PLEISTOCENE GEOLOGY OF THE RANDALL REGION, CENTRAL MINNESOTA

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Pleistocene Geology of the Randall Region, Central Minnesota

BY

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FOREWORD

The systematic investigation of the glacial history of Minnesota goes back sixty to eighty years, to the days of N. H. Winchell and Warren Upham, who were as competent in the interpretation of the terrain and surface deposits as they were in working out the relations of the bedrock. A resurvey of the glacial history of the State was completed just before World War I by Frank Leverett of the U.S. Geological Survey, whose comprehensive report, however, was not published until 1932. Leverett had already mapped most of the other states in the Great Lakes region, so the picture for Minnesota fitted consistently with the others.

Each successive generation of geologists, however, has different approaches, based on new techniques and on increased understanding of geological processes. After World War II the Minnesota Geological Survey initiated a program of re-examination of the glacial deposits of the State, which has an exceptionally fine record of the complex interactions of ice lobes that invaded the area from different directions. The recent Bulletin 39 on the Geology of Cook County incorporated a modern study of the glacial history of the northeastern corner of the State by Robert P. Sharp, and the present Bulletin by Allan F. Schneider describes a detailed study of an area in central Minnesota northwest of Little Falls.

To this problem Dr. Schneider brought the necessary energy and enthusiasm to do the detailed field work required to unravel the complex relationships.

In work on a problem of this sort a broad background on the region as a whole is necessary. This was furnished by H. E. Wright, Jr., who has supervised the work on the Pleistocene geology of Minnesota since 1947.

Although the field work was supported by the Minnesota Geological Survey, it should be emphasized that untold hours were spent by Dr. Schneider on laboratory work and on drafting and writing the report while he was otherwise employed.

The Minnesota Geological Survey is indebted to both Dr. Schneider and Professor Wright for their devoted service.

GEORGE M. SCHWARTZ

ACKNOWLEDGMENTS

This study was suggested by Dr. H. E. Wright, Jr., of the Department of Geology at the University of Minnesota, who guided the project throughout its course. The writer is deeply indebted to Professor Wright for his frequent visits to the area and inspection of the field evidence, for his many valuable suggestions, and for his careful criticism of the entire manuscript.

The field work was supported in full by the Minnesota Geological Survey, Dr. George M. Schwartz, Director. Many hours were spent in the field and in discussion of the Pleistocene geology of central Minnesota with Mr. Leonard W. Weis and Dr. Harold F. Arneman. The author also wishes to acknowledge the comments of those persons who visited the area on the Friends of the Pleistocene (Midwest) field conference in May 1954; special thanks are accorded Dr. J Harlen Bretz for his critical observations and suggestions.

The writer is indebted to Mr. Robert Schneider, District Geologist, U.S. Geological Survey, Ground Water Branch, who provided data on drift thickness and other information obtained from Survey test holes drilled in connection with a ground-water investigation of the Camp Ripley Military Reservation. Several profitable hours were spent discussing the distribution and thickness of drift in western Morrison County with Mr. Ray Van Hercke, well driller at Little Falls.

Special thanks go to several persons associated with the Department of Geology at the University of Minnesota who have assisted the writer in various ways: to Dr. John W. Gruner, Dr. Deane Smith, and Mr. Harry Taylor for X-ray analyses of clay samples; to Dr. Samuel S. Goldich and Mr. C. O. Ingamells for chemical determinations of iron content in clay fractions, and to Professor Goldich for his encouragement and valuable suggestions throughout the study; and to Dr. George A. Thiel for suggestions on laboratory analyses and for reviewing that part of the manuscript dealing with their description.

Field work within the Camp Ripley Military Reservation was authorized by Maj. Gen. J. E. Nelson, Adjutant General, Department of Military and Naval Affairs for the State of Minnesota. Arrangements for work within the reservation were made with Col. R. A. Rossberg, the camp commander.

Finally, the writer wishes to express deep appreciation to his wife Betty-Lou for her capable assistance in the field, for drafting the illustrations, and for typing the manuscript.

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ABSTRACT

During the Cary subage of the Wisconsin glacial age, central Minnesota was invaded by ice from several directions, as indicated by diagnostic landforms and by tills of distinctive lithology. Many of the significant stratigraphic and geomorphic relationships attesting to the complex Cary history of central Minnesota occur in and near the Randall region, immediately west of the Mississippi River in western Morrison and eastern Todd counties. The surficial geology and Pleistocene history of this area are described in detail and significant regional relations are reviewed.

Four ice lobes of Cary age are recognized: (1) the Wadena lobe, which deposited calcareous gray (yellowish-brown where oxidized) sandy till derived largely from the Paleozoic limestone terrane of southern Manitoba; (2) the Superior lobe, which deposited red sandy till acquired by passage over Upper Keweenawan red sandstone of eastern Minnesota; (3, 4) the Pierz and Brainerd lobes, which brought noncalcareous brown sandy till derived from dark-colored Precambrian crystalline rocks of northeastern Minnesota. Field and laboratory data concerning the lithologic characteristics of these drifts are discussed in detail.

The Wadena lobe entered central Minnesota from the northeast, spread radially to the south and west to form the fan-shaped Wadena drumlin field of Wadena and Todd counties, and probably terminated at the Altamont-Gary moraine. It entered the Randall region from the northwest and advanced eastward across the Mississippi River. As the Wadena lobe withdrew, the Superior lobe from the Lake Superior basin pushed westward and probably reached its terminus about 15 miles west of Little Falls. Interbedding and reverse superposition of gray and red drifts suggest that the lobes were locally concurrent.

The Pierz lobe entered central Minnesota from the east, radiating westward to form the fan-shaped Pierz drumlin field of eastern Morrison and Benton counties. As the ice penetrated northwestward into the Randall region, it encountered the retreating Wadena lobe, so that its noncalcareous brown till not only overlies but is also interbedded with calcareous gray Wadena-lobe drift. The terminus of the Pierz lobe is represented generally by an arcuate segment of the St. Croix moraine south of Pillager gap, but extramorainic brown till indicates that a tongue of Pierz ice extended farther northwest.

Pierz-lobe meltwater deposited an extensive outwash plain west of the moraine along the Long Prairie and Crow Wing rivers. Leverett believed that this plain was deposited in Glacial Lake Wadena, which drained to the south. As the Pierz lobe retreated eastward, the meltwater found addi-

tional routes of southward escape around the western edge of the ice; this resulted in the development of an anastomotic spillway system along the inner margin of the moraine.

By this time the Brainerd lobe from the northeast had fashioned the Brainerd drumlin field of southern Crow Wing County. East of the Mississippi River part of its southern terminus is represented by the Nakasippi moraine. West of the river the ice pushed southwestward to Cushing, obliquely overriding part of the St. Croix moraine that had just been built by the Pierz lobe.

Accelerated retreat of the Pierz and Brainerd lobes at the close of the Cary subage resulted in the formation of the Green Prairie terrace by the newly established Mississippi River. North of Fort Ripley the terrace grades into a pitted outwash plain, which was deposited as the Brainerd lobe retreated northward. This retreat opened Pillager gap, permitting the eastward drainage of Lake Wadena and thus the reversal of the Long Prairie River, its former outlet. During the Mankato and Valders subages, central Minnesota was not reglaciated and the course of the Mississippi River between Brainerd and St. Cloud remained open.

PLEISTOCENE GEOLOGY OF THE RANDALL REGION, CENTRAL MINNESOTA

1. INTRODUCTION

GENERAL STATEMENT

In the introduction to his comprehensive report on the Quaternary geology of Minnesota and adjacent areas, Leverett (1932, p. 2) states that "there is perhaps no part of the United States in which the complexity of the glacial movements is better illustrated than in Minnesota." Investigations during the past few years have apparently only begun to disclose the several implications of this statement. The Quaternary history of the state now appears to be far more complex than even so experienced a student of the Pleistocene as Leverett had realized. During the Cary subage of the Wisconsin glacial age alone, for example, central Minnesota was invaded by no fewer than four discrete ice tongues.

PURPOSE AND SCOPE OF INVESTIGATION

Purpose. The study treated in this report was undertaken with the purpose of investigating the late Wisconsin glacial history of part of central Minnesota. Many of the significant stratigraphic and geomorphic relationships attesting to the complex glacial history of this area during the Cary subage are found in and adjacent to the Randall region, northwest of Little Falls (Figs. 1 and 2). This area was therefore selected for detailed study.

Location. The Randall region comprises an area of approximately 320 square miles immediately west of the Mississippi River in western Morrison and eastern Todd counties. It includes all the Cushing quadrangle (15-minute series) and that part of the Belle Prairie quadrangle (15-minute series) which is west of the Mississippi River. The sinuous course of the river defines the eastern border of the Randall region at about 94°22′ W. longitude; the western boundary is 94°45′ W. longitude. Parallels 46°00′ N. and 46°15′ N. respectively delimit the area on the south and north.

Field Work. Field studies were conducted under the auspices of the Minnesota Geological Survey, as part of its program to resurvey the glacial deposits of the state. Twenty-three weeks were spent in the field during the summers of 1952, 1953, and 1954; this time was supplemented by occasional week-end visits during spring and fall.

The Randall region was studied and mapped in detail (Pl. 1), except for the northeastern part of the region which lies within the expanded boundaries of the Camp Ripley Military Reservation. Much of this latter area was relatively inaccessible because of the rugged topography, lack of roads, and military training operations; work here was limited to about a week or 10 days and must be classified as semi-detailed reconnaissance.

General reconnaissance studies were extended beyond the Randall region proper, chiefly to the east and south in southwestern Crow Wing, eastern Morrison, northern Benton, and northeastern Stearns counties, but also to the west and south in central and southeastern Todd County (Fig. 1). Visits to these areas were made mainly for the purpose of supplementing

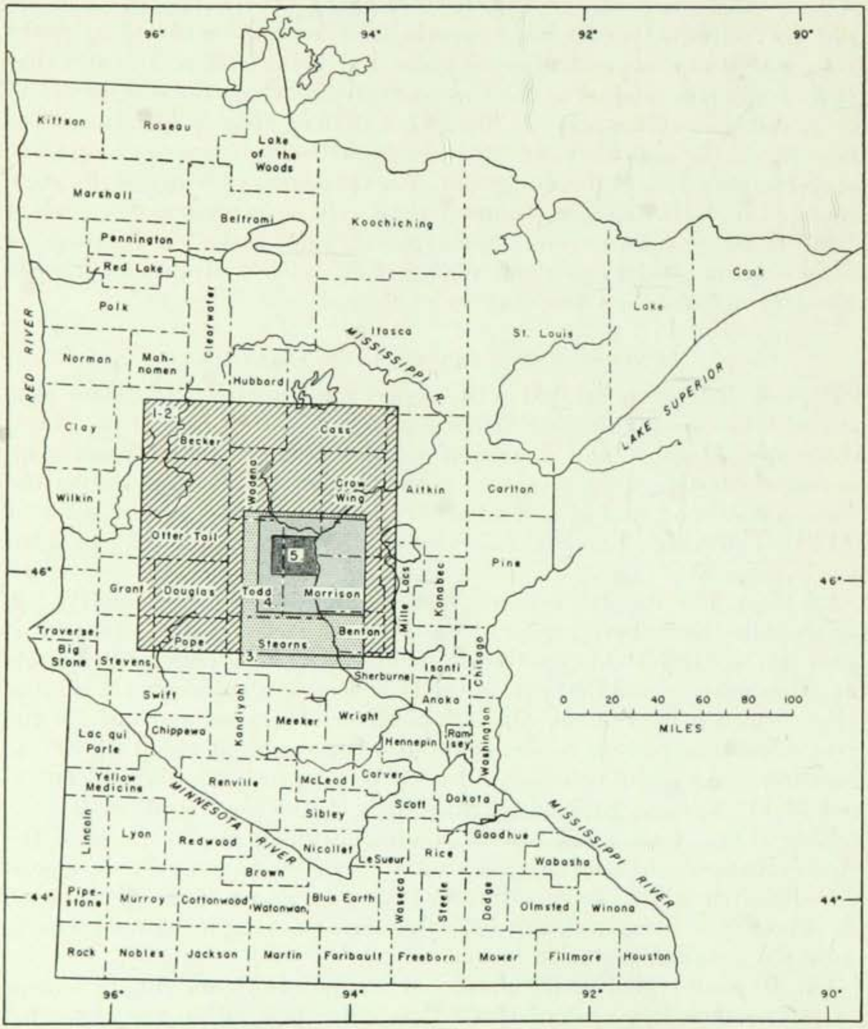


FIGURE 1. — Index map of Minnesota. Numbered areas 1 to 5 are covered by other maps in this report as follows: 1. End moraines and drumlins of central Minnesota, Figure 3; 2. Soil associations of central Minnesota, Figure 5; 3. Index map of central Minnesota, Figure 2; 4. Index map showing locations of analyzed samples, Figure 26; 5. Pleistocene geology of the Randall region, Plate 1.

the stratigraphic and lithologic data of drifts exposed in the Randall region and none of these adjacent areas was mapped.

