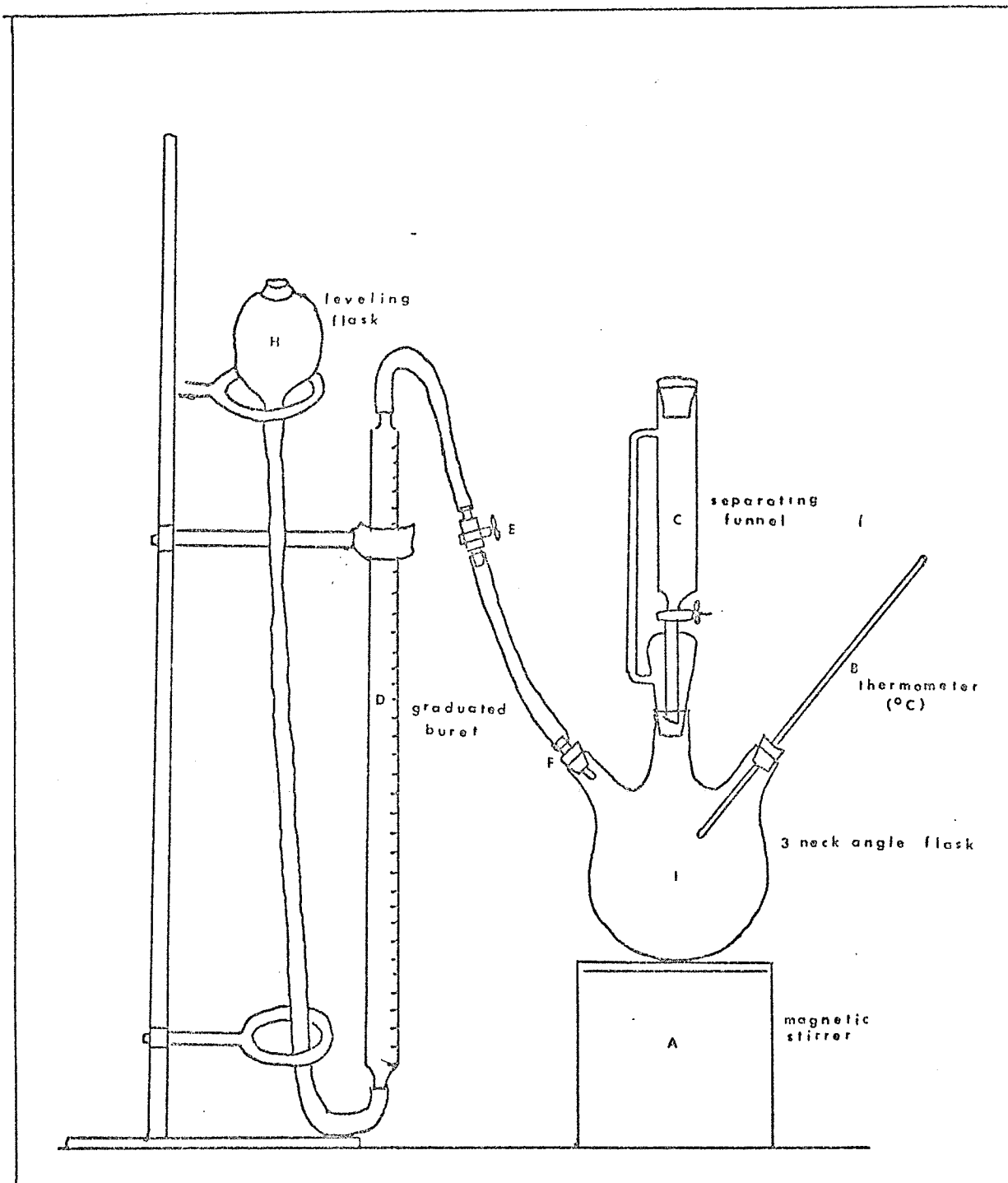


Fig. B-1. Diagram of Modified Chittich Apparatus.

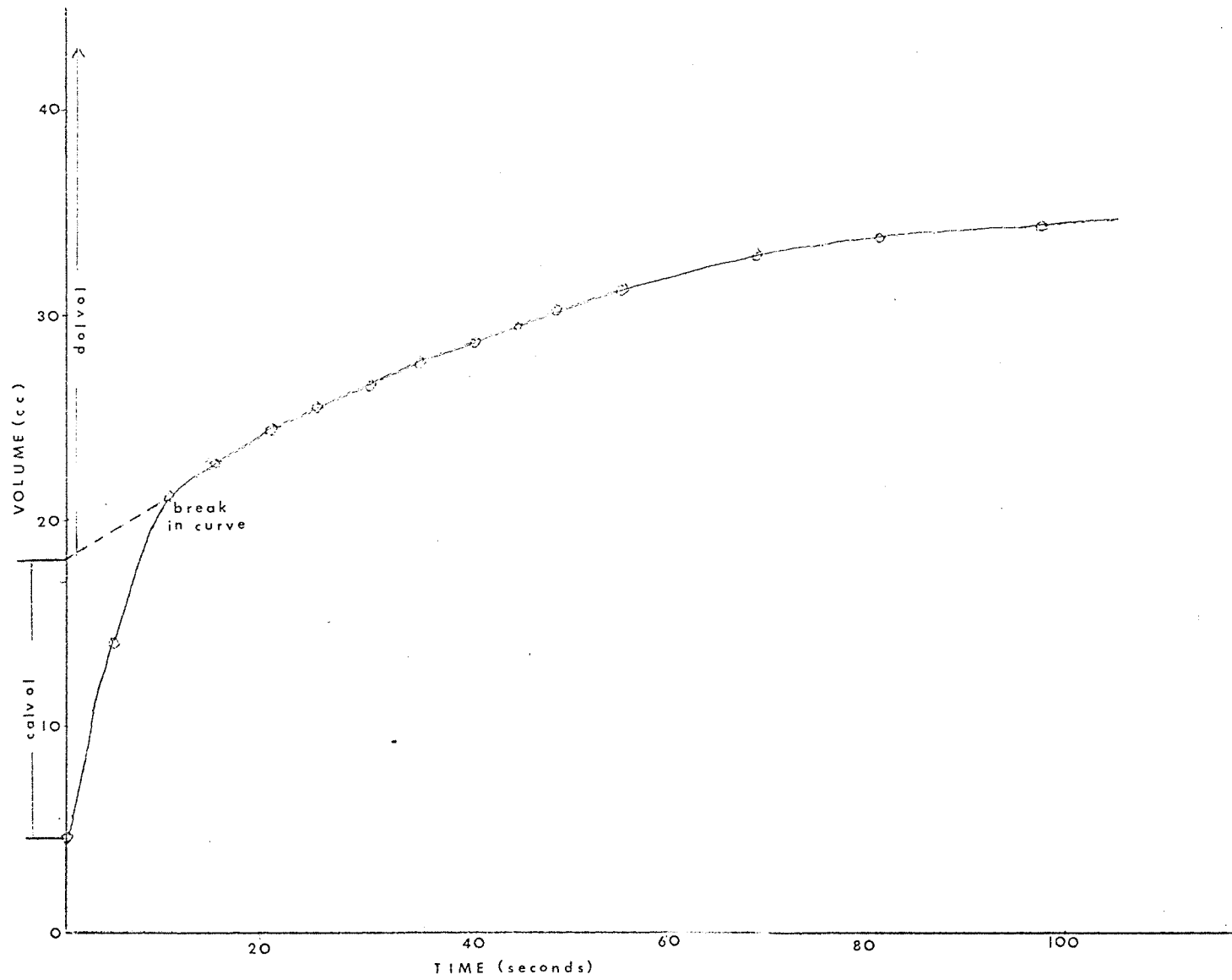


Fig. B-2. Chittich Apparatus Volume Plot.

12. Calculate the percent dolomite in sample using:  
 % Dolomite = (volume of CO<sub>2</sub> derived from dolomite) X

$$\frac{273^{\circ}\text{K}}{760\text{mm}} \times \frac{\text{Final pressure}}{\text{Final temperature}} \times \frac{\text{Molecular weight of dolomite}}{\text{cc gas from 1 mole of dolomite}}$$

$$\times 100 = (\text{DolVol}) \times (0.3592) \times \frac{P_f}{T_f} \times (0.00412) \times (100)$$

$$= (\text{DolVol}) \times (0.148) \times \frac{P_f}{T_f}$$

Note: for both calculations temperature readings should be in degrees Kelvin, barometric pressure readings in mm of mercury.

## APPENDIX C

### SOIL MECHANICS PROCEDURES

(modified from Foth and Jacobs, 1959: and Jacobs, et al, 1971)

Plastic limit -- a measure of the boundary between the plastic solid state and the friable solid state.

1. Place 150 to 200 g dried sample in beaker and mix thoroughly with distilled water to the consistency of a very thick paste.
2. Roll a portion of the sample approximately the size of a  $\frac{1}{2}$  inch cube on a sheet of glass plate to reduce the water content. Roll the piece into a thread  $\frac{1}{8}$  inch in diameter, then fold into a thicker thread and roll again. Repeat this process until the threads start to crumble during the rolling operation.
3. Immediately place the crumbled sample in a small dish and weigh to 0.001 g.
4. Dry the sample in a 105°C oven for at least 4 hours.
5. Remove from oven, allow to cool and weigh to 0.001 g.
6. Calculate the water content in percent dry weight from the ratio of the weight of the water removed by drying to the weight of the dry sample.