Map Coverage. Topographic quadrangle maps published by the U.S. Geological Survey (1:62,500) and the Army Map Service (1:50,000 and

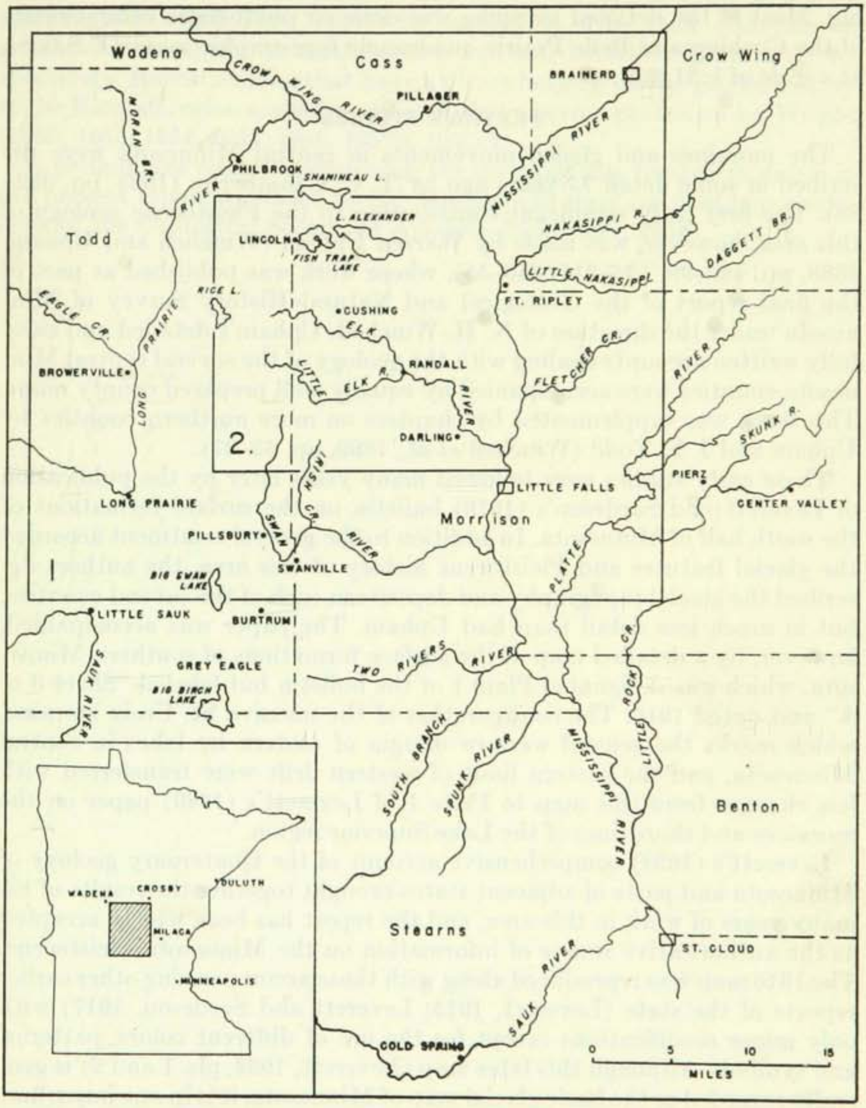


FIGURE 2. — Index map of central Minnesota. Area 1 shows area covered by stage diagrams of Figures 24 and 25, and also approximates the area shown in Figures 14 and 15. Area 2 is the Randall region.

1:25,000) cover much of the southeastern part of central Minnesota. Contact prints (approx. 1:21,000) and photo indexes of single-lens vertical aerial photographs completed in 1939 and 1940 for the U.S. Department of Agriculture were utilized in the field with the maps; only alternate photos were available, however, so that stereoscopic coverage was lacking. Most of the detailed mapping was done on photostatic enlargements of the Cushing and Belle Prairie quadrangle topographic maps (U.S.G.S.) at a scale of 1:31,250.

PREVIOUS STUDIES

The moraines and glacial movements in central Minnesota were described in some detail 75 years ago by T. C. Chamberlin (1883, pp. 382–88). The first truly significant contribution to the Pleistocene geology of this area, however, was made by Warren Upham (Winchell and Upham, 1888, pp. 426–98, 534–611, 646–55), whose work was published as part of the final report of the Geological and Natural History Survey of Minnesota under the direction of N. H. Winchell. Upham's detailed and carefully written accounts dealing with the geology of the several central Minnesota counties were accompanied by equally well prepared county maps. This work was supplemented by chapters on more northern counties by Upham and J. E. Todd (Winchell *et al.*, 1899, pp. 55–97).

These early studies were followed many years later by the publication of Leverett and Sardeson's (1919) bulletin on the surface formations of the south half of Minnesota. In addition to the general treatment accorded the glacial features and Pleistocene history of this area, the authors described the glacial topography and deposits in each of the several counties, but in much less detail than had Upham. The paper was accompanied, however, by a detailed map of the surface formations of southern Minnesota, which was designated Plate 1 of the bulletin but labeled "Sheet 3 of A" and dated 1916. The configuration of the massive St. Croix moraine, which marks the general western margin of eastern ice lobes in central Minnesota, and the eastern limit of western drift were transferred with few changes from this map to Plate 1 of Leverett's (1929) paper on the moraines and shore lines of the Lake Superior region.

Leverett's (1932) comprehensive account of the Quaternary geology of Minnesota and parts of adjacent states brought together the results of his many years of work in this area, and the report has been widely accepted as the authoritative source of information on the Minnesota Pleistocene. The 1916 map was reproduced along with those accompanying other earlier reports of the state (Leverett, 1915; Leverett and Sardeson, 1917) with only minor modifications except for the use of different colors, patterns, and symbols. Although this later map (Leverett, 1932, pls. 1 and 2) is generally regarded as the basic glacial map of Minnesota, it is in one important respect less nearly complete than the earlier maps: it does not show textural differences in the moraines, till plains, and outwash deposits as do the earlier maps.

Leverett's professional paper was followed shortly by the publication of Cooper's (1935) critical study of the Late Wisconsin and postglacial history of the upper Mississippi River, with special emphasis on drainage development between St. Cloud and the Minneapolis-St. Paul region. The surficial deposits of central Minnesota were reviewed in some detail by Allison (1932) and Thiel (1947) in connection with their bulletins on ground-water supply in northwestern and northeastern Minnesota, respectively. Recent studies that have a direct bearing on the glacial history of the Randall region and adjacent areas have been reported on by Wright (1952, 1953, 1954, 1955, 1956, 1957b, 1957c).

A preliminary paper summarizing the investigation treated in detail in the present report appeared in the Minneapolis meeting field-trip guidebook of the Geological Society of America (Schneider, 1956).

2. REGIONAL SETTING

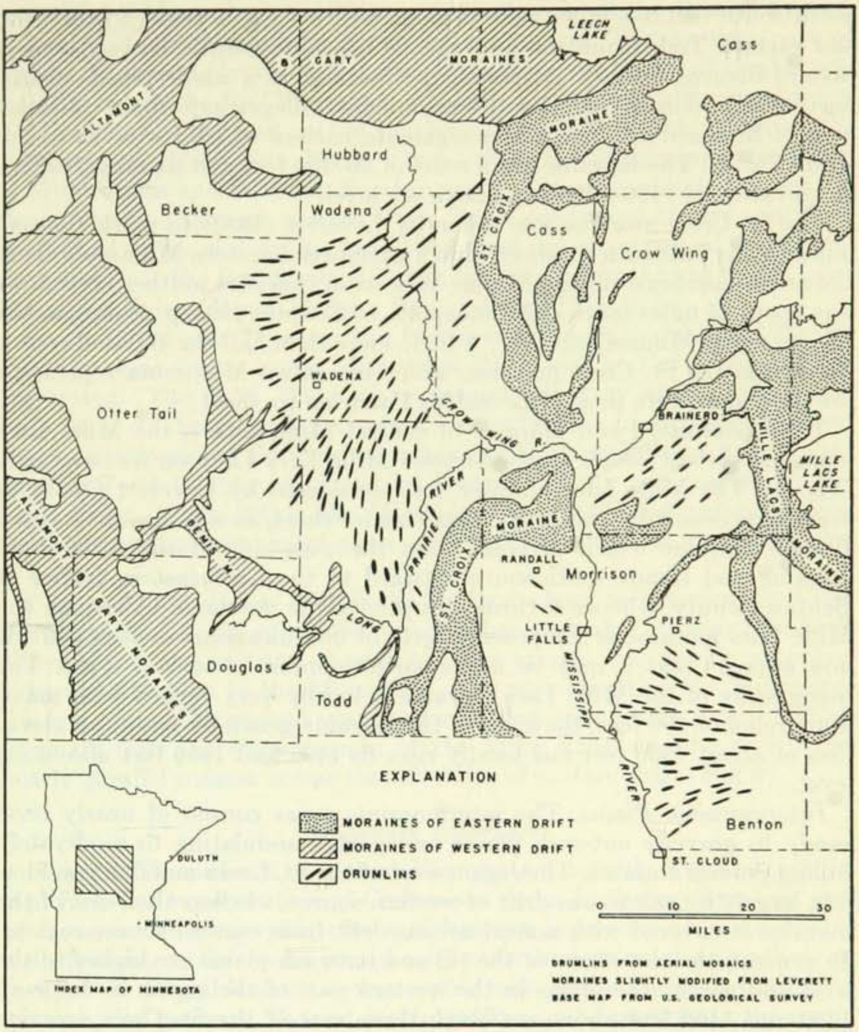
PHYSIOGRAPHY

General. Central Minnesota is located in the Western Young Drift section (Fenneman, 1938, pp. 559–88) or Western Lake section (Fenneman, 1946) of the Central Lowland province. This part of Minnesota is often referred to as the Lake Park region of the state because of the hundreds of picturesque lakes and prominent hills that characterize its morainic topography. Except for the relatively minor effects of postglacial erosion, the topography is almost wholly the result of late Wisconsin glaciation. The strongest elements of the landscape are rugged end moraines (Fig. 3), which are separated from each other by nearly level to undulating outwash plains and ground moraine 100–300 feet below the morainic crests.

End Moraines. The most massive end moraine in central Minnesota is the Altamont-Gary morainic system, which includes some of the roughest topography in the state. The moraine trends northwestward and northward through Douglas, Otter Tail, and Becker counties in west-central Minnesota, thence curves eastward to cross the northern edge of the area through Becker, Hubbard, and western Cass counties (Fig. 3). This belt is commonly between 15 and 20 miles wide except at its constricted eastern end south of Leech Lake. Although the crest of the moraine is generally about 1500–1600 feet above sea level, some of the higher knobs and ridges in Becker County reach an elevation of 1700–1800 feet. Intramorainic relief is commonly 200 feet and locally approaches 300 feet.

The north-south segment of the Altamont-Gary morainic system was described by Upham (Winchell and Upham, 1888) as the Fergus Falls and Leaf Hills moraines, formed at the west edge of an ice lobe that was retreating to northwestern Minnesota. It is composed of calcareous gray drift, and Leverett (1932) considered that the moraine marked a recessional stand of his Late Wisconsin Keewatin ice sheet along the eastern edge of the Des Moines lobe, which spread southeastward across western and southern Minnesota to central Iowa. The east-west segment of the Altamont-Gary moraine in Hubbard and adjacent counties was believed by Leverett to mark the southern terminus of the St. Louis sublobe, an eastward protrusion of the Des Moines lobe which covered a large area in northern Minnesota. Upham had earlier called this segment the Itasca moraine, and considered that it represented a further stage in the northward retreat of the western ice.

Another moraine of calcareous gray drift mapped by Leverett (1932, pl. 3) extends from western Todd County across the northeastern corner of Douglas County and northward through eastern Otter Tail County



DRUMLINS FROM AERIAL MOSAICS
MORAINES SLIGHTLY MODIFIED FROM LEVERETT
BASE MAP FROM U.S. GEOLOGICAL SURVEY

FIGURE 3. — End moraines and drumlins of central Minnesota.

(Fig. 3). This belt constitutes part of Upham's Dovre, Fergus Falls, and Leaf Hills moraines but Leverett correlated it as the Bemis moraine of the Des Moines lobe. The Bemis moraine is locally almost as rugged as the Altamont-Gary moraine to the west, but is narrower and less continuous.

South of Leech Lake the knobby topography of the Altamont-Gary or Itasca moraine unites with that of the St. Croix morainic system, a massive moraine composed largely of noncalcareous eastern drift that forms a north-south belt 3–8 miles wide through western Cass, western Morrison, and eastern Todd counties, and thence continues southeastward across eastern Stearns County. Although the moraine as a whole trends nearly north-south, it is divided by the prominent Pillager gap about 12 miles west of Brainerd into two major segments, each of which is convex to the west (Fig. 3). The moraine has a relief of 50–200 feet and its crest reaches an elevation of 1400–1500 feet above sea level.

The St. Croix moraine was taken by Leverett (1932) to mark the terminus of his Patrician ice sheet, which overspread eastern Minnesota from the north-northeast during Middle Wisconsin time. Its southern terminus was about 25 miles south of Minneapolis, so Cooper (1935, p. 6) designated the ice as the Minneapolis lobe. A little more than half the Randall region lies within the St. Croix moraine, which in central Minnesota represents the general western limit of Leverett's Patrician ice sheet.

The easternmost end moraine of central Minnesota is the Mille Lacs morainic system which nicely encloses Mille Lacs Lake on its inner side (Fig. 3). The Mille Lacs moraine was considered by Leverett (1932) to mark a recessional stand of the Patrician ice sheet, as was also the narrow Beroun moraine which diverges from the west side of the Mille Lacs moraine and trends south-southeastward to the northeastern corner of Benton County, whence it turns abruptly to the northeast. Although the Mille Lacs moraine is composed largely of noncalcareous eastern drift, it now appears that it may be a composite moraine of several drifts. The topography of the Mille Lacs moraine is locally very rugged with maximum relief of 200 feet; the crest of the moraine generally lies at an elevation of about 1350 feet but locally rises to 1400 and 1450 feet above sea level.

Intermorainic Plains. The intermorainic areas consist of nearly level sandy to gravelly outwash plains and gently undulating to moderately rolling ground moraine. The region west of the St. Croix moraine is underlain largely by calcareous drift of western source, whereas that east of the moraine is covered with noncalcareous drift from eastern source regions. In general, the elevations of the till and outwash plains are higher to the west and north: the plains in the western part of the region lie between 1300 and 1400 feet above sea level; those east of the St. Croix moraine decrease in elevation from 1200–1300 feet above sea level in Cass and Crow Wing counties to about 1200 feet in Morrison County and 1100–1200 feet in southern Benton County.

Much of the ground moraine is nicely fluted or drumlinized. Three discrete drumlin fields are recognized: a large field west of the St. Croix moraine in which the drumlins are composed of calcareous western drift, and two smaller fields in the eastern-drift region east of the St. Croix moraine (Fig. 3). Because of their significance in the interpretation of the glacial history of central Minnesota, the drumlin fields are described in detail in the following chapter.

Drainage. Most of central Minnesota, including all the Randall region, is located in the Mississippi River drainage basin. The western part of central Minnesota, however, lies within the drainage basins of the Minnesota River and the Red River of the North (Fig. 1). The streams of western Douglas County and part of southern Otter Tail County drain southward into the Minnesota River, which enters the Mississippi just south of Minneapolis and St. Paul. Farther north a drainage divide follows the Bemis moraine through eastern Otter Tail County and thence continues northward across eastern Becker County; the drainage west of this watershed flows into the Red River, which in turn drains northward to the Lake Winnipeg–Nelson River–Hudson Bay system of Manitoba.

Much of the area between the Bemis-moraine watershed and the St. Croix moraine drains to the Mississippi River via the Crow Wing drainage system. The Crow Wing River, largest tributary of the Mississippi from the west above the Minnesota River, enters the master stream about 9 miles southwest of Brainerd after passing through Pillager gap. Southwestern Todd County and much of Stearns County are drained by the Sauk River, which enters the Mississippi near St. Cloud after passing through a second prominent gap in the St. Croix moraine at Cold Spring (Fig. 2).

The area immediately east of the St. Croix moraine between the Crow Wing and Sauk rivers is drained by a number of smaller streams that head either within the moraine or near its inner margin and flow in a general eastward direction to the Mississippi. The region east of the Mississippi River is drained by several southwestward-flowing streams, most of which originate near the outer margin of the Mille Lacs moraine and follow nearly parallel courses across the till plains of eastern drift (Fig. 2).

BEDROCK GEOLOGY

General. The bedrock of central Minnesota is entirely Precambrian except for a few small outliers of Cretaceous shale. In the southeastern part of the area the geographic extent of bedrock types has been reasonably well delineated; the rocks consist of metasedimentary and iron-bearing rocks of the Animikie series, metamorphic rocks of the Thomson formation, granites, and gneisses. The distribution of Precambrian rocks in the northern and western parts of central Minnesota is poorly known, however, because of the lack of exposures. Bedrock outcrops in central Minnesota have been described in detail by several workers, notably Upham (Winchell and Upham, 1888) and Harder and Johnston (1918).

Inasmuch as the lithologic characteristics of the various drifts described or mentioned in this paper are directly related to the bedrock geology of northern Minnesota and adjoining Canada, it seems desirable to describe the lithology and geographic distribution of the rocks in some detail. The writer has drawn freely from Thiel's (1947) bulletin on the geology of northeastern Minnesota and from the more recent paper by Grout *et al.*

(1951) on the Precambrian stratigraphy of Minnesota. Other sources of information include earlier publications by Allison (1932) and Thiel (1944). The general distribution of rock types is shown in Wright's sketch map of Figure 4; for details of the bedrock geology the reader is referred to the geologic map of Minnesota (Grout *et al.*, 1932). The stratigraphic succession of the Precambrian rocks of northeastern Minnesota is given in Table 1.

North Shore Flows and Intrusives. The North Shore Highland of Lake Superior is underlain by lava flows and intrusive rocks of Middle Kewee-

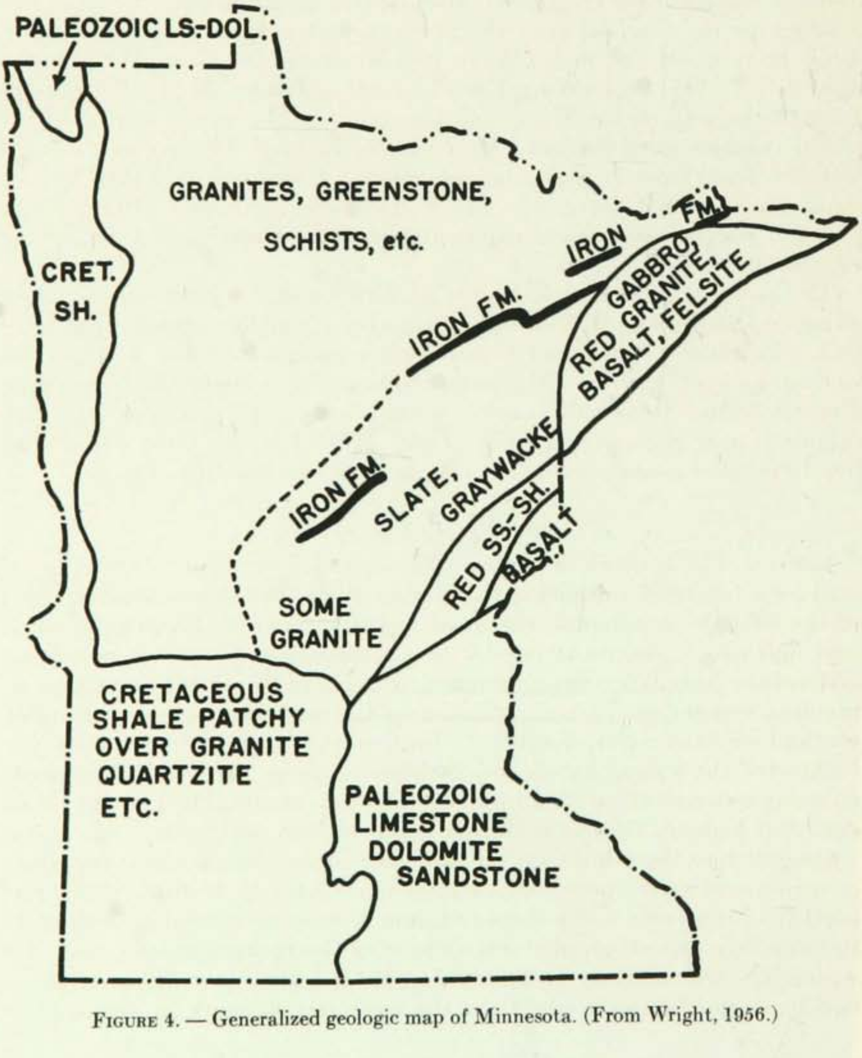


FIGURE 4. — Generalized geologic map of Minnesota. (From Wright, 1956.)

TABLE 1. PRECAMBRIAN SUCCESSION OF NORTHEASTERN MINNESOTA
(After Schwartz, 1956, Table 1)

LATER PRECAMBRIAN

- Keweenawan
  - Upper
    - Hinckley sandstone
    - Fond du Lac beds, red clastics
  - Middle
    - Duluth gabbro complex
    - Beaver Bay complex
    - Logan sills and dikes
    - Keweenaw Point volcanics
  - Lower
    - Puckwunge formation

.... unconformity ....

- Animikie
  - Virginia slate, Rove formation
  - Biwabik and Gunflint iron formations
  - Pokegama quartzite

.... unconformity ....

- Algoman
  - Giants Range, Vermilion and other batholithic intrusions

MEDIAL PRECAMBRIAN

- Knife Lake
  - Knife Lake formation
  - Slate, graywacke, conglomerate, tuff, etc.

.... unconformity ....

EARLIER PRECAMBRIAN

- Laurentian
  - Saganaga granite
- Keewatin
  - Soudan iron-formation member
  - Ely greenstone

nawan age. The flows occur in a belt generally 10–20 miles wide and about 125 miles long that extends northeastward from Duluth through southern Lake and Cook counties nearly to the Canadian border. These rocks are predominantly basalts, most of which are vesicular or amygdaloidal in their upper parts. Purple to red felsites (rhyolites), some of which are porphyritic, are locally abundant.

The flows are bordered on the northwest by a great intrusive mass known as the Duluth gabbro complex, which underlies a belt 12–25 miles wide that extends northward from Duluth through eastern St. Louis County, thence curves northeastward and eastward to Lake Superior. Granitic rocks and also anorthosite occur at several localities along the North Shore Highland. The entire Middle Keweenawan sequence, including flows, thin interflow sediments (sandstone and conglomerate), and the basic and acidic rocks of the Duluth gabbro complex, is cut by numerous dikes and sills of diabase, which are also dated as Middle Keweenawan.

Crystalline Rocks of Northeastern Minnesota. The triangular-shaped area north of the Mesabi iron district and the Duluth gabbro is marked by a great variety of Precambrian rocks. The oldest of these comprise a thick series of highly deformed and recrystallized basaltic rocks of Keewatin age, known as the Ely greenstone. These rocks form a nearly continuous belt 5–10 miles wide and about 40 miles long that extends from the international boundary in northern Lake County southwestward to central St. Louis County. An area of several hundred square miles in west-central St. Louis, southeast Koochiching, and eastern Itasca counties is also underlain by greenstone, but its geographic extent in this region is not well known because of the thick cover of glacial drift. Greenstone outcrops are also abundantly distributed in the central part of the Mesabi district.