Natural water content

1. Place 20 to 50 g of air dried and weighed sample in evaporating dish.
2. Heat sample at 105°C for at least 12 hours.
3. Remove from oven, allow to cool and weigh to 0.001 g.
4. Calculate the water content in percent dry weight from the ratio of the weight of the water removed by drying to the weight of the dry sample.



APPENDIX D

QUANTITATIVE VALUES FOR METHODOLOGY COMPARISON

	Sample HB-2			Sample HB-4			Sample HB-6		
	Ill	Mont	K+C	Ill	Mont	K+C	Ill	Mont	K+C
Thickness variation									
7 mg	30	37	33	21	40	39	20	49	30
15 mg	28	36	36	20	42	36	18	52	29
20 mg	28	35	36	21	42	37	20	49	31
30 mg	27	37	34	20	44	36	21	52	29
mean	28	37	35	20	42	37	20	50	30
$\sigma$	.36	.99	.44	.16	.46	.95	.36	.46	.27
Mounting variation									
Aqueous media-pipette	28	36	36	20	42	36	18	52	29
Acetone media-pipette	31	31	38	24	37	37	29	34	36
Smear	30	32	37	21	46	31	29	45	25
Suction	31	31	38	29	36	34	29	41	30
mean	30	32	37	23	40	35	26	43	30
$\sigma$	.41	.68	.91	1.1	1.6	1.2	1.6	1.4	1.3
Computing variation									
direct comp. - height	28	36	36	20	42	36	18	52	29
direct comp. - area	24	46	22	18	60	21	18	55	27
weighted - height	30	47	23	31	48	21	37	30	32
weighted - area	36	32	31	40	31	29	38	26	36
mean	29	41	29	29	46	27	29	44	32
$\sigma$	2.9	2.1	1.9	2.9	3.5	2.1	3.3	6.0	1.1

Ill = percent Illite group

Mont = percent Montmorillonite group

K+C = percent Kaolinite plus Chlorite group

APPENDIX E

VARIATION OF NON-CLAY MINERALS IN SEDIMENTS  
FROM THE CENTRAL LAKE AGASSIZ BASIN

Quartz and feldspar content was evaluated by interpretation of X-ray diffraction.

Calcite and dolomite content was evaluated using a modified Chittich apparatus (Appendix B). Values with an asterisk (\*) indicate laboratory work done by Dr. J. Teller.

The letters VS, S, M, W represent Very Strong, Strong, Moderate and Weak and refer to the relative strength of the particular peak on the X-ray diffractogram. Note however that due in part to the differences in diffracting power of the various minerals, the strengths do not represent the relative abundance of each mineral.

A dash (-) indicates no peak present. A blank indicates no interpretation was attempted.

Hole and Sample	Depth (ft)	Quartz	Feldspar	% Calcite	% Dolomite	Unit
HA-1	12	M	W			3
2	26	M	W	5.1	9.8	3
3	37	S	W			3
4	45	W	W			2
5	55	S	W	3.1	7.9	1
6	70	M	-	.8	7.2	1
7	80	M	-			1
8	99					1
HB-1	4	M	-	7.0*	29.1*	3
2	8	M	-	3.6*	22.5*	3
3	14	VS	W	5.7*	10.4*	2
4	26	M	-	4.5*	7.2*	2
5	36	S	-	4.2*	8.7*	2
6	45	VS	-	4.5*	8.8*	2
7	65	W	W	4.4*	8.7*	1
8	73	W	W	4.3*	9.1*	1
9	80	VS	W	4.4*	13.7*	1
10	89	S	M	5.0*	13.8*	1

Hole and Sample	Depth (ft)	Quartz	Feldspar	% Calcite	% Dolomite	Unit
HC-1	4	S	W			3
2	8	M	-	2.2	14.2	3
3	18	M	-			3
4	28	S	W	0	8.1	2
5	35	M	W			2
6	45	S	W	0	7.1	2
7	55	S	-			1
8	65	M	-			1
9	98	M	-	0	8.6	1
WR-7-1	10	S	W			3
2	20	S	W	4.9	7.1	3
3	30	S	W	5.0	7.0	3
4	40	M	-	9	11.0	2
5	60	-	-			2
6	65	-	-			2
7	75	-	-	3.8	30.6	1
WR-9-1	10	S	W			3
2	15	M	W	4.9	7.1	2
3	25	S	M			2
4	30	S	W	5.1	7.0	2
5	35	M	W			2
6	50	M	W	5.0	7.0	2
7	65	M	W			1
8	70	M	W	9.0	11.0	2
WR-21-1	10	M	W			3
2	20	S	W			3
3	30	W	W			2
4	40	W	W			1
5	50	M	W			2
6	60	M	W			2
7	70	VS	W			1
WR-24-1	10	S	W			2
2	20	M	W			2
3	25	S	W			2
4	30	S	W			2
5	35	S	W			2
6	40	S	-			2
7	45	S	-			2
8	50	S	-			2
9	60	VS	W			1
10	70	VS	-			1
11	80	S	W			1

Hole and Depth Sample (ft)	Quartz	Feldspar	% Calcite	% Dolomite	Unit
WR-26-1 5	S	W			3
2 10	S	W			3
3 20	S	W			3
4 30	S	W			3
5 40	S	W			3
6 50	M	W			2
7 60	S	-			2
8 70	M	-			2
9 80	M	-			2
WR-25-1 10	S	W			2
2 20	M	W			2
3 30	S	W			2
4 40	S	W			2
5 50	M	W			2
6 60	S	W			2
7 70	-	M			1
8 80	M	W			2
9 90	S	W			1
10 100	S	-			1
WR-27-1 5	VS	W			3
2 10	S	W			3
3 20	M	M			3
4 30	S	W			3
5 40	S	W			2
6 50	S	W			2
7 60	M	W			2
8 70	M	W			2
9 80	VS	W			1
10 90	M	W			2
11 100	S	W			1

APPENDIX F

RESULTS OF TEXTURAL AND CLAY MINERALOGICAL ANALYSES

An asterisk (\*) indicates almost all of the value is due to kaolinite.

The amount of illite, montmorillonite and kaolinite and chlorite is given in percentages.

M/I indicates the montmorillonite:illite ratio.

Crystallinity of montmorillonite - 0 = very poorly crystalline  
1 = very highly crystalline

Unit designations are based on the author's interpretation of all criteria studied.

A question mark (?) refers to doubtful value or unit designation.

Locations and lithologic descriptions are given in Appendix G (See also Fig. 3).

A blank space indicates that the data was not available.

Sample	Ill	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
HA-1	25	31	43*	1.2	.4	0	18	82	3
2	27	34	38*	1.2	.9	TR	19	81	3
3	27	31	41	1.1	.3	0	10	90	3
4	11	60	28*	5.4	.1	1	15	84	2
5	35	7	61*	.2	.5	2	13	85	1
6	36	27	36	.7	.2	1	12	87	1
7	27	27	44*	1	.8	0	5	95	1
8	29	31	40*	1.1	.8	TR	17	83	1?
HB-1	39	21	39*	.5	.4	10	42	48	3
2	28	36	36*	1.2	.3	3	44	52	3
3	20	51	27*	2.5	.2	TR	18	82	2
4	20	42	36*	2.1	.6	TR	11	89	2
5	17	52	30*	3.0	.6	TR	31	69	2
6	18	52	29*	3.0	.2	TR	13	87	2
7	25	33	41*	1.3	.7	0	5	95	1
8	26	36	36	1.3	.8	TR	15	85	1
9	29	29	42*	1	.9	TR	33	67	1
10	21	35	43	1.6	.5	TR	32	68	1

Sample	Ill	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
HC-1	7	35	57*	5	.3	1	37	63	3
2	50	0	50*	0	0	TR	23	77	3
3	24	36	40	1.5	.4	TR	6	94	3
4	13	67	18*	4.5	.9	TR	6	94	2
5	13	67	18*	4.5	.2	TR	11	89	2
6	15	52	32*	3.5	.9	TR	7	93	2
7	43	25	31*	.5	.3	TR	32	68	1
8	36	21	42*	.5	.4	TR	9	91	1
9	33	20	46*	.6	.4	TR	16	84	1
HD-1	36	7	57	.2	.3	1	22	77	3?
2	41	4	54	.1	.1	4	16	81	3?
HG-1	32	22	45*	.6	.1	7	18	75	3?
HH-1	27	8	47	.3	.2	2	20	78	3
2	21	51	27*	2.4	.6	8	67	25	2
HP-1	50	0	50	0	0	8	84	8	3?
HS-1	43	4	43	.3	.4	TR	6	94	3
2	16	50	33*	3.4	.1	2	6	93	2
3	16	54	29*	3.5	.1	2	10	88	?
4	38	9	53*	.2	.8	4	31	66	1
GA-1	6	50	43*	8.5	.3	7	73	20	3?
2	56	0	44	0	.2	16	72	12	3?
3	25	25	50*	1	.6	9	72	19	3?
4	60	40	0	.6	.3	TR	17	83	3
5	29	33	37	1.1	.2	0	9	91	3
6	0	87	13	>2	.3	TR	12	88	3
7	35	45	20*	1.2	.3	0	17	83	3
8	41	13	56	.3	.3	4	48	48	3?
9	36	21	42	.5	.8	4	44	51	3?
10	57	0	33		.5	4	64	32	3?
11	12	53	25*	4.4	.7	3	37	60	2
12	34	6	60*	.1	.9	15	20	65	?
EA-1	42	0	57	<1	0	22	76	2	3?
2	33	0	66	<1	0	7	66	26	3?
3	50	0	50	<1	0	12	88	0	3?
4	21	47	32*	2.2	.2	10	90	0	2?
EB-1	50	13	38*	.2	0	25	57	18	3?
2	33	33	33	1	.1	1	13	86	3
3	44	19	38	.4	.2	2	3	95	3
B-1-1	32	16	52*	.5	.4	6	59	35	3?
2	22	45	32*	2	.5	0	1	99	3
3	25	75	0	3	.5	TR	75	25	?
4a	20	42	36*	2.1	.4	0	4	96	2
4b	36	18	45*	.5	.9	0	7	93	1
4c	46	13	40*	.2	.1	0	5	95	1