Although the Keewatin greenstone consists mainly of lava flows, the formation also includes diabases and diorites and fragmental volcanic ejecta. Most rocks have been metamorphosed to greenstone or to schist with hornblende, biotite, serpentine, or chlorite. Pillow structures are particularly characteristic of the basalts, and some of the flows exhibit amygdaloidal and spherulitic structures.

The upper part of the greenstone sequence contains the Soudan iron-formation member, a ferruginous chert that yields the rich hematite ore of the Vermilion district in northeastern St. Louis County. Geographically, the formation is limited to the greenstone regions and is known to outcrop only in the easternmost greenstone area. Most of the Soudan formation consists of jaspilite, a rock composed of interlaminated chert and iron oxide.

Possibly the oldest intrusive rock of northeastern Minnesota is the Saganaga granite, a mass that occupies a roughly oval-shaped area of about 100 square miles in northwestern Cook County and almost as much in southern Ontario. The principal rock type is a pink to nearly white hornblende granite with aggregates of coarse quartz grains up to half an inch in diameter.

The Ely greenstone and the Saganaga granite are unconformably overlain by a thick sequence of intensely deformed sedimentary rocks of probable Timiskamian age known as the Knife Lake series. Similar rocks are widely distributed in eastern Koochiching and central St. Louis counties to the north and east of the larger greenstone area, and also between the eastern greenstone and the Saganaga granite areas along the international boundary in northern Lake County. These rocks consist of metamorphosed clastic sediments of diverse lithologic character, mainly slate, graywacke, and conglomerate.

Except for a narrow belt of Animikian rocks east of the Saganaga granite, the remainder of northeastern Minnesota is underlain by granite. Two large intrusive masses are recognized, the Giants Range batholith immediately north of the Mesabi district and the Vermilion batholith along the international border. These and several smaller granitic intrusions (stocks) have been assigned to the Algoman.

The Giants Range batholith as exposed is about 100 miles long and up to 15 miles wide. It rises from the flat drift-covered area of Itasca County to a prominent 400-foot ridge that trends northeastward across central St. Louis County. In general, the western half of the intrusion is biotite granite, whereas the older eastern half is mostly hornblende granite. In Minnesota the Vermilion batholith occupies an area 30 by 80 miles, mostly in northern St. Louis County. From here it extends northward across the Canadian border into southern Ontario.

Along the international boundary in northern Cook County there is a narrow belt about 70 miles long underlain by rocks of Animikie age. These include the Gunflint iron formation and overlying Rove slates, which include green, dark-gray, and black slates and graywackes interbedded with nearly white to gray quartzites.

East-Central Metamorphic and Sedimentary Units. Rocks of Animikian age are believed to underlie several thousand square miles in a zone that extends from the Duluth gabbro and the Giants Range granite on the east and north, respectively, southwestward into central Minnesota. This belt is nearly 220 miles long and has a maximum width of about 45 miles. In the Mesabi iron district and on the southern slope of the Giants Range, where the upturned edges of the Animikie beds are well exposed, the group is divided into the Pokegama quartzite, the Biwabik iron formation, and the Virginia slate.

The Pokegama quartzite is marked by a basal conglomerate that grades upward into thin-bedded fine- to medium-grained gray micaceous quartzite, which in turn passes upward into hard massive coarse-grained pink to red and greenish-gray quartzite. Above the quartzite are ferruginous chert, ferruginous slate, siliceous carbonate, and iron ore of the Biwabik iron formation. Most of the siliceous rock is characterized by a peculiar granular texture and is commonly referred to as taconite. The Biwabik formation is conformably overlain by the Virginia slate, a clastic sedimentary unit of thin-bedded gray to black argillite and thick-bedded graywacke.

Rocks of probable Animikie age are thought to extend southwestward from the Mesabi district through southern St. Louis, southern Itasca, northern Aitkin, Crow Wing, and eastern Morrison counties to southwestern Todd County. Much of this area appears to be underlain by the Cuyuna slates, a group of gray, green, brown, and red slates, phyllites, and schists, and the associated Deerwood iron formation, which is the productive horizon of the Cuyuna district.

On the southeast the Animikian series is bordered by a zone of granites and metamorphic rocks that extends from the western edge of the Duluth gabbro southwestward to Stearns County, a distance of about 170 miles. The metasedimentary rocks are well exposed west of Duluth in northeastern Carlton County, where they consist of slate, graywacke-slate, and graywacke of the Thomson formation. Southwest of here the rocks are progressively metamorphosed to phyllite, mica schist, and garnet-mica schist as they approach the granite region of central Minnesota.

Central Minnesota Granites. The linear belt of the Thomson formation is broken in central Minnesota by an intrusive granitic mass 70–75 miles long and up to 40 miles wide. Many exposures of this intrusion occur in southern Aitkin, northwestern Kanabec, northern Mille Lacs, and eastern Morrison counties. Scattered exposures are found elsewhere in central Minnesota; a large outlier has been mapped in the vicinity of St. Cloud. The rock is a medium-grained gray to light-pink biotite granite or light-colored syenite; it is locally very gneissic.

The gray granite is bordered on the south by a coarse-grained red and pink granite of probable Keweenawan age which appears to underlie a large area in Benton, southern Mille Lacs, northwestern Sherburne, and eastern Stearns counties. Isolated outcrops and well records indicate that the red granite occurs at many other localities in Stearns, Todd, and Morrison counties.

Eastern Minnesota Sandstones. Southeast of the Thomson formation and the central Minnesota granites is a belt of Upper Keweenawan sandstone and shale. These clastic rocks underlie the lowland continuation of the Lake Superior basin along a belt 10–25 miles wide which extends southwestward from the head of the lake for a distance of at least 100 miles. The rocks are divided into the Fond du Lac beds below and the Hinckley sandstone above.

The Fond du Lac beds, which are sometimes referred to as the Red Clastic series, consist of massive red to brown argillaceous to arkosic sandstone with interbeds of thinly laminated dark-red to pink arenaceous shale. The overlying Hinckley sandstone is a medium- to coarse-grained salmon-pink to yellow and red or nearly white sandstone. Some of the beds are arkosic and some are conglomeratic, but most of the rock is a nearly pure quartz sand partly cemented with varying amounts of limonite or hematite.

South of the outcrop areas in Pine and Kanabec counties the Upper Keweenawan sandstones pass beneath St. Croixian sandstones of the Cambrian system. A narrow continuation of the outcrop belt may, however, extend for an additional 40 miles southwestward across the Mississippi River into northeastern Wright County. The Precambrian sandstone belt is bordered on the east by Middle Keweenawan lava flows on the upthrown (southeast) side of the Douglas fault. These flows are chiefly basalts, similar to those along the North Shore, and represent a continuation of flows exposed on the Wisconsin side of the Superior syncline. The regional relations suggest, therefore, that Lake Superior itself may be underlain by red sandstone and shale similar to that of the lowland belt southwest of the lake head.

Sandstone and conglomerate of the Lower Keweenawan Puckwunge formation also occur in eastern Minnesota. Exposures of this unit are restricted to the region just west of Duluth and northeast of Duluth in Cook County.

Rocks of Northwestern and West-Central Minnesota. The lithology and distribution of bedrock formations in northwestern and west-central Minnesota are very poorly known, mainly because of the thick drift cover. There are in fact no natural exposures of bedrock in 19 of the 23 counties that lie west and north of the Stearns-Todd-western Morrison block of counties, so knowledge of bedrock comes almost entirely from drill holes and magnetic surveys. Even the few exposures that do exist are generally small, and the total area of surface rock does not exceed a few square miles.

Except for the Red River Valley, where subsurface data are more abundant, the rocks of the northwestern third of Minnesota are largely undifferentiated. Much of the area is believed to be underlain by Animikian slates and older rocks. Granite, gabbro, gneiss, schist, slate, greenstone, graywacke, and iron-formation belts are present, but the distribution and relative abundance of these rocks are virtually unknown.

Shale and Limestone of the Red River Valley and Manitoba. The Red River Valley of western Minnesota is underlain by soft bluish-gray Cretaceous shale with a basal layer of white quartzose sand. These sediments represent a continuation of the gray to green-gray Cretaceous shales that lie beneath the drift throughout thousands of square miles in the Dakotas and southern Canada.

The northwest corner of Minnesota is marked by Ordovician limestone which overlies sandstone and shale above Precambrian granite. Although its geographic distribution in Minnesota is not great, the limestone is of particular significance as a source of certain Minnesota drifts because it represents the southern limit of carbonate rocks which underlie the Manitoba lowland. Geologic maps of Canada (1945) and Manitoba (1946) show that early to middle Paleozoic sediments, most of which are limestones and dolomites, occur in a zone up to 140 miles wide and more than 400 miles long that trends northwestward across southern Manitoba between the Cretaceous escarpment on the west and the Precambrian shield on the east.

Rocks of Southern Minnesota. Much of southwestern Minnesota is underlain by Cretaceous sediments similar to those of the Red River Valley. These consist of soft blue shale, some of which is calcareous, and thinner beds of poorly consolidated sand and gravel.

The Precambrian is represented by granites and granite gneisses and by pink quartzite and local red shale ("pipestone") of the Sioux formation. The granitic rocks are exposed almost continuously for a distance of about 120 miles in the Minnesota River (Glacial River Warren) valley and also at scattered localities in the prairie upland; exposures of Sioux quartzite occur mainly in the southwest corner of the state.

Southeastern Minnesota is underlain by a thick sequence of Paleozoic formations consisting of limestone and dolomite, sandstone, and shale. Most of these rocks are of Upper Cambrian and Ordovician age, but the Devonian system is also represented. Like the Cretaceous and Precambrian rocks of southwestern Minnesota, the Paleozoic formations are of little significance as source materials of central Minnesota drifts.

CLIMATE AND SOILS

Climate. Climatic conditions of central Minnesota are about average for the state as a whole. The mean annual temperature ranges from 37° F. across the northern part of the area to 42° F. in southeastern Morrison and Benton counties. Yearly temperatures in the Randall region average 40°–41° F. January is normally the coldest month and July the warmest; winter and summer extremes in temperature are common. The average annual precipitation ranges from 23 to 26 inches, with more than half falling during the late spring and summer months. The length of the growing season averages close to 130 days throughout most of the area, but ranges from 110 days in northern Becker County to almost 140 days in southwestern Benton and northern Stearns counties (McMiller, 1947, pp. 4–7).

Soils. Detailed soil surveys of only three counties in central Minnesota have been published: Mille Lacs County (Bodman *et al.*, 1927), Wadena County (Elwell *et al.*, 1926), and Hubbard County (Alway and McMiller, 1935). The soils of Crow Wing County have recently been mapped by H. F. Arneman and associates but the results of this study are not yet available. Figure 5, adapted from a recent generalized soils map of the state prepared by McMiller (1954, pp. 4–5), shows broad soil associations. The general characteristics of the soil series represented on this figure are summarized below.*

The soils of the Clarion-Nicollet-Webster association are dark-colored medium- and fine-textured upland Prairie soils developed under grassland vegetation on calcareous gray clayey till of Cary or Mankato age. The three series represent in order the well drained, moderately well drained, and imperfectly drained members of the Clarion catena, occurring on gently rolling, slightly undulating, and nearly level surfaces, respectively.

The soils of the Lester-Hayden association are well-drained soils derived from calcareous gray clayey till on gently rolling to rolling surfaces. Their profile characteristics differ from each other and from those of the Clarion series mainly because of differences in native vegetation. The Hayden series is a Gray-Brown Podzolic soil developed under forest vegetation, whereas the Lester series is a Prairie Border soil.

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* This discussion was prepared chiefly from unpublished sources; the author is indebted to Minnesota soil scientists, particularly the late Prof. P. R. McMiller, for furnishing the information. Similar treatment is accorded the soil associations here summarized in Odell *et al.* (1960. *Soils of the north central region of the United States*: North Central Regional Publication No. 76, Univ. Wis. Agr. Exp. Station Bull. 544, 192 pp.), which was published while the present report was in press.

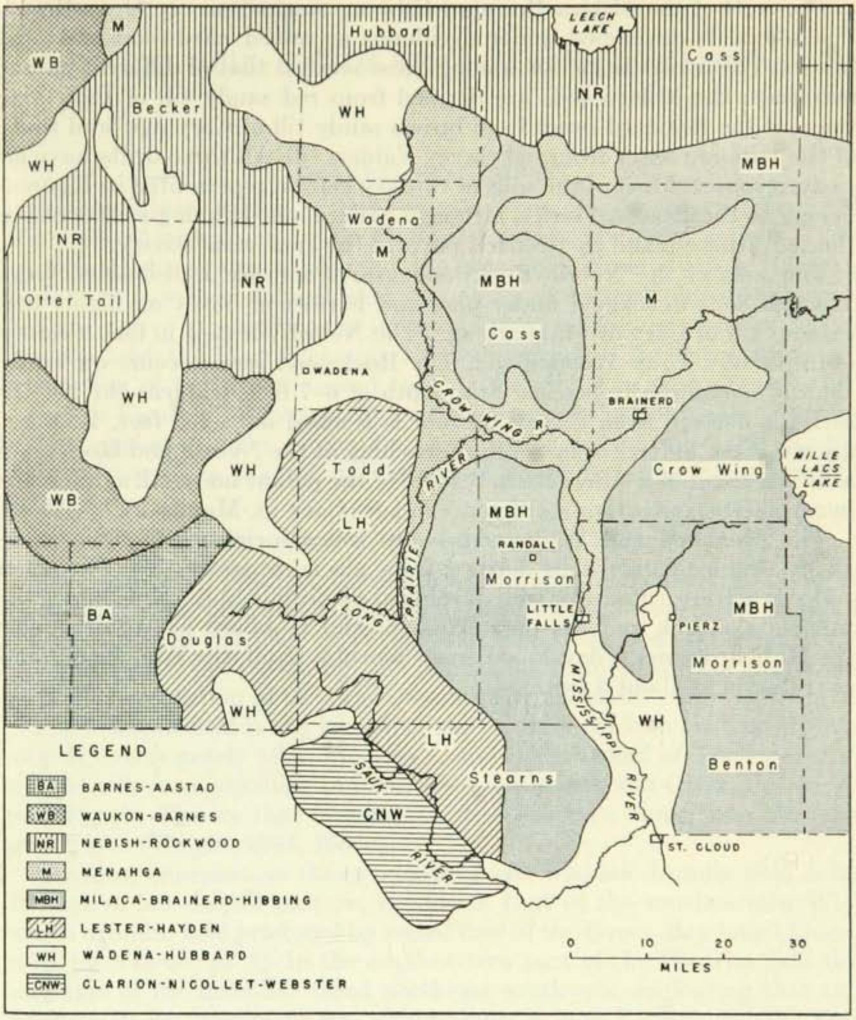

FIGURE 5. — Soil associations of central Minnesota. (Adapted from McMiller, 1954.)

The soils of the Barnes-Aastad and Waukon-Barnes associations are also derived from calcareous gray clayey till of late Wisconsin age. Barnes and Aastad are Chernozem soils developed under tall-grass vegetation; the former is the well-drained member and the latter the moderately well-drained member of the Barnes catena. Associated with these soils are the Flom and Parnell series, which represent the imperfectly drained and the poorly drained or Humic-Glei members of the Barnes catena. The Waukon series is a well-drained Degraded Chernozem soil, produced by the encroachment of forest vegetation upon the prairie grasses.

The soils of the Milaca-Brainerd-Hibbing association are Gray-Brown Podzolic soils developed under deciduous or mixed hardwood and pine forests. The main distinction among these series is that of different parent materials; the Milaca soils are derived from red sandy till of Cary age, those of the Brainerd series from brown sandy till of Cary age, and those of the Hibbing series from red clayey Valders till. All three drifts have an eastern source. Most of the soils of this association represented in Figure 5 belong to the Brainerd series, although Milaca and Hibbing soils occur in the southeastern and east-central parts of the area, respectively.

The soils of the Nebish-Rockwood association are well-drained Gray Wooded soils developed under pine and hardwood forest on highly calcareous till of Cary or Mankato age. The Nebish series is in fact a classic example of a Gray Wooded soil. The Rockwood series occurs on sandy till and is reportedly leached to a depth of 6–7 feet, whereas the Nebish series is derived from clayey till and is leached only 2–3 feet. It is not known if the difference in depth of leaching of the Nebish and Rockwood soils is a result of a difference in texture of the parent material, a difference in carbonate content, or a difference in age (Cary vs. Mankato).

The Menahga and Wadena-Hubbard soil associations include excessively drained sandy soils derived from glacial outwash. The Menahga series is a Brown Podzolic soil, developed on deep pebbly sands under the influence of jack and red pine. Wadena and Hubbard are Prairie soils; the Hubbard series is developed on deep pebbly sand, the Wadena on sand over gravel at about 3 feet.

3. DRUMLIN FIELDS OF CENTRAL MINNESOTA

GENERAL STATEMENT

Present interpretation of the complex Pleistocene geology of central Minnesota in general, and of the Randall region in particular, relies heavily upon excellent evidence afforded by drumlins. Three discrete drumlin fields have now been defined, each having its own geographic distribution and distinctive arrangement of individual forms. These are known as the Wadena field, the Pierz field, and the Brainerd field. The distribution and orientation of the drumlins and their relationships to end moraines are shown in Figure 3. Although the scale of this map prohibits the plotting of all drumlins and the accurate representation of their absolute dimensions, relative sizes, shapes, and density of distribution are approximately correct.

WADENA DRUMLIN FIELD

The designation Wadena drumlin field was applied by Wright (1954) to an extensive area of drumlins located to the north and west of the Randall region. A part of this field previously had been described and mapped by Leverett (1932, pp. 62–63; fig. 13) but recent studies indicate that Leverett's interpretation of the drumlins must be modified.

The Wadena field is the largest of the drumlin fields in central Minnesota. It covers nearly all of Wadena County, about half of Todd County, and extends into adjoining parts of Cass, Hubbard, and Otter Tail counties (Fig. 3). The ice that formed this field has been named the Wadena glacial lobe (Wright, 1954, 1957c).

The most conspicuous characteristic of the Wadena drumlin field is its distinctive fan-shaped pattern, similar to that of the southeastern Wisconsin drumlin field produced by radial flow of the Green Bay lobe (Alden, 1918, pp. 248–56; pl. 3). In the northeastern part of the Wadena field the long axes of the drumlins trend northeast-southwest, indicating that the direction of ice movement was either about N. 50° E. or S. 50° W. This trend gradually diverges to the west and south, so that the axes strike nearly east-west in the northwestern part of the field and north-south near the southern margin. Indeed, at the southern end of the field, particularly along the eastern margin adjacent to the St. Croix moraine, the drumlins are oriented northwest-southeast. To the present writer such a pattern indicates that the Wadena lobe entered central Minnesota from the northeast, spreading radially to the west and to the south and southeast.

Wright (1957b) subscribes to the same conclusion and offers two addi-

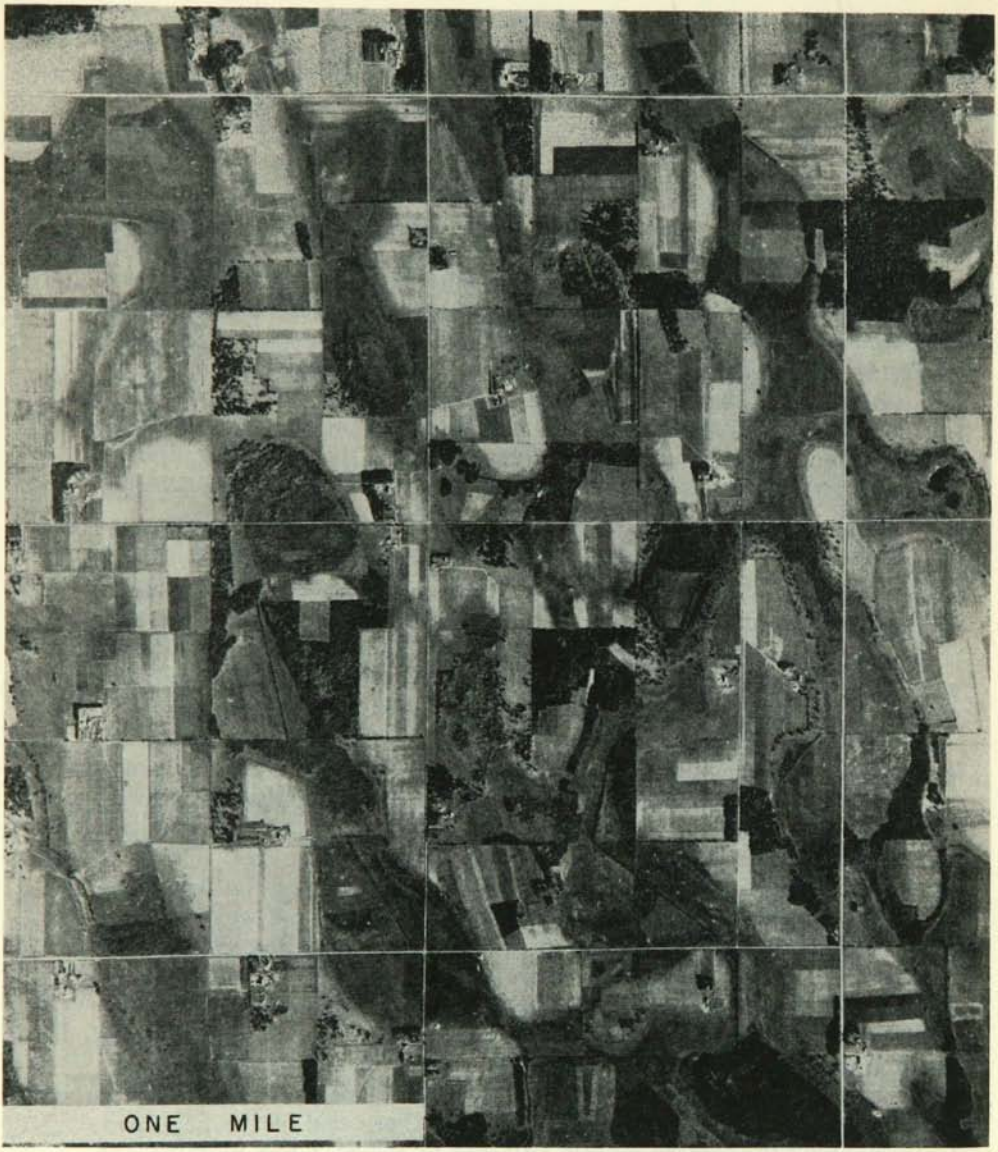

FIGURE 6. — Aerial photo of part of the Wadena drumlin field. North is toward the top. Location is central Todd County, 5 miles southwest of Browerville in T. 130 N., R. 34 W. (Photo by U.S.D.A., BYH 5-38, Sept. 16, 1939.)

tional lines of evidence in support: (1) Till-fabric analyses indicate a preferred orientation of long axes of stones parallel to the longitudinal axes of the drumlins; most of the pebbles are inclined to the northeast. This preferred direction of plunge is interpreted by Wright as the result of orientation along flow planes sloping gently up-glacier to the northeast. (2) The more ovate shapes of the drumlins in the southern (terminal) part of the field, in contrast to the more elongated forms to the north, suggest a loss of drumlin-forming ability as the ice became less active.

On the east the drumlin field is truncated by the St. Croix moraine. This truncation is especially sharp in western Cass County; as observed on aerial photographs, the elongated forms of the drumlins appear as a series of white streaks that emerge from beneath the moraine. The truncation is less sharp in eastern Todd County but none the less apparent. On the west and southwest the drumlins generally become obscure a few miles from the inner margin of the Bemis moraine of Leverett, although in east-central Otter Tail County the pattern continues to the base of the moraine. Wright (1954) states that the drift composing the drumlins is lithologically indistinguishable from that of the Bemis moraine and from that of most of Leverett's Altamont-Gary moraine a few miles farther west. He suggests, therefore, that the Altamont-Gary moraine may represent the terminal position of the Wadena lobe in this area. The northern limit of the drumlin field lies about 8–10 miles south of the massive east-west part of Leverett's Altamont-Gary moraine.