Sample	Ill	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
B-2	28	42	30*	1.8		3	14	83	3?
B-3	20	41	39*	2.1		1	18	80	2
B-4	39	38	23	.9		2	10	87	3?
B-5	17	49	33	2.5		3	11	86	2
B-6	30	38	32	1.2		5	16	79	3?
PV-1	54	0	46	<1	0	TR	93	6	
2	23	48	28*	2	.8	2	6	93	2
3	46	7	46*	.1	.8	TR	58	42	
4	25	50	25	.9	.2	TR	7	93	2
T-3	38	27	35*	.8		0	3	97	1
4a	18	45	37*	2.6		TR	66	34	2
4b	21	50	35*	2.1		0	1	99	2
5	28	28	42	1		5	63	32	3
SW-Ass R									
-1-9	75	0	25*	.1		2	87	10	
8	75	0	25*	<1		1	90	9	
7	68	10	22	.2		1	85	14	
6	75	0	25*	<1		2	79	19	
5	57	0	43	<1		1	87	12	
4	44	0	56*	<1		3	97	0	
3	37	0	63	<1		1	89	10	
2	33	33	33	1		1	64	35	
1	29	29	42	1		29	67	3	
P-4-1	18	59	23*	3.2	.4	0	11	89	2?
2	30	34	36*	1.1	.1	2	48	54	3
3	30	28	42*	.9	.1	TR	31	69	3
4	34	20	46*	.5	0	TR	30	70	2
P-5-1	41	20	39*	.4	.2	TR	28	72	3
2	46	17	37	.3	.1	2	42	56	3
3	39	34	27*	.8		TR	29	71	3
P-6-1	32	25	43	.7	.8	TR	37	62	3
2	30	31	39*	1.0		TR	25	75	3
3	20	51	29*	2.5	.4	TR	19	81	2
4	17	46	37*	2.7	.1	1	42	57	2
P-8-1	42	29	29*	.7		2	30	68	3
2	40	29	31*	.7		2	21	77	3
3	36	18	45	.5		1	38	61	3
4	50	25	25*	.5		1	29	76	3
5	43	14	43	.3		2	15	83	3
6	44	22	33	.5		2	37	61	3
7	20	39	42			TR	20	81	2?

Sample	Ill	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
P-9-1	35	28	35*	.8		21	30	49	3
2	36	27	36	.7		3	25	73	3
3	16	33	50*	1.8		4	55	41	3
P-10-1	37	0	62*	<1		4	28	68	3
2	50	0	50*	<1		2	15	83	3
3	44	0	56*	<1		4	16	80	3
4	27	27	45*	1		2	9	89	3
5	42	29	29	.5		1	21	78	3
6	20	43	37*	2.1		3	12	85	2
P-11-1	27	27	36	1		27	24	49	3
2	38	27	33	.7		22	23	55	3
3	42	21	35	.5		14	28	58	3
4	23	52	23*	2.2		2	15	83	2
5	21	50	28*	2.3		15	13	72	2
P-12-1	62	0	37			1	30	69	3
2	30	15	53	.2		1	38	61	3
3	25	37	37	1.4		2	35	63	3
P-14-1	32	27	41*	.8	.1	2	33	64	3
2	39	41	20*	1.0	.2	0	20	80	3
3	40	18	42	.4	.1	TR	25	75	3
P-18-1	36	27	36	.7		TR	33	67	3
2	26	33	40	1.2		TR	31	69	3
3	23	23	53	1		1	26	73	3
4	27	27	45	1		3	35	62	3
5	33	33	33	1		3	58	39	3
6	33	25	41	.7		2	52	46	3
P-28-1	29	24	47*	.8	.3	4	42	54	3?
2	53	16	31*	.3	.3	2	31	68	3
3	24	31	45*	1.3	.4	1	38	62	3
M-8-1	33	22	44*	.6		5	43	52	3?
2	21	51	27*	2.4		1	2	97	2
3	40	39	30*	1.3		5	9	86	1
M-21-1	34	29	37*	.8		3	10	87	1
2	46	22	32*	.5		TR	11	89	1
M-22-1	16	16	66*	1		1	52	47	3
2	33	33	33	1		1	4	95	3
3	21	58	20*	2.8		1	17	82	2
4	13	50	36*	3.8		2	21	77	2
M-30-1	17	52	31*	3		1	12	87	2
2	20	48	32*	2.4		TR	12	88	2



Sample	Ill	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
M-39-1	29	16	55*	.5		2	37	62	3
2	41	24	35*	.5		1	5	93	1?
M-43-1	33	16	50*	.4		3	66	31	3
2	45	18	36*	.4		3	45	52	3
M-56-1	23	23	53	1		3	47	50	3
2	41	8	50	.2		3	45	52	3
M-59-1	53	23	23	.4		4	28	68	3
2	33	16	50*	.5		1	13	86	1?
3	40	10	50	.2		14	20	66	1?
M-67-1	21	52	27*	2.4		1	30	69	2
2	25	49	25*	1.9		2	9	89	2
WR-1-1	21	50	28*	2.3		1	23	77	2
2	32	36	32*	1.1		TR	18	82	1?
3	17	53	28*	3.1		3	20	77	2
4	35	25	40*	.7		1	29	70	1
5	31	27	42*	.8		TR	27	73	1
WR-2-1	21	42	36*	2		1	24	75	2
2	16	38	44	2.3		2	40	58	2?
3	20	41	39	2.0		1	17	82	2
4	17	41	42*	2.3		TR	12	88	2
WR-4-1	41	26	33*	.6		TR	20	80	3
2	39	29	32	.7		3	19	78	3
3	42	30	28*	.7		2	25	73	3
4	19	59	22*	3		0	3	97	2
WR-5-1	16	41	33*	2.8		1	38	61	2
2	20	32	48*	1.6		2	40	58	1
3	39	21	40*	.5		0	12	88	1
4	42	20	38*	.4		TR	11	89	1
5	35	34	30*	.9		1	21	78	1
WR-7-1	29	28	43*	.9		2	23	75	3
2	41	31	27*	.7		TR	27	73	3
3	30	31	39	.9		TR	30	70	3
4	15	56	28*	5.4		0	12	88	2
5	13	49	33*	2.8		0	22	78	2
6	20	46	34*	2.2		TR	13	87	2
7	39	31	30*	.8		3	21	76	1
WR-9-1	38	22	40	.5		TR	15	86	3
2	17	59	24*	3.4		TR	15	85	2
3	20	64	16*	3.2		0	10	90	2
4	19	68	22	3.5		1	18	82	2
5	18	61	21*	3.3		0	9	91	2
6	17	69	13	4		TR	13	87	2
7	36	18	45*	.5		2	19	79	1?
8	17	68	16*	4		TR	19	81	2

Sample	Ill	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
WR-10-1	25	45	29*	1.8		TR	14	86	3
2	36	31	31*	.8		TR	7	93	3
3	23	38	38*	1.6		2	14	84	3
4	29	37	36	1.2		TR	11	89	3
WR-12-1	45	9	45*	.2		1	26	74	3
2	38	15	46*	.4		1	12	87	3
3	38	23	38	.8		1	18	82	3
4	20	40	40	2		1	31	68	2?
WR-13-1	46	20	33*	.5		1	14	85	3
2	18	50	31*	2.7		1	23	76	2
3	0	62	37*	>2		2	28	70	2
4	21	56	23*	2.8		1	17	82	2
5	24	49	27*	2					
WR-21-1	43	12	43	.2	.3	1	16	83	3
2	75	25	0	.3	.1	TR	28	72	3
3	15	53	31*	3.5	.9	1	21	78	2
4	40	28	31*	.2	.7	1	19	80	1?
5	16	53	30*	3.5	.2	TR	24	76	2
6	13	67	18*	4.8	.8	1	23	76	2
7	40	20	40*	.5	.5	1	17	82	1
WR-22-1	16	64	20*	4	.6	1	7	89	2
2	14	58	28*	4.1	.6	1	11	88	2
3	28	57	15*	.8	.7	2	31	67	2
4	13	72	13*	5.5		2	11	87	2
WR-23-1	15	48	36*	2.8		TR	5	95	2
2	18	47	34*	2.1		TR	1	99	2
3	58	16	25*	.2		0	23	77	3?
4	23	46	30*	2		TR	10	90	2
5	18	51	33*	3.5		2	25	73	2
6	38	15	46*	.4		TR	8	92	1?
7	15	51	33	3.4		1	11	88	2
8	27	51	21*	1.8		1	12	88	2
WR-24-1	16	63	20*	3.9		TR	7	93	2
2	26	52	22*	2		1	6	93	2
3	18	60	22*	3.3		TR	14	86	2
4	25	43	31*	1.7		0	13	87	2
5	9	76	14*	8.5		1	6	93	2
6	10	66	23*	6.6		TR	15	85	2
7	21	63	15*	3		TR	18	82	2
8	17	56	26*	3.2		1	17	82	2
9	33	33	33*	1		1	21	78	1
10	35	21	42	.6		TR	42	58	1
11	38	31	31*	.8		3	22	78	1

Sample	Ill.	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
WR-25-1	17	58	24*	3.4		3	26	71	2
2	22	60	18*	2.2		1	17	82	2
3	17	67	15*	3.9		TR	15	85	2
4	15	62	22*	4.1		TR	26	74	2
5	17	56	26*	3.2		TR	17	83	2
6	21	57	21*	2.7		TR	23	77	2
7	32	26	41*	.8		TR	15	85	1
8	22	49	23*	2.2		1	11	88	2?
9	24	46	30*	1.9		1	20	79	1
10	28	37	34*	1.3		1	21	78	1
WR-26A-1	31	34	35*	1.1		3	14	83	3
2	38	29	43*	.7		TR	10	90	3
3	47	39	15	.8		TR	9	91	3
4	30	31	29	1.0		4	21	76	3
5	21	48	20*	2.2		0	9	91	2
6	18	61	20*	3.4		TR	13	87	2
WR-26-1	32	26	42*	.8		4	21	75	3
2	33	31	36*	.9		2	8	90	3
3	41	27	31*	.6		TR	12	89	3
4	39	30	31*	.7		4	18	77	3
5	30	42	27*	1.4		TR	8	92	3
6	21	61	38*	2.9		1	12	87	2
7	17	59	24*	3.4		TR	10	90	2
8	19	64	17*	3.3		TR	13	88	2
9	20	51	28*	2.5		TR	20	79	2
WR-27-1	42	28	28*	.6		TR	28	72	3
2	31	36	33*	1.1		TR	17	83	3
3	40	31	29*	.7		1	10	89	3
4	30	36	33*	1.2		TR	13	87	3
5	21	42	38*	2.1		TR	17	83	2
6	20	59	21*	2.9		0	10	90	2
7	16	61	23*	3.8		0	11	89	2
8	21	58	21*	2.8		TR	11	89	2
9	29	42	29*	1.4		2	16	82	1?
10	20	49	31*	2.4		1	9	90	2?
11	31	29	41*	.9		1	8	91	1
WR-28-1	36	31	33*	.8		1	9	91	3
2	39	25	36*	.6		TR	11	89	3
3	27	31	42	1.1		1	12	87	3
4	28	20	51	.7		TR	10	89	3
5	20	49	32*	2.4		TR	8	92	2
6	18	68	14*	3.7		TR	17	83	2
7	31	61	7*	1.9		TR	12	88	1?
8	22	42	36*	1.9		1	11	88	1?
9	17	67	14*	3.8		1	18	81	2

Sample	Ill	Mont	K & C	M/I	Crys Mont	Sand	Silt	Clay	Unit
WR-29-1	40	30	30*	.7	.4	TR	29	71	3
4	59	16	25	.2	.1	TR	52	48	3
5	14	66	20*	4.7	.8	TR	20	80	2
7	25	25	50*	1	.3	TR	24	76	3?
9	10	60	30*	5	.2	0	42	58	2
10	22	61	17*	2.7	.7	TR	4	96	2
11	31	26	45*	.6	.1	1	9	90	1
12	21	45	34*	2.1	.8	2	9	89	2?
WR-30-1	31	46	23*	2		TR	16	84	3
3	24	59	17*	2.5		1	21	79	2
7	17	59	24*	3.4		TR	18	82	2
10	19	68	13*	3.6		0	3	97	2
13	49	31	20*	.6		TR	8	91	1
WR-31-1	22	52	26*	2.5		1	8	91	2
3	17	72	11*	4.3		2	13	85	2
7	20	69	11*	3.5		TR	11	89	2
10	32	19	49*	.6		1	20	80	1
13	38	37	24*	.9		TR	9	90	1
WR-32-1	36	30	34*	.8		1	28	71	3
3	26	53	31*	2		0	12	88	2
7	21	68	31*	3.3		TR	17	83	2
10	20	59	21*	2.9		TR	9	91	2
14	32	38	30*	1.2		TR	13	87	1
WR-33-1	17	49	34*	2.7		3	31	66	2

APPENDIX G  
DRILL HOLE LOGS

The following are logs of holes drilled and described by Dr. J. Teller. The holes are identified by two letters: the first corresponding to the letter of the 1:250,000 map the hole is located in, the second referring to the specific location on that sheet.

<u>Hole No.</u>	HA	<u>Location:</u> LSD4-5-3-3W 4 miles east of Winkler, Manitoba
<u>Depth (ft.)</u>		<u>Lithology</u>
0-4		Silty sand, tan, calcareous, pebbly near base, lower boundary distinct.
4-6		Sand, yellow brown, calcareous.
6-21		Slightly silty clay, mottled yellowish brown and blue gray, oxidized-unoxidized boundary gradational from $\pm 15$ - $\pm 21$ ft.
21-101		Silty clay, blue-gray clay, light gray silty blebs (more calcareous than clay), lower 10 ft. tougher, no laminations visible, very plastic so that cannot be broken

Total depth of hole

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
12	HA-1
26	HA-2
37	HA-3
45	HA-4
55	HA-5
70	HA-6
80	HA-7
99	HA-8

Hole No. HB Location: LSD15-13-2-1W  
4 miles northeast of  
Altona, Manitoba

<u>Depth (ft.)</u>	<u>Lithology</u>
0-15	Clayey silt, grading downward into silty clay, mottled yellow brown and gray, white calcareous nodules and coarse grains of sand in lower part, matrix weakly calc., lower boundary gradational.
15-90	Slightly silty clay, blue gray with occ. white non-calc. nodules gradually decreasing downwards, calc. silty blebs (and 2 dolomite pebbles) scattered throughout lower 50 ft., very plastic so that cannot be broken, no laminations visible.

Total depth of hole

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
4	HB-1
8	HB-2
14	HB-3
26	HB-4
36	HB-5
45	HB-6
55	HB-7
73	HB-8
80	HB-9
89	HB-10

<u>Hole No.</u>	HC	<u>Location:</u> LSD3-26-1-3E 6 miles northeast of Emerson, Manitoba
<u>Depth (ft.)</u>		<u>Lithology</u>
0-5		Sandy and silty clay, occ. nodules of CaCO <sub>3</sub> , gray, lower boundary indistinct.
5-12		Sli. silty clay, occ. CaCO <sub>3</sub> nodules, mottled yellowish brown and gray, laminated with clayey silt.
12-17		Sli. silty clay, mottled yellowish brownish gray, no laminations visible, occ. nodules and blebs of CaCO <sub>3</sub> .
17-100		Sli. silty clay, gray occ. blebs of CaCO <sub>3</sub> , two dolomite pebbles at 60-65 ft., very plastic in nature so cannot be broken, no laminae visible.

Total depth of hole

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
4	HC-1
8	HC-2
18	HC-3
28	HC-4
35	HC-5
45	HC-6
55	HC-7
65	HC-8
98	HC-9

Hole No. HD Location: LSD4-22-1-4E  
12 miles northeast of  
Emerson, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-2	Sand, boulders on surface.
2-8	Silty till, somewhat sandy in lower foot, mottled yellow brown and gray.
8-12	Sand with pebbles increasing towards base of unit, mottled yellow brown and tan.
12-33	Clayey till, gray.
23-24	Silty sand, dark gray, possibly with fine disseminated organic material, calcareous, no bedding visible.
24-36	Slightly silty clay, tough, bluish gray, calcareous, laminae of silty clay throughout.
36-47	Silty sand, calcareous, gray, no bedding noted.
47-49	Silty clay, gray, weakly calc., laminae not visible.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
30	HD-1
48	HD-2

Hole No. HG Location: LSD14-1-2-8E  
18 miles east of Tolstoi,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-8	Sand grading down into silty sand, bedded.
8-9	Small pebble and granule gravel.
9-12	Silty sand grading downward into pebbly silty sand (till?).



- 12-13 Silty clay (medium dark gray), laminated with clayey silt, (light gray) calcareous, upper and lower boundary distinct.
- 13-20 Till, upper two ft. silty clay, grading downward into a silty, sandy till, no noticeable break in this transition, calcareous gray.
- 20-30 Cobbles or boulders (not seen).
- Total depth of hole.

Depth (ft.)Samples used in this Study

12

HG-1

Hole No.

HH

Location: LSD14-6-2-10E  
24 miles east of Tolstoi,  
Manitoba.