The drumlins of central Todd County (Fig. 6) were described by Leverett (1932, p. 62) as follows: "They stand usually about 25 feet above intervening swales but range in height from 10 feet to fully 50 feet. Few of them are a mile in length and the more common length is about half a mile. The width is usually not more than one-third the length." Farther to the north, however, in Wadena and Cass counties, the forms become distinctly more elongated, as mapped by Leverett (1932, fig. 13, p. 63), ranging up to 3 miles in length and having a length-breadth ratio as great as 10 to 1. In the southern part of the field, on the contrary, the streamlined pattern atrophies and several of the drumlins possess a nearly circular outline.

Reconnaissance studies in north-central Todd County have shown that the drumlins here are composed of limestone-rich yellowish-brown sandy till. Investigations by Wright in Wadena, Todd, and Cass counties indicate that the drift is lithologically similar throughout the drumlin field. There is, however, no known source of limestone, either beneath the drift or to the northeast. The bedrock in these regions consists largely of Precambrian crystalline rocks, with local outliers of Cretaceous shale. Possibility of contamination from an older drift must be ruled out because the highly calcareous character of the till persists throughout an area now known to exceed 2500 square miles. The only apparent source of the limestone is at least 175 miles to the northwest, in the Paleozoic carbonate terrane of southern Manitoba and the adjacent northwestern corner of Minnesota. Thus, it seems possible that the Wadena lobe entered Minnesota from the northwest and then swung sharply from a southeasterly advance to a southwesterly heading at some unknown distance to the north of the Wadena area. Its course can not be followed in this critical area because of deep burial by younger drift. Wright (1954; 1957b, pp. 23–24) has postulated the presence of a contemporaneous ice lobe advancing from the east or northeast which acted as a barrier to the southeastward flow of the Wadena lobe, and which served to deflect it westward.

As indicated by the fan-shaped pattern of the Wadena drumlin field and by the orientation of drumlin axes just west of the St. Croix moraine, the Wadena lobe advanced into the Randall region from the northwest, flowing in a direction about S. 35°–40° E. Evidence will eventually be presented to show that the Wadena glacier advanced at least 40 miles beyond the eastern edge of the drumlin field, probably covering the entire Randall region.

PIERZ DRUMLIN FIELD

The second drumlin field in central Minnesota covers an area of several hundred square miles in the southern half of eastern Morrison County and much of adjacent Benton County (Fig. 3).

Like the Wadena drumlin field, the Pierz field also exhibits a distinctive fan-like pattern. In the east-central and central parts of the field individual drumlins strike east-west but this trend gradually diverges northwestward and southwestward to cover an arc of approximately 80 degrees. The over-all pattern thus implies radial flow of ice advancing from the east and spreading out to the north and south.

No attempt was made to study the Pierz drumlin field in its entirety. Reconnaissance studies of the morphology and composition of the drumlins were largely restricted to the northern part of the field where the general direction of ice movement was from southeast to northwest. South and east of Pierz the topography exhibits a conspicuous and consistent fluting, marked by elongated swells rising from about 25 to 60 feet above the intervening lows (see U.S. Geological Survey topographic map of the Pierz quadrangle). The latter are commonly occupied by small creeks, all of which drain to the northwest. Although their linear dimensions vary, the drumlins are typically about 1 mile in length, or slightly longer, and from 0.3 to 0.4 mile across. No apparent asymmetry in longitudinal section has been detected.

The Pierz-area drumlins are composed of noncalcareous brown sandy till. At some localities thin layers of red sandy till have been noted to occur as interbeds within the brown drift but the total percentage of red drift is not significant. None of the drumlins appears to possess a bedrock core.

North and west of Pierz the drumlins become obscure and the southeast-northwest fluting appears to pass into a faint northeast-southwest pattern

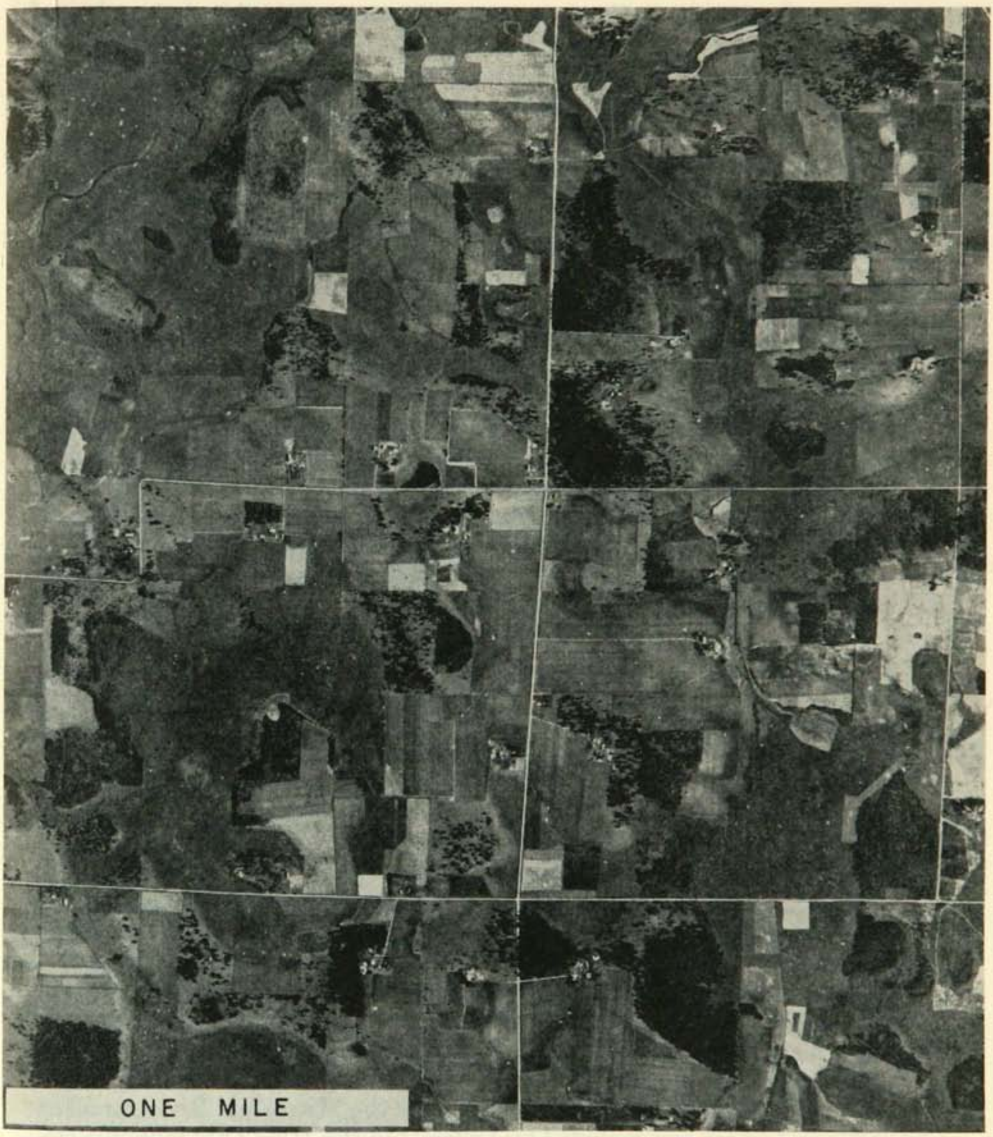

FIGURE 7. — Weakly drumlinized ground moraine south of Randall. Culdrum-Parker till plain. Note faint southeast-northwest fluting. Part of Lake Randall plain and the underfit Little Elk River are shown in northwest corner. Location is just south of Randall in T. 130 N., Rs. 30–31 W. (Photo by U.S.D.A., BYA 12-29, July 8, 1940.)

of unknown origin. Approximately 5 miles west of the Mississippi River, however, in the southern part of the Randall region, the southeast-northwest lineation reappears. The pattern here is not so conspicuous as in the Pierz region but may be discerned both in the field and on aerial photographs (Fig. 7). It is expressed by a group of low drumlins with an average trend of about N. 55° W. (Fig. 3 and Pl. 1). The drumlins are about 15 to 25 feet high, averaging 3000 to 3500 feet in length and ranging in width from 500 to 1800 feet. Like those in the main part of the field near Pierz, the drumlins south of Randall exhibit no apparent asymmetry in longitudinal section.

The southeast-northwest orientation of the drumlin axes in the Randall region parallels glacial striae at Randall and the trend of the near-by Darling esker. When projected to the southeast, the axes tie in perfectly with those near Pierz. The brown sandy till which composes the drumlins is identical to that of the Pierz drumlins except for minor local variations in pebble content and texture. Thus, the ice lobe responsible for the shape and composition of the drumlins near Pierz must also be responsible for the configuration and constitution of the streamlined hills south of Randall. This ice tongue, which entered the southern part of the Randall region from the southeast and which deposited brown sandy till, is named the Pierz lobe.

Whether the northeast-southwest lineation of the drumlins in Benton County may be attributed to the Pierz lobe has not been determined, but the unbroken continuity of the fan pattern suggests that the drumlins in this area were also probably formed by the Pierz lobe. Reconnaissance work in Benton County and more detailed studies farther south and east, however, indicate a significant increase in the occurrence of red sandy till deposited by the Superior lobe (Wright, 1952, 1953, 1955, 1956).

BRAINERD DRUMLIN FIELD

The smallest of the central Minnesota drumlin fields is located south and east of Brainerd in southern Crow Wing County (Fig. 3). The field is truncated on the north and east by the Mille Lacs moraine, which was believed by Leverett (1932, p. 48) to represent a recessional stage of a lobe of the Patrician ice sheet, but which now appears to be a composite moraine made of at least two, probably three, and possibly five late Wisconsin drifts. Northeast of Brainerd the field is bordered on the northwest by a rugged kame complex, which is followed by the Mississippi River for many miles and which was included by Leverett in the Mille Lacs morainic system. Southwest of Brainerd the northwestern edge of the field is bounded by dune and terrace sands (Cooper, 1935, pp. 87–93). On the southwest the drumlins terminate in a segment of the St. Croix moraine east of the Mississippi River that has been separated from the main part of the moraine by late glacial and postglacial erosion. This segment of the St. Croix moraine (Pl. 1), which in this report is called the Nakasippi moraine, is believed to represent part of the terminal position of the Brainerd lobe east of the Mississippi.

As shown on the southern half of the topographic map of the Brainerd quadrangle, nearly all the drumlins are distinctly streamlined, their long axes trending northeast-southwest. Although longitudinal profiles are not consistent, close inspection of the map reveals that slightly more than half the drumlins have a steeper northeastern slope. Individual ridges are typically from three-quarters of a mile to a mile or more in length and from one-quarter to one-half mile wide, with an average relief of 30–35 feet. All the drumlins examined are composed of brown sandy till.

Unlike the drumlins of the Wadena field and those of the Pierz field, the Brainerd drumlins do not exhibit a fan-like pattern. Thus, the absolute direction of ice movement is somewhat more difficult to interpret. After studying the morphology of the drumlins and the distribution of bedrock types in the till, L. W. Weis (unpub.) concluded that the direction of flow was from northeast to southwest. Other workers have concurred in this conclusion. The ice tongue responsible for the production of the Brainerd drumlin field has come to be known as the Brainerd lobe; it entered the Randall region from the northeast, flowing about S. 40°–45° W., as indicated by the elongation of the drumlins.

4. ESKERS AND STRIATIONS

ESKERS

General. Strong supporting evidence attesting to the direction of flow of the Wadena, Pierz, and Brainerd ice lobes is provided by several eskers and esker-like ridges. Aerial photographs show a fair abundance of these forms scattered throughout central Minnesota, but only a few have ever been studied in any detail. The following discussion is limited to those within and immediately adjacent to the Randall region.

Wadena-Lobe Esker. A short sinuous ridge in north-central Todd County (mainly SW¼ Sec. 15, T. 132 N., R. 33 W.) that trends northwest-southeast was discovered from an aerial photograph after field investigations had been concluded. It is located about 4 miles beyond the western boundary of the Randall region, or 1.3 miles directly west of the moderately sharp change in direction of flow of the Long Prairie River from northward to northeastward.