Depth (ft.)Lithology

- 0-5 Silty sand, granules and pebbles scattered throughout, no bedding noted, lower boundary distinct.
- 5-26 Silty fine to medium grained sand, calcareous, bluish-gray, no bedding observed, becoming sandy silt downward with numerous coarse grains and granules, lower boundary distinct.
- 26-28 Silty sand (near top) to slightly sandy silt with occ. coarse grains and small granules, two mollusk shells.
- 36-37 Silty clay (dark gray), with clayey silt (light gray) laminae, lower boundary distinct.
- 37-43 Slightly silty clay, dark gray to gray, occ. pebbles in lower foot, lower boundary gradational.
- 43-45 Slightly silty and sandy clay with pebbles (till?), grading downward into clayey till (pebbly silty sandy clay).
- Total depth of hole

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
36	HH-1
32	HH-2

Hole No. HP      Location: LSD3-21-4-10E  
3 miles north of  
Woodridge, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-1	Sand, very clayey in lower half, leached.
1-3	Sandy silty gravel, calc.
3-5	Sand, silty.
5-9	Gravelly sand at top grading downward into sandy, silty gravel.
9-28	Till, silty in upper part grading downward into clayey till.
28-61	Clayey silt with granules.
61-75	Gravelly sand, grading downward into very sandy fine grained gravel (predom. granules and coarse sand).
75-83	Silt and very fine sand, lower boundary gradational over one foot.
83-100	Sand, fine to medium grained.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
35-50	HP-1

Hole No. HS      Location: LSD13-4-9-6E  
Dufresne, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-28	Clay, weakly calc., dark gray, occ. granules and calc. silty blebs, silty laminae near base.

28-37	Till, silty, tan ("pinkish" in contrast to overlying clay).
37-40	Till, clayey, gray.
40-44	Clay, calc., dark brownish gray.
41-65	Till, gray, hard, stoney below 50 ft.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
8	HS-1
21	HS-2
25	HS-3
40	HS-4

Hole No.                      GA                      Location: LSD19-12-3-5W  
5 miles east of Morden,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-14	Silty sand and sandy silty clay, laminated.
14-26	Sli. clayey silt, occ. grains and granules, laminated, dark gray, lower boundary distinct.
26-60	Silty clay grading down to sli. silty clay clay, no laminations visible, bluish gray, occ. light coloured blebs of calcareous silt, lower boundary indistinct, plastic.
60-73	Sli. silty sandy clay, occ. pebbles, dark gray, no laminations visible, lower boundary gradational.
73-83	Sli. silty clay, occ. grains and pebbles, laminations not visible, dark gray, scattered light gray blebs.
83-87	Sandy silty clay with granules (till?), very dark gray, dry, lower boundary distinct.
87-90	Silty clay, very dark gray, dry, calcareous, appears shale-like but includes occ. white grains.

90-95

Calc. dry clay (shale?) crude oil  
smell.

Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
15	GA-1
19	GA-2
24	GA-3
28	GA-4
39	GA-5
47	GA-6
55	GA-7
60-65	GA-8
65-69	GA-9
70-73	GA-10
77	GA-11
90	GA-12

Hole No.

EA

Location: LSD16-19-1-13E  
7 miles west of Sprague,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-10	Sand, some granules, calcareous, bedded.
10-11	Silt, no laminations visible.
11-13	Till, sandy, calc., tan.
13-27	Sand to silty sand, poorly bedded.
27-38	Sandy silt, laminations visible in upper 2 ft., tan.
38-70	Silt to sli. sandy silt, grades into clayey silt at about 60 ft., no laminations visible, gray, calc.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
45	EA-1
55	EA-2
64	EA-3
69	EA-4

Hole No. EB      Location: LSD16-8-8-12E  
7 miles southwest of  
Prawda, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-5	Sand, calc.
5-6	Sandy gravel.
6-8	Silt grading down into clayey silt, calc., gray.
8-20	Sli. silty clay (dark gray) laminated with silt (light gray) in upper few feet, non-calc., pebbles, till balls and silt balls scattered through lower 5 ft.
20-45	Silty, sandy till, gray.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
8	EB-1
10	EB-2
16	EB-3

The following are logs of holes drilled and described by the Water Resources Branch prior to 1973. They are identified by the letters WR followed by a number less than 20.

<u>Hole No.</u>	WR-1	<u>Location:</u> NE24-9-3W Bryson Dr. East
<u>Depth (ft.)</u>		<u>Lithology</u>
0-2		Fill.
2-24		Clay; brown, pure.
24-52		Clay; gray, laminated, pure.
52-55		Gravel, sand.
55-71		Till; medium gray to medium brown.
71-80		Gravel; fine.
		Total depth of hole.
<u>Depth (ft.)</u>		<u>Samples used in this Study</u>
15-16		WR-1-1
20-21		WR-1-2
25-26		WR-1-3
30-31		WR-1-4
40-41		WR-1-5

<u>Hole No.</u>	WR-2	<u>Location:</u> NE23-9-4W Bryson Dr. East
<u>Depth (ft.)</u>		<u>Lithology</u>
0-4		Fill; clay, gray.
4-38		Clay; brown, medium, pure.
38-46		Clay; gray.
		Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-11	WR-2-1
25-26	WR-2-2
35-36	WR-2-3
45-46	WR-2-4

Hole No.                      WR-4                      Location: 12-6-4W  
Bunn's Creek

<u>Depth (ft.)</u>	<u>Lithology</u>
0-27	Clay; brown.
27-50	Clay; gray.
50-55	Gravel, silt, sand.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
20-21	WR-4-1
25-26	WR-4-2
30-31	WR-4-3
35-36	WR-4-4

Hole No.                      WR-5                      Location: 24-13-3W  
Assiniboine River

<u>Depth (ft.)</u>	<u>Lithology</u>
0-2	Fill.
2-12	Sand, gravel, bedded coarse, fine.
12-15	Sand.
15-21	Clay; brownish gray.
21-39	Clay; gray, dark, plastic.
39-55	Till; brownish buff.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
15-16	WR-5-1
20-21	WR-5-2
25-26	WR-5-3
30-31	WR-5-4
35-36	WR-5-5

Hole No. WR-7      Location: 3-8-4W  
PTH 21, PL 393, R.M. Woodworth

<u>Depth (ft.)</u>	<u>Lithology</u>
0-3	Fill.
3-16	Clay; brownish gray.
16-77	Clay; gray, pure.
77-90	Till.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-11	WR-7-1
20-21	WR-7-2
30-31	WR-7-3
40-41	WR-7-4
60-61	WR-7-5
65-66	WR-7-6
75-76	WR-7-7

Hole No. WR-9      Location: 8-3-3W  
R.M. Rhineland

<u>Depth (ft.)</u>	<u>Lithology</u>
0-2	Fill.
2-18	Clay; brown, streaked.
18-74	Clay; gray, dark, plastic.
	Total depth of hole.



<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-11	WR-9-1
15-16	WR-9-2
25-26	WR-9-3
30-35	WR-9-4
50-55	WR-9-5
65-66	WR-9-6
70-71	WR-9-7

Hole No. WR-10      Location: NE5-4-2E  
Lafond Dr.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-21	Clay; brown.
21-53	Clay; gray.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
15-16	WR-10-1
25-26	WR-10-2
35-36	WR-10-3
45-46	WR-10-4

Hole No. WR-12      Location: NE19-9-3W  
Bryson Dr. East

<u>Depth (ft.)</u>	<u>Lithology</u>
0-6	Fill; gravel, clay.
6-16	Clay; brown.
16-20	Clay; gray.
20-21	Clay; brown, slightly silty.
21-56	Clay; gray, pure.
56-60	Till; brown.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-11	WR-12-1
15-16	WR-12-2
25-26	WR-12-3
30-31	WR-12-4

Hole No.                 WR-13                 Location:   E21-9-2W  
  Bryson Dr. Branch

<u>Depth (ft.)</u>	<u>Lithology</u>
0-2	Fill.
2-3	Gravel.
3-17	Clay; brownish gray, pure.
17-54	Clay; gray, pure, slightly silty in lower.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
15-16	WR-13-1
20-21	WR-13-2
25-26	WR-13-3
35-36	WR-13-4
45-46	WR-13-5

The following are general lithologic descriptions of holes drilled and described by the Water Resources Branch. These holes were used for their soil mechanics data only. No samples were provided.

Hole No.                 ED-3                 Location:   SE35-3-1E  
  1 mile east of St. Jean  
  Baptiste, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-15	Clay, brownish gray, highly plastic, hard.

15-50		Clay, brown, highly plastic with light and dark silt pockets, very stiff.
<u>Hole No.</u>	ED-1	<u>Location:</u> NE32-6-3E 6 miles southeast of St. Agathe, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-6		Fill.
6-15		Clay, light brown, highly plastic, slightly silty.
15-25		As above, brown.
25-30		As above, gray.
30-35		As above, brown.
35-50		Clay, slightly silty, plastic, light gray.
<u>Hole No.</u>	ED-2	<u>Location:</u> NE35-3-1E 1 mile east of St. Jean Baptiste, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-30		Clay, grayish brown, highly plastic, stiff.
30-50		Clay, gray, highly plastic.
<u>Hole No.</u>	ED-5	<u>Location:</u> SW2-5-2E 4 miles northeast of Morris, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-20		Clay, highly plastic, very stiff, brown.
20-40		Clay, highly plastic, gray.
40-60		Clay, slightly silty, very stiff, gray.
<u>Hole No.</u>	ED-6	<u>Location:</u> SW1-5-2E 4 miles northeast of Morris, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-20	Clay, highly plastic, very stiff, brown, some sand.
20-35	Clay, more sand, highly plastic, very stiff, gray.
35-60	Clay, some sand, gray.
60-70	Clay, stiff to hard, gray.
70-80	Till.