The sinuous form of the ridge is typically eskerine. The general highway map of Todd County shows two adjacent gravel pits along that part of the ridge which is well defined on the photograph. A third pit is located less than a mile away, directly aligned with the other two and with the trend of the more distinct part of the crest. There is no reason to doubt, therefore, that the feature is an esker. Its Wadena-lobe association is inferred from its geographic position in an area of yellowish-brown drift and from its trend of S. 40° E., almost parallel to the long axes of near-by Wadena-lobe drumlins.

Pierz-Lobe Eskers. Several eskers which trend southeast-northwest were described and mapped by Leverett (1932, p. 44; pl. 2) in Morrison County. The first is referred to in this report as the Darling esker (Pl. 1), named from a small unincorporated community 5 miles northwest of Little Falls. The Northern Pacific railroad tracks and U.S. Highway 10 here pass through one of several gaps in the ridge.

The easternmost segment of the Darling esker begins abruptly 0.9 mile west of the Mississippi River near the southeastern corner of the Randall region (SE¼ Sec. 31, T. 130 N., R. 29 W.). For approximately half a mile it trends directly east-west, thence swings northwestward. From one-half mile west of U.S. Highway 10 to its northwestern tip (SE¼ Sec. 20, T. 130 N., R. 30 W.) the esker is nearly straight, trending N. 50° W., and parallels the long axes of the near-by Pierz-lobe drumlins.

The total length of the ridge, including gaps, is nearly 6 miles. It is typically single crested, steep sided, and narrow; its greatest breadth is approximately 1800 feet but the usual distance across is from one-quarter to one-half this figure. It rises locally to about 60 feet above the surrounding ground moraine, the eastern part of which is covered by a veneer of sandy outwash.

A second prominent esker is located east of the Mississippi River just south of the Nakasippi moraine. This is the well-known Fort Ripley esker, first photographed by Cooper (1935, fig. 1) and now widely illustrated in introductory geology and geomorphology textbooks. The Fort Ripley esker is an extremely sinuous, steep-sided, narrow ridge. It is commonly between 20 and 40 feet high but ranges in relief from less than 10 to more than 60 feet; its typical width is about 225–250 feet. Total length, as measured along the curvature of the crest and including the gaps that break the esker into several segments, is approximately 6¾ miles.

The eastern end of the esker is less distinct than the conspicuous western part but its serpentine form can be traced on aerial photographs and topographic maps across the eastern half of the Belle Prairie quadrangle (Pl. 1) into the adjacent Lastrup quadrangle, where it terminates (NW¼ Sec. 23, T. 42 N., R. 31 W.) near the western limit of the northeast-southwest topographic lineation northwest of Pierz. The over-all trend of the eastern segments of the esker is about N. 80° W. In the western half the trend gradually swings northwestward, with the westernmost segment of the ridge (SW¼ Sec. 12, T. 42 N., R. 32 W.) oriented nearly north-south.

The sand and gravel of both the Darling and Fort Ripley eskers are locally crossbedded. Pebble assemblages indicate a general eastern source. Associated kames and similar ice-contact hills likewise contain erratics derived from the east. Marked by numerous gravel pits, the ridges remain largely unfarmed and tree covered, with the usual abundance of jack pine and related species.

Four additional eskers, not visited during the course of this investigation, were mapped by Leverett (1932, pl. 2) and attributed by him to his Patrician ice sheet. The first is just west of the Mississippi River and trends northwest; its outline is shown in part on the topographic map of the Belle Prairie quadrangle (Pl. 1; W½ Sec. 32 and NE¼ Sec. 31, T. 131 N., R. 29 W.). A second esker is located east of the river about 2 miles south of the Fort Ripley esker (S½ Sec. 30, T. 42 N., R. 31 W.); the form of this ridge is not so well expressed on the map (Pl. 1) and the orientation is more nearly east-west than the first. The third occurs immediately west of Little Falls; its eastern end trends south-southwest for about a mile and then turns sharply through nearly a right angle, continuing to the west-northwest for a distance of 2 miles. The last of the four eskers is shown on Leverett's map as trending N. 8° W. for approximately 2 miles from near the northwestern tip of Shamineau Lake.

Brainerd-Lobe Eskers. A small but well-defined esker in southwestern

Crow Wing County (SW¼ Sec. 24, T. 43 N., R. 32 W.) supplements the drumlin evidence of a southwesterly-flowing Brainerd lobe. Its features are favorably shown on the topographic map of the Belle Prairie quadrangle (Pl. 1), as well as on aerial photographs. The esker occurs along the northwestern edge of the gravelly Nakasippi moraine near its western margin.

By comparison with the Darling and Fort Ripley eskers, the ridge is relatively short, barely reaching half a mile in length. Moderately sinuous, it has a rather uniform width of about 200 feet and a height of between 40 and 60 feet. On the northwest it is bordered by the swampy floodplain of the Nakasippi River and on the southeast by two large kettles. The trend of the esker is S. 45°–50° W., parallel to the axes of the Brainerd drumlins a short distance northeast.

South and east of Lake Alexander the St. Croix moraine is marked by a striking northeast-southwest lineation expressed by a series of elongated lakes (e.g., Bass Lake, Fish Lake, Johnson Lake, Pugh Lake, Mallard Lake, Lake Alott, Long Lake) and steep ice-contact ridges (Pl. 1). Some of the ridges exhibit a distinctly serpentine outline and must certainly be interpreted as eskers. One of the better examples (SE¼ Sec. 3, T. 131 N., R. 30 W.) resembles the Brainerd-lobe esker just described; it is moderately sinuous, about 0.6 mile long, has a maximum relief of 140 feet, and trends S. 40°–50° W. Most of the ridges in this vicinity, however, are not so curvate and many are nearly straight. Insofar as it has been possible to determine, they are composed principally of sandy gravel derived from the northeast. However, deep road cuts through the highest and most conspicuous of the linear forms near the southeastern extremity of Lake Alexander (SW¼ Sec. 32, T. 132 N., R. 30 W.) show approximately 50 feet of calcareous Wadena-lobe outwash sand capped by a variable thickness of noncalcareous northeastern-source gravel.

Similar elongated ridges, several of which display serpentine outlines, are abundantly distributed throughout the rugged and largely inaccessible part of the St. Croix moraine that lies between Lake Alexander on the south and west and the Crow Wing and Mississippi rivers on the north and east, respectively. The majority trend northeast-southwest and are nearly parallel to the long axes of the streamlined hills of the Brainerd drumlin field. The sinuous ridges are interpreted as eskers and the linear forms, including those near Lake Alexander, as crevasse fillings. Although their full significance (fan-handles?) must await the results of future investigation, they appear to have formed normal to the ice front during an early stage of Brainerd-lobe stagnation.

STRIATIONS

General. Glacial striae within and adjacent to the Randall region are rare, partly because of the relative scarcity of bedrock exposures. Upham (Winchell and Upham, 1888, pp. 569, 603) was unable to cite the location of a single striated bedrock surface in the entire area of Wadena, Todd, Crow Wing, and Morrison counties. Leverett (1932, pl. 2; pp. 44–45) plotted two sets of striae at Randall, and stated that "an older set of striae bears eastward and is probably of pre-Wisconsin age, and a later set bears west-northwestward toward the St. Croix morainic system and appears to be correlative with it."

Striations at Randall. Careful examination of the numerous small outcrops of chlorite schist around Randall has failed to disclose the location(s) of the older set of striae mentioned by Leverett. Fortunately the markings are shown on Leverett's map, where they are plotted as bearing S. 86° E. When the curvature of the Wadena drumlins west of the St. Croix moraine is extrapolated eastward, the imaginary long axes of the drumlins approach a trend of S. 86° E. Thus, it appears possible that the earlier striae recognized by Leverett were engraved by the Wadena lobe advancing over Randall in a direction slightly south of east.

The second set of striations mentioned by Leverett, and plotted on his map as N. 47° W., was found upon two bedrock surfaces approximately 225 feet apart. The first outcrop is located just north of the railroad station at Randall, between U.S. Highway 10 and the Northern Pacific tracks; the second outcrop is situated in a clump of trees behind a dwelling, almost directly across the highway from the first exposure. In neither case do the striae exhibit any apparent asymmetry in longitudinal section and, therefore, give no indication as to the absolute direction of ice movement. When considered in association with all other lines of evidence, however, the striae lend strong support to Leverett's interpretation and to the present conclusion of ice flow from southeast to northwest. The striae gave nearly identical compass readings at the two exposures: N. 54° W. and N. 55° W. These bearings are consistent with the orientation of the drumlin axes south of Randall and with those near Pierz. It seems almost certain, therefore, that the Pierz lobe advanced over the south-central part of the Randall region in very nearly the same direction as in the vicinity of Pierz.

Striations near Little Falls. Two additional sets of striae, apparently unnoticed by previous workers, were discovered in the Randall region. These are located along the Elk River, 2 miles north of Little Falls, where the river is crossed by Morrison County Aid Road 45. The outcrop, a mica phyllite or phyllitic schist, is on the north side of the river about 15 feet upstream from the concrete bridge (SW cor. SE¼ Sec. 31, T. 130 N., R. 29 W.). A relatively large number of good striations and a group of several shallow grooves are oriented N. 9° W.; two wider striations trend N. 14° W. Two additional small grooves, striking N. 31° W., intersect both groups of markings giving the 9° bearing. It was not possible to determine which, if either, of the two sets of crossing striae was produced by an earlier ice movement. None of the scratches or grooves is sufficiently asymmetrical to indicate absolute direction of flow.

South of the bridge, dark-brown Pierz-lobe till and yellowish-brown Wadena-lobe till are discontinuously exposed in the river banks for several hundred feet downstream, suggesting that the striae may have been produced by either or both of these lobes. According to all lines of evidence, the Pierz lobe in this vicinity advanced in a direction about N. 55° W. Northward radiation of the ice, at least to the extent indicated by the 9° and 14° markings, is discredited by the east-west trend of the easternmost segment of the Darling esker, less than a quarter of a mile north of the striae locality. The orientations of the grooves and striations do not approach the postulated direction of flow of the Wadena lobe which, as stated earlier, appears to have been about S. 85° E. The Brainerd lobe almost certainly did not push this far south, at least in the area west of the Mississippi River, and there is no evidence favoring assignment of the markings to the Superior lobe. It is concluded that the striations and grooves are not indicative of the general direction of advance of any known glacier. It may only be rationalized that both sets were produced under conditions of very localized flow of the Pierz lobe caused by minor topographic irregularities.

5. LITHOLOGIC CHARACTER OF CENTRAL MINNESOTA DRIFTS

METHODS OF STUDY

In order to determine which of the lithologic characteristics of the central Minnesota Pleistocene deposits are most significant, several methods of study were chosen. These may be grouped into two categories, (1) field observations and (2) laboratory analyses. Field observations included determinations of (a) texture, (b) color, (c) degree of calcareousness and depth of leaching, (d) approximate pH, (e) pebble content, and (f) miscellaneous drift characteristics. Discussion of these criteria follows immediately. Laboratory analyses included investigations of (a) size distribution, (b) soluble matter, (c) heavy minerals, and (d) clay mineralogy. Discussion of laboratory procedures and results is reserved for a later section of this report.

FIELD OBSERVATIONS

Texture. Field determinations of texture were made by rubbing moist samples of drift between the fingers, supplemented by hand-lens examination. Textural class names used by the U.S. Department of Agriculture (Soil Survey staff, 1951, pp. 207–16) were applied to all deposits described in detail. In the case of till, only the matrix was considered in the selection of a class name; modifying adjectives denoting shapes and sizes of coarse fragments (greater than 2 mm.) were omitted. Unusually high or low percentages of granules and pebbles were noted in a general way, however.

The soils terminology was employed in order to define more specifically the texture of a till in the field than has commonly been practiced by geologists. A deposit is described as a loam till or as a sandy loam till, for example, instead of simply as a "sandy" till.