Hole No.                    ED-7                    Location: NE2-7-3E  
1 mile east of St. Agathe,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-10	Fill.
10-25	Clay, stiff, slightly silty.
25-45	Clay, stiff, plastic, brown to gray.

The following are logs of holes drilled by the Water Resources Branch during 1973 and logged by J. Little. The holes are identified by the letters WR followed by a number greater than 20.

Hole No.                    WR-21                    Location: SE36-7-3W  
14 miles northeast of  
Carman, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-4	Fill.
4-25	Clay, brown, slightly silty at 4-10.
25-72	Clay, gray, pure.
72-84	Till, medium gray, slightly stoney.
84-98	Till, gray, hard.
98-108	Clay, gray firm, hard; 105-110: pebbly clay.

108-120	Till, brownish gray, very clayey.
120-130	Till, brownish gray, stoney.
130-133	Gravel, fine.
133-137	Till, brown.
137-144	Till.
144-171	Bedrock, limestone and shale.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-20	WR-21-1
20-30	WR-21-2
30-40	WR-21-3
40-50	WR-21-4
50-60	WR-21-5
60-70	WR-21-6
70-72	WR-21-7

Hole No. WR-22      Location: NW1-8-1W  
4 miles south of Sanford,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-2	Fill.
2-18	Clay, brown, pure.
18-49	Clay, gray, pure.
49-59	Till, cream brown, sandy.
59-180	Bedrock, limestone, shale.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5-10	WR-22-1
15-20	WR-22-2
35-40	WR-22-3
45-49	WR-22-4

Hole No. WR-23      Location: NW6-8-3E  
2 miles west of Glenlea,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-6	Fill.
6-22	Clay, brown, dark.
22-52	Clay medium gray, soft, plastic.
52-68	Till, dark grayish brown.
68-71	Till, light cream brown.
71-90	Bedrock, limestone.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-23-1
15-20	WR-23-2
20-25	WR-23-3
25-30	WR-23-4
30-35	WR-23-5
35-40	WR-23-6
40-45	WR-23-7
45-50	WR-23-8

Hole No. WR-24      Location: SE1-6-1W  
1 mile west of Rosenort,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-5	Fill, gray clay.
5-21	Clay, dark brown, at 10 ft. softer.
21-78	Clay, gray, soft, plastic.
78-86	Till, light gray, mixed stoney mud.
86-95	Till, dark gray, more clayey, 90-95 grades to a brownish gray.

95-107	Till, medium gray, clayey.
107-111	Bedrock, limestone.
<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-24-1
20-25	WR-24-2
25-30	WR-24-3
30-35	WR-24-4
35-40	WR-24-5
40-45	WR-24-6
50-55	WR-24-7
60-65	WR-24-8
70-75	WR-24-9
75-80	WR-24-10

Hole No. WR-25      Location: SE6-6-2W  
12 miles southwest of  
Carman, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-8	Fill.
8-28	Clay, medium brown, pure.
28-102	Clay, gray, pure.
102-132	Till, light gray.
132-135	Clay?
135-172	Till, dark brownish gray, sandy.
172-186	Till, dark gray.
186-192	Till, bouldery.
192-200	Gravel, coarse, well rounded.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-25-1
20-25	WR-25-2
30-35	WR-25-3
40-45	WR-25-4
50-55	WR-25-5
60-65	WR-25-6
70-75	WR-25-7
80-85	WR-25-8
90-95	WR-25-9
100-102	WR-25-10

Hole No. WR-26A      Location: SE6-6-4W  
4 miles south of Carman,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-3	Fill.
3-19	Clay, brown, pure.
19-36	Clay, dark gray and brown, layered, pure.
36-40	Clay, silty, brown.
40-60	Clay, gray, pure.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5-10	WR-26A-1
10-15	WR-26A-2
20-25	WR-26A-3
30-35	WR-26A-4
40-45	WR-26A-5
50-55	WR-26A-6
55-60	WR-26A-7



Hole No. WR-26      Location: SW8-6-4W  
3 miles south of Carman,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-1	Topsoil.
1-19	Clay, brown, soft.
19-33	Clay, gray, soft.
33-37	Clay, gray-brown with silty layers.
37-84	Clay, gray, soft.
84-103	Till, dark gray, boulders.
103-105	Gravel.
105-107	Till, dark gray.
107-108	Sand and gravel.
108-119	Till, gray with layers of sand and gravel.
119-121	Sand and gravel.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5-10	WR-26-1
10-15	WR-26-2
20-25	WR-26-3
30-35	WR-26-4
40-45	WR-26-5
50-55	WR-26-6
60-65	WR-26-7
70-75	WR-26-8
80-84	WR-26-9

Hole No. WR-27 Location: SE2-4-1E  
1 mile west of St. Jean  
Baptiste, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-4	Clay, black.
4-19	Clay, brown.
19-22	Clay, gray.
22-29	Clay, brown.
29-106	Clay, gray.
106-110	Till, light gray.
110-113	Gravel, medium.
113-127	Till, gray medium.
127-161	Till, light gray, sandy.
161-174	Till, gray, clayey.
174-176	Till, reddish brown.
176-178	Till, gray, sandy.
178-243	Bedrock, limestone, shale.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5-10	WR-27-1
10-15	WR-27-2
20-25	WR-27-3
30-35	WR-27-4
40-45	WR-27-5
50-55	WR-27-6
60-65	WR-27-7
70-75	WR-27-8
80-85	WR-27-9
90-95	WR-27-10
100-105	WR-27-11

Hole No. WR-28      Location: NE5-4-1W  
10 miles west of St. Jean  
Baptiste, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-6	Dike fill.
6-22	Clay, brown.
22-92	Clay, gray.
92-94	Sand and gravel.
94-123	Till, light brownish gray, sandy with boulders.
123-137	Till, dark gray, clay.
137-176	Till, brownish gray.
176-195	Till, light gray, sandy, soft.
195-202	Gravel and till.
202-250	Bedrock, shale and limestone.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-28-1
20-25	WR-28-2
30-35	WR-28-3
40-45	WR-28-4
50-55	WR-28-5
60-65	WR-28-6
70-75	WR-28-7
80-85	WR-28-8
90-92	WR-28-9

Hole No. WR-29      Location: NW35-3-3W  
8 miles northeast of  
Winkler, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-16	Clay, brown, dark-medium.
16-113	Clay, gray.
113-126	Clay, light gray.
126-132	Till, brownish gray.
132-152	Till, dark gray.
152-153	Gravel.
153-165	Till, "gritty" at 162-165 ft.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-29-1
40-45	WR-29-4
50-55	WR-29-5
70-75	WR-29-7
90-95	WR-29-9
100-105	WR-29-10
110-115	WR-29-11
120-125	WR-29-12

Hole No. WR-30      Location: SE3-2-1E  
8 miles east of Altona,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-1	Topsoil.
1-16	Clay, grayish brown.
16-127	Clay, gray, soft.
127-131	Till, gray.

131-132	Gravel.
132-161	Till, gray.
161-178	Till, gravelly, light gray.
178-180	Gravel, coarse.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-30-1
30-40	WR-30-3
70-80	WR-30-7
100-110	WR-30-10
120-127	WR-30-12

Hole No. WR-31      Location: LSD3-1-2-2W  
3 miles west of Altona,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-14	Clay, brown.
14-142	Clay, gray.
142-147	Till, light gray, silty.
147-154	Till, dark gray, hard.
154-155	Gravel, fine.
155-165	Till, dark gray, hard.
165-172	Till, brownish gray, silty.
177-180	Bedrock, limestone.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-31-1
30-40	WR-31-3
70-80	WR-31-7
100-110	WR-31-10
130-140	WR-31-13

Hole No. WR-32      Location: LSD3-2-2-3W  
10 miles west of Altona,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-13	Clay, brown.
13-40	Clay, gray.
40-166	Till, light gray.
166-175	Clay, silty, dark gray.
175-182	Clay, dark gray, hard, pebbly.
182-213	Till, dark gray, very clayey.
213-231	Till, medium gray, very silty.
231-234	Till? silty, clayey, gray.
234-236	Till, shaley.
266-281	Till, very shaley.
281-284	Bedrock, shale, brown.
415	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	WR-32-1
30-40	WR-32-3
70-80	WR-32-7
100-110	WR-32-10
130-140	WR-32-14

Hole No. WR-33      Location: LSD1-1-2-5W  
20 miles west of Altona,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-1	Topsoil.
1-9	Sand, brown, fine.
9-18	Sand, gray, fine.

18-29	Clay, gray, soft.
29-42	Till, dark gray, sandy.
42-46	Gravel.
46-107	Till, dark gray, very silty, bouldery.
107-242	Bedrock, shale.
441	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
20-30	WR-33-1

The following are logs of holes drilled and described by Fenton (1970). The holes are identified by the letter P followed by a number.

Hole No.                      P4                      Location: SW22-13-7W  
10 miles northwest of Portage,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-5	Interbedded sand and clay; sand medium to fine-grained, grayish-brown (2.5Y5/2 wet), clay olive-gray (5Y5/2 wet), soft, calcareous.
5-10	Clay; silty, occasional granules and dark specks, olive-gray (5Y5/2 wet), calcareous, occasional iron staining.
10-20	Clay; silty, dark grayish-brown (2.5Y4/2 wet), abundant pebbles and light grayish-brown silt clasts, thin colour banding, calcareous.
20-27	Clay; very silty, dark grayish-brown (2.5Y4/2 wet), abundant pebbles and silt and till clasts ( 1/2 in.), massive, calcareous.
27-56	Till; sandy, stoney, silty, clayey, grayish-brown (2.5Y4/2 wet), calcareous.

56-74	Till, sandy, silty, stoney, clayey, calcareous.
74-75	Clay, silty, calcareous.
75-120	Till; silty, sandy, clayey, stoney, calcareous.
120-130	Bedrock, gypsum and dolomite.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5	P-4-1
10	P-4-2
15	P-4-3
20	P-4-4

Hole No. P5      Location: SW22-13-8W  
14 miles northwest of Portage,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-5	Silt; clayey, olive-gray to grayish-brown (3.75Y5/2 wet), occ. iron staining, thin colour banding, soft, calc.
5-10	Clay; silty, interbedded dark gray (5Y4/1 wet), organic rich and olive-gray (5Y5/2 wet) layers, occ. granules and shell fragments, soft, calc.
10-15	Clay; silty, grayish-brown (2.5Y5/2 wet), occ. stone and buff clay clasts and gypsum crystals.
15-28	Clay; silty, grayish-brown (2.5Y5/2 wet), occ. stones and buff clay clasts colour banded; each band laminated, the silt, stones and clasts concentrated in the lighter bands.
28-30	Till; clayey, silty, stoney, sandy, grayish-brown (2.5Y5/2 wet), calc.
30-60	Till; sandy, silty, stoney, clayey, dark grayish-brown (2.5Y4/2 wet), calc.



60-66	Clay?
66-75	Gravel.
75-86	Till; sandy, silty, stoney, clayey, calc.
86-98	Till; as above with sand.
98-115	Till; very sandy, calc.
115-150	Bedrock; clay, limestone.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10	P-5-1
15	P-5-2
20	P-5-3

Hole No. P6      Location: SW26-13-9W  
18 miles northwest of  
Portage, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-23	Clay; silty, grayish-brown (2.5Y5/2 wet), occ. (i) stones, (ii) light grayish-brown silt and till clasts, and (iii) buff and pink clay clasts, colour banded, bands laminated with stones, etc., concentrated in the lighter bands, occ. gypsum crystals, calc.

23-45      Till; sandy, silty, stoney, clayey, grayish-brown to dark grayish-brown (2.5Y4/2), calc.

Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
7	P-6-1
10	P-6-2
15	P-6-3
20	P-6-4

<u>Hole No.</u>	P8	<u>Location:</u> SE16-12-8W 6 miles northwest of Portage, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-5		Silt to very fine-grained sand; grayish-brown to olive-gray (3.75Y5/2 wet), laminated, calc.
5-20		Clay; silty, dark grayish-brown (2.5Y4/2 wet), colour banded, bands laminated, occ. gypsum crystals, light gray and pink clay, clasts and pebbles, calc.
20-50		Clay; silty, dark olive-gray (5Y3/2 wet), laminated, loc. silt rich laminae, buff and light gray clay clasts and pebbles, laminae in some cases appear to be rythmite couplets, calc.  -from 50 feet, rotary chips.
50-65		Clay, as above, silt content increasing with depth, calc.
65-78		Silt; clayey, dark gray (5Y4/1 wet), laminated, occ. silt and till clasts, stones at 74 ft., calc.
78-80		Gravel, sandy, light grayish-brown (2.5Y5/2 wet), calc.
80-87		Till; sandy, silty, stoney, calc.
87-130		Clay, silty, laminated, calc.
130-137		Clay; silty, calc.
137-153		Till; sandy, silty, stoney, calc.
153-193		No sample.
193-200		Bedrock, dolomite.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	P-8-1
20-25	P-8-2
25-30	P-8-3

30-40	P-8-4
40-45	P-8-5
45-50	P-8-6
60-65	P-8-7

Hole No. P9      Location: SW15-12-7W  
5 miles northwest of  
Portage, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-6	Silt; clayey, dark grayish-brown (2.5Y <sub>4</sub> /2 wet), iron stained spots, soft, calc.
6-37	Sand; medium to coarse grained, well-sorted, dark grayish-brown (2.5Y <sub>4</sub> /2 wet), occ. mollusk and wood fragments, black organic and clay rich 25-27 ft., calc.
37-45	Clay; silty, olive-gray to grayish-brown (3.75Y <sub>5</sub> /2 wet), colour banding, bands laminated, loc. stones and buff and light gray clay clasts, calc.
45-55	Clay; silty, dark olive gray (5Y <sub>3</sub> /2 wet), laminated, occ. buff clay and silt clasts.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
37-40	P-9-1
46-50	P-9-2
50-55	P-9-3

Hole No. P10      Location: NW10-12-6W  
5 miles north of Portage,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-3	Disturbed material.
3-10	Silt; clayey, grayish-brown (2.5Y <sub>5</sub> /2 wet), soft, laminated, iron stained areas, calc.

10-13	Sand, medium-grained, grayish-brown (2.5Y5/2 wet), calc.
13-35	Clay; silty, grayish-brown (2.5Y5/2 wet), colour banded, colour darkening to grayish-brown in lower part, laminated, occ. gypsum crystals, calc.
35-50	Clay; silty, dark gray (5Y4/1 wet), occ. silt laminae, some internally bedded occ. light gray and buff clay clasts, sticky, calc.  -from 50 feet, rotary chips.
50-86	Clay; silty, dark gray (5Y4/1 wet), interbedded with light and dark laminated silt, occ. light gray and buff silt clasts, increasing with depth, calc.
86-91	Gravel; sandy, calc.
91-126	Till; sandy, silty, stoney, calc, and sand and clay.
126-147	Bedrock; clay, anhydrite and dolomite.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
13-15	P-10-1
20-25	P-10-2
35-40	P-10-3
45-50	P-10-4
55-60	P-10-5
65-70	P-10-6

Hole No. P11      Location: SE17-12-5W  
6 miles northeast of  
Portage, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-5	Clay; silty, sandy, grayish-brown to olive-gray (3.75Y5/2 wet), laminated, calc.
5-16	Sand, fine to medium-grained grayish-brown to dark grayish-brown (2.5Y4.5/2 wet), occ. pebble, calc.

16-25	Clay, silty, very dark grayish-brown (2.5Y3/2 wet), colour banded, laminated, occ. buff and light gray clay clasts and gypsum crystals, calc.
25-40	Clay; silty, dark gray (5Y4/1 wet), laminated, calc.
40-65	Clay; very silty, dark olive gray (5Y4/2 wet), laminated, occ. pebbles and buff silt and sand clasts, calc.
65-72	Clay; silty, grayish-brown (2.5Y5/2 wet), occ. pebbles and silt and till clasts.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
16-20	P-11-1
25-35	P-11-2
40-50	P-11-3
50-60	P-11-4
65-72	P-11-5

Hole No. P12      Location: SE28-11-8W  
8 miles west of Portage,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-10	Silt; clayey, olive (5Y5/3 wet), laminated, occ. buff pockets and iron stained spots, calc.
10-20	Silt; clayey, dark grayish-brown to grayish-brown (2.5Y4.5/2 wet), colour banded, calc.
20-25	Interbedded silt and very fine sand, very dark gray to light gray, calc.
25-50	Silt; clayey, very dark gray (5Y3/1 wet), colour banded, occ. granule and light gray or brownish-yellow silt clasts, calc.

50-90 Clay; silty, very dark gray (5Y3/1 wet), colour banded, laminated, occ. granules and brownish-yellow clasts, calc.

Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
50-60	P-12-1
70-80	P-12-2
80-90	P-12-3

Hole No. P14      Location: NE9-14-8W  
14 miles northwest of Portage,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-5	Silt; sandy clayey, gray to olive-gray (5Y5/1.5 wet), laminated iron stained, calc.
5-12	Clay; silty, gray (5Y5/1 wet), calc.
12-18	Clay; silty, dark gray to grayish-brown (3.75Y 5/1.5 wet), colour banded, occ. pebbles and buff clay clasts, stiff, calc.
18-29	Clay; silty, grayish-brown (2.5Y5/2 wet), colour banded, occ. pebbles and buff clasts, calc., becomes very sandy and stoney 25-29 ft.
29-40	Till; silty, sandy, stoney, clayey, light grayish-brown (2.5Y6/2 wet), calc.
40-45	Clay; silty, dark grayish brown, colour banded, laminated, occ. till clast and pebble, calc.
45-70	Till; silty, sandy, stoney, clayey, calc.
70-75	Till; as above interbedded with sand and silt.
75-87	Till; very sandy, silty, stoney.
87-105	Bedrock; limestone, dolomite.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
12	P-14-1
15	P-14-2
22	P-14-3

Hole No. P18      Location: NW15-11-6W  
13 miles north of Portage,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-5	Sand; very fine-grained, silty, olive-gray (5Y5/2 wet), laminated, occ. mollusk fragments and medium-grained sand lenses, soft, calc.
5-10	Silt; clayey, olive gray (5Y5/2 wet), laminated, occ. plant fragment, soft, calc.
10-13	Clay; silty, olive to olive gray, laminated, abundant specks of plant material, soft, calc.
13-15	Clay; silty, olive gray (5Y5/2 wet), contains approximately 50% fragments of dark olive clay, calc.
15-29	Clay; silty, dark olive gray to grayish-brown (3.75Y4/2 wet), colour banding, occ. gypsum crystals and iron streaks, calc.
29-30	Silt; clayey, olive gray (5Y5/2 wet), laminated, calc.
30-35	Clay; silty, dark olive gray (5Y3/2 wet), occ. fragments of olive gray clay, occ. light gray silt clasts, calc.
35-50	Clay; silty, dark olive gray (5Y3/2 wet), occ. granule and light gray or pink clay or silt clasts, calc.
50-55	Clay; silty, gray (2.5YN5/ wet), laminated, calc.
55-65	Clay; silty, dark olive gray (5Y3/2 wet), colour banding, laminated?, occ. pebbles and light gray and buff silt to clay clasts, calc.

65-70 Clay as above except occ. lenses or streaks of grayish-brown till, massive.

70-80 Clay; very silty, dark olive gray (5Y3/2 wet), buff and light gray silt to clay clasts, calc.

Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
20-25	P-18-1
35-40	P-18-2
45-50	P-18-3
55-60	P-18-4
65-70	P-18-5
70-80	P-18-6

Hole No. P28 Location: SEL-13-6W  
7 miles northeast of Portage,  
Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-7	Clay; silty, olive-gray (5Y5/2 wet), calc.
7-15	Clay; silty, olive-brown to grayish-brown (2.5Y 4.5/3 wet), occ. stones and silt clasts, laminated, calc.
15-24	Clay; silty, dark grayish-brown (2.5Y4/2 wet), occ. pebbles, laminated.

Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5	P-28-1
10-15	P-28-2
20-24	P-28-3



The following are logs of holes drilled and described by McPherson (1970). The holes are identified by the letter M followed by a number.

<u>Hole No.</u>	M8	<u>Location:</u> SW14-15-10E 3 miles northwest of Lac du Bonnet, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-5		Pale yellowish brown (10Y R 6/2 wet), silty sand.
5-15		Moderate olive brown (5Y 4/4 wet), lake clay silty lenses.
15-33		Light olive gray (5Y 5/2 wet), laminated lake clay, numerous silty lenses and carbonate rock fragments.
33-55		Light olive gray (5Y 6/1 wet), clayey, silty till, more silty with depth.
		Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5	M-8-1
10	M-8-2
20-25	M-8-3

<u>Hole No.</u>	M21	<u>Location:</u> NW12-13-7E 2 miles north of Beausejour, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-5		Moderate yellowish brown (10Y R 5/4 wet), sandy silt.
5-20		Olive gray (5Y 4/1 wet), lake clay, numerous silt pockets.
20-48		Light olive gray (5Y 6/1 wet), calc., silty till, granitic and carbonate rock fragments.
		Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
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10	M-21-1
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15	M-21-2
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<u>Hole No.</u>	M22	<u>Location:</u> SE20-14-8E 12 miles north of Beausejour, Manitoba.
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<u>Depth (ft.)</u>	<u>Lithology</u>
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0-30	Pale yellowish brown (10Y R 6/2 wet), sandy silt to clayey silt.
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30-72	Medium dark gray (N5 wet) lake clay.
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72-93	Light olive gray (5Y 6/1 wet) calc., silty till, carbonate and granitic rock fragments.
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Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
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5	M-22-1
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10	M-22-2
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30-35	M-22-3
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40-60	M-22-4
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<u>Hole No.</u>	M30	<u>Location:</u> NE9-11-6E 12 miles east of Winnipeg, Manitoba.
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<u>Depth (ft.)</u>	<u>Lithology</u>
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0-20	Light olive gray (5Y 6/1 wet) lake clay, silty lenses, minor rock fragments.
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20-24	Pale yellowish orange (10Y R 8/6 wet) calcareous quartz sand.
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24-38	Pale yellowish orange (10Y R 8/6 wet) calc. silty till, numerous carbonate rock fragments.
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Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10	M-30-1
15	M-30-2

Hole No. M39      Location: NE17-12-11E  
8 miles south of Seven Sisters  
Falls, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-4	Pale yellowish brown (10Y R 6/2 wet) silty lake clay.
4-12	Medium dark gray (N4 wet) massive, lake clay.
12-85	Light olive gray (5Y 6/1 wet) calc., silty till, minor carbonate rock fragments.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
5	M-39-1
10	M-39-2

Hole No. M43      Location: NE30-17-11E  
2 miles northwest of Great  
Falls, Manitoba.

<u>Depth (ft.)</u>	<u>Lithology</u>
0-20	Light olive gray (5Y 6/1 wet) laminated sandy silt, minor clay.
20-55	Light olive gray (5Y 6/1 wet) laminated silty clay.
	Total depth of hole.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
10-15	M-43-1
30-35	M-43-2

Hole No. M56 Location: NW10-17-7E  
Beaconia, Manitoba.

Depth (ft.) Lithology

0-18 Pale yellowish brown (10Y R 6/2 wet)  
sandy to clayey silt.

18-33 Light olive gray (5Y 6/1 wet) lake  
clay, numerous silty pockets.

33-56 Light olive gray (5Y 6/1 wet) calc.  
silty till, numerous carbonate and  
granitic rock fragments.

Total depth of hole.

Depth (ft.) Samples used in this Study

5-10 M-56-1

20-35 M-56-2

Hole No. M59 Location: NW5-17-9E  
10 miles south of Powerview,  
Manitoba.

Depth (ft.) Lithology

0-10 Light olive gray (5Y 6/1 wet) sandy silt.

10-60 Medium dark gray (N5 wet) lake clay.

60-70 Light olive gray (5Y 6/1 wet) calc.  
silt, carbonate, granite and volcanic  
rock fragments.

Total depth of hole.

Depth (ft.) Samples used in this Study

5-10 M-59-1

40-45 M-59-2

50-60 M-59-3

<u>Hole No.</u>	M67	<u>Location:</u> SW9-11-5E 5 miles east of Winnipeg, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-5		Road fill.
5-12		Olive gray (5Y 4/1 wet) silty to sandy clay.
12-29		Olive gray (5Y 4/1 wet) lake clay minor silt lenses.
29-55		Rounded sand and gravel composed of mainly carbonate and minor granitic and volcanic rock fragments.
55-57		Till, yellowish gray, calc., silty.
		Total depth of hole.
<u>Depth (ft.)</u>		<u>Samples used in this Study</u>
5-10		M-67-1
15-20		M-67-2

The following are logs of cuts and/or shallow surface holes. The material was collected and described by the author.

<u>Hole No.</u>	B-1	<u>Location:</u> Site of new sewage treatment plant, approximately 3.6 miles northeast of St. Norbert, Manitoba.
<u>Depth (ft.)</u>		<u>Lithology</u>
0-1		Soil and fill.
1-4		Slightly clayey, sandy silt, medium yellowish brown (10Y R 5/4), very finely laminated, lower boundary sharp and broadly undulating.
4-7		Clay; laminated, dark to medium brown (5Y R 4/1), some soft medium to large silt blebs, clasts and pockets present, lower boundary sharp and flat.

- 7-8 Silt, slightly clayey, sandy, very finely laminated with crossbedding in the upper 2 in., light to medium yellowish brown (10Y R 5/4), several interbeds of darker, finer material.
- 8-22 Clay; slightly silty, laminated, medium to dark brownish gray (5Y R 3/1), with silt pockets and occ. granitic pebble, subrounded carbonate pebbles collected from an unknown depth below 22 ft. The unit apparently extends at least 10 ft. below the 22 ft. depth but close examination of this lower interval was impossible due to construction.

<u>Depth (ft.)</u>	<u>Samples used in this Study</u>
2	B-1-1
5	B-1-2
7	B-1-3
9	B-1-4A
13	B-1-4B
22	B-1-4C

B-2 to B-6 are samples from shallow pits dug in various areas south and southeast of Winnipeg. All cuts expose slightly silty clay, laminated, medium brown to medium gray (5Y B/1). All except B-2 were taken at a depth of approximately 3 feet. B-2 was taken at a depth of 12 feet. The locations are as follows:

B-2	Pharmacy Building, University of Manitoba.
B-3	SW14-9-3W
B-4	SW25-9-1W
B-5	SE14-9-1E
B-6	NE11-7-2W

PV-1, 2, 3, 4 and T-3, 4A, B, 5 were collected from the Powerview site at Pine Falls, Manitoba (14-30-18-10E). The samples are all laminated clay, medium gray to grayish-brown (5 YR 3/1) with numerous silt blebs present.

SW-Assin. River-1-1 through 9 were collected at a cut along the Assiniboine River approximately 8 miles north of Glenboro, Manitoba (2-25-14-8W). The cut exposes over 50 ft. of clayey silt, dark gray (N3), slightly laminated with indefinite crossbedding.