Color. Color measurements were made in the field by use of the modified Munsell color chart widely employed by soil scientists (Soil Survey staff, 1951, pp. 194–203, figs. 30–36). Each sample was assigned a color name and a Munsell notation that includes hue, value, and chroma. All determinations were made on moist specimens and performed in the shade. Mottling, if unusually marked, was also noted.

Dreimanis and Reavely (1953, p. 241) met with some difficulties in applying a rock-color chart to tills along the north shore of Lake Erie because of differences in moisture content and degree of oxidation. It is known that the value of a moist soil is from ½ to 3 steps darker than that of a dry sample, and that the chroma may change from −½ to +2 steps; the hue, however, is seldom affected by moisture changes (Soil Survey staff, 1951, p. 193).

Dissimilar hues of the central Minnesota tills are associated with other lithologic differences, particularly degree of calcareousness and pebble content. Hue is concluded to be an important criterion of drift discrimination. Variations in value and chroma are not considered significant in this respect and are attributed to differences in moisture content and/or intensity of oxidation.

Degree of Calcareousness. The presence of free carbonates was tested with a dilute (approximately 1:4) solution of hydrochloric acid. Five degrees of relative calcareousness were recognized in the field, based upon intensity of effervescence and the quantity of acid necessary to promote an observable reaction. Since reaction is a function of texture and permeability in addition to the amount of acid-soluble carbonate present, only a general relationship between these categories and total carbonate is implied. Noncalcareous drifts are those which exhibit no apparent effervescence. A very slightly calcareous deposit is defined as one in which a reaction may be heard when a highly acid-moistened sample is held to the ear; the effervescence can not be seen, however, as in the case of a slightly calcareous material. A drift is described as distinctly calcareous when the emission of bubbles is readily apparent after a few drops of acid have been applied. If the reaction is violent and occurs immediately upon the addition of only one or two drops of acid, the sediment is considered highly or extremely calcareous.

Depth of leaching of calcareous drift was determined in the usual manner. In general, the contact between leached and unleached horizons could be located within 2 or 3 inches of its actual depth.

Approximate pH. The Truog soil-reaction tester, model number 693, was employed to determine colorimetrically the approximate pH values of the drifts. In this test two or three drops of an indicator solution are placed on a spot plate and just enough sample is added to fill the depression. A light film of reaction powder is then sprinkled over the paste and the resultant color is compared with a standard set of colors, graduated in 0.5 units of the pH scale.

The accuracy of this method appears to be very satisfactory for field determinations, as suggested by the close correlation between acid reaction and pH values. Tests of distinctly calcareous and highly calcareous drifts consistently resulted in pH values of 8.0, whereas noncalcareous materials gave pH readings of 7.0 or below.

Pebble Content. Close attention was devoted to the bedrock types represented in the drifts of central Minnesota. The general pebble and cobble assemblage was noted at each locality visited and a search for characteristic erratics undertaken at the more critical exposures. Stones of pebble size (4–64 mm.) were collected from till and gravel deposits, washed, broken, and identified with the aid of a hand lens. Collections were made from well below the base of the B soil horizon after the exposures had been scraped clean of all superficial debris. A total of 100 stones was counted from each of 30 localities (Appendix A); results of the pebble analyses are given in Tables 2 and 3.

Miscellaneous Observations. In addition to the lithologic characteristics described above, several miscellaneous items were noted. These included depth and degree of oxidation, drainage conditions and moisture relations, degree of compaction, nature of contacts, thickness of beds, sorting and roundness of sand grains, and soil-profile characteristics.

"KEEWATIN" DRIFT

General. In the north-central United States the term "Keewatin" is used to designate all drift deposited by ice that advanced from the northwest, i.e., from the general direction of the Keewatin "center" of glaciation west of Hudson Bay. As pointed out by Ruhe and Gould (1954, p. 791), the term is employed in a sense of provenance and does not necessarily imply deposition by an independent glacier. Thus, instead of a single late Wisconsin "Keewatin ice sheet" several discrete lobes and sublobes of Keewatin origin are now recognized. (See Leverett, 1932; Cooper, 1935; Ruhe, 1950b, 1952a; Ruhe and Gould, 1954; Wright, 1952, 1953, 1954, 1955, 1956, 1957c.)

The Keewatin drift discussed in this report was deposited by the Wadena lobe and its glacio-fluvial derivatives. The lithologic name "gray sandy till" suggests the general characteristics of the ice-deposited material.

Gray Sandy Till. Wadena-lobe deposits are widely distributed in central Minnesota, having been identified over an area exceeding 2500 square miles. Gray sandy till is the surficial material throughout much of the Wadena drumlin field and appears also to make up Leverett's Bemis and most of his Altamont and Gary moraines west and southwest of the drumlin field (Wright, 1954). In the Randall region it only locally occurs as the surface drift, but it is well exposed beneath younger deposits in numerous cuts and can be reached with the auger at several points. Observations of the lithologic characteristics of the till were made at roughly 80 localities within and adjacent to the Randall region and in the drumlin field a few miles west of the Long Prairie River.

Because of the loose sandy texture and consequently good internal drainage of the Wadena-lobe till, its unoxidized dark-gray to blue-gray color is seldom observed. Highway and railroad cuts, some more than 30 feet deep, fail to disclose the original color of the deposit. In fact, only one exposure of unaltered drift (horizon 5 of Leighton and MacClintock, 1930) is known from the Randall region; at this locality, which is about 5 miles west of Randall in north Parker Township (SW¼SE¼ Sec. 5, T. 130 N., R. 31 W., Morrison Co.), the till is very compact and abnormally high in clay. These conditions explain the poor drainage and virtual arrest of oxidation. Drillers in the area locally encounter "blue clay" or "bluish-gray clay" at depths of 15–20 feet or more, beneath either brown sandy till or the oxidized equivalent of the gray. Thus, it is apparent that the Wadena till is too deeply oxidized for its unaltered color to be of practical value in its identification. Numerous measurements disclose that the typical color of oxidized Wadena till is yellowish brown (10YR 5/4–10YR 5/6). At shallow depths where the deposit is more severely oxidized or is enriched in clay and iron oxide (B_2 soil horizon) the color is dark yellowish brown (10YR 4/4). Locally where the till is less sandy and contains more silt and clay than usual, though not so much as the unoxidized drift near Randall, the hue is more yellow and the over-all color is grayish brown (2.5Y 5/2) when very moist and light olive-brown (2.5Y 5/3) or olive-brown (2.5Y 4/4) when drier. Exposures of this nature are not abundant, however, and the typical oxidized color of the till is yellowish brown.

The designation "gray sandy till" is somewhat misleading, therefore, inasmuch as the term "gray" applies only to unoxidized till which is not commonly exposed. The same statement has been made by Ruhe and Gould (1954) with reference to Upper Wisconsin "gray" drifts of southern Minnesota and Iowa. Perhaps it would be more accurate to identify the Wadena-lobe drift as "yellowish" or "yellowish brown." To nearly all geologists and pedologists of the region, however, the term "gray drift" has long implied a deposit rich in limestone derived principally from southern Manitoba. In this sense it is virtually synonymous with "Keewatin drift" and it seems best, for the sake of clarity, to retain the term "gray."

In western Morrison and eastern Todd counties the Wadena till typically is a sandy loam. Variations from this textural class are uncommon but at a few localities the drift is a loam, sandy clay loam, clay loam, or clay (the unoxidized till at the north Parker exposure). The till generally is highly calcareous and moderately alkaline (pH 8.0). Depth of leaching where the till reaches the surface averages about 30 inches but is known to vary from 26 to 40 inches, depending upon topographic position, texture of the till, and degree of soil development. At most places the base of the leached zone and the bottom of the B horizon coincide.

Soil Profile 1 illustrates podzolic development upon the till and the interrelationships among color, texture, and calcareousness of the soil and parent material.

The light color, high degree of calcareousness, and moderate alkalinity of the Wadena till are due to the incorporation of enormous quantities of limestone. Pebbles and granules of limestone are abundantly distributed throughout the matrix of the till at nearly all localities visited. Analyses of pebble samples collected from eight exposures of till and two of stratified drift (Table 2 and Appendix A) show a predominance of limestone over all other rock types; limestone, including a small fraction of dolomitic limestone, averages 38 per cent — about 16 per cent and 24 per cent greater

TABLE 2. ANALYSES OF PEBBLE SAMPLES FROM GRAY, RED, AND BROWN DRIFTS OF CENTRAL MINNESOTA
(Percentage by count in each rock type)

Sample	Quartz	Granite	Micro-granite	Gneissic granite	Syenite	Gabbro	Micro-gabbro	Felsite	Porphyritic felsite	Basalt	Chert	Sandstone	Siltstone	Limestone	Quartzite	Graywacke	Slate	Schist	Greenstone	Iron formation
Gray drift																				
PT25–52*	3	8	1	3		2	4	4	2	9	1			45	3	1	2	4	6	2
PG37–52†	1	16	2	1		1	2		1	15				57		2			2	
PT39–52	3	27	1	1		3	14		2	18	2			15	1	6	1		6	
PT42–52	2	17	2	1		3	11	5	10	15	1			11	4	16	1			1
PT56–52	5	18		1	2		7	9	3	23	1			12	3	5		3	7	1
PT6–53		8	1							10				75	3		1		2	
PT19–53	4	14			1		9	3	3	20	3	1		36	3	3				
PT20–53	3	17	1	2			6		5	6	1			46	1	4	3	1	4	
PG83–53	1	10		3				1		13	1	2		56	4	3	1	1	4	
PT94–53	1	30	1		4		9	2	3	10				27	2	9			1	1
Red drift																				
PT60–52	2	5	1	2	1		4	11	4	32		18	3		1	12			3	1
PT18–53	5	10	1	1		7	5	11		28		10	2	5	1	7			6	1
PT25–53		7			1	3	4	6	5	18	1	34			1	8		6	4	2
Brown drift																				
PT54–52	3	18	3	1	1	4	11	5	9	7	1					17	3	1	5	11
PT59–52	1	22	3		2	2	6	3	9	14						16	5	7	4	6
PT62–52		18	2		1	1	5	9	2	17		2	1		3	18	5	3	6	7
PT5–53	1	19	5		4	6	6	9	8	15	1					18	1		4	3
PG23–53		18			3	8	12	5	3	15					1	17	3	5	5	5
PT24–53	1	15			2	1	10	10	1	34		2	2		2	2	3	3	6	6
PG28–53	1	16		11	2	7	4	13	1	21					3	8	2	4	2	5
PT45–53	4	16	1	1	2	6	5	2	3	19	2	1			2	20	4	6	2	4
PT66–53	2	25	4		2	5	5	1	7	6					1	19	1	7	7	8
PG67–53	2	32		2		4	4	9	10	15	1				3	12		1	2	3
PT71–53	2	18	5	2	2	7	4	1	13	10		1			1	15	1	8	4	6
PG72–53	2	20	5	3	2	11	10	2	2	9					1	15	1	8	6	3
PG74–53	5	20	2		1	8	2	12	6	9	1		2		2	10	1	5	12	2
PG77–53		23	4	2	2	5	11	4	5	14	3				1	14	4		6	2
PT81–53		16	1	3	1	2	6	5	12	18	1					20	3	3	5	4
PT91–53	2	16	1	3	2	3	5	7	10	15					1	19	1	2	6	7
PT93–53	2	25		2	2		11	3	11	18		2			2	17		1	3	1

* PT prefix denotes pebble sample from till. † PG prefix denotes pebble sample from gravel.

SOIL PROFILE 1

Location: NW¼ Sec. 4, T. 131 N., R. 33 W., Todd Co.; road cut on south side of State Aid Road 14, near crest of first hill (drumlin) east of State Aid Road 2.

Conditions: Gently rolling topography, A slope, present vegetation grass, moisture at field capacity, depth of leaching 30 inches.

Horizon	*Depth (inches)*	*Description*
A_1	0–6	Dark grayish-brown (10YR 4/2) sandy loam; finely granular structure.
A_2	6–15	Yellowish-brown (10YR 5/4) loamy fine sand; nearly structureless, loose.
B_1	15–27	Yellowish-brown (10YR 5/6) sandy loam; finely granular structure.
B_{21}	27–30	Dark yellowish-brown (10YR 4/4) sandy clay loam; slightly blocky structure, plastic when moist.
B_{22}	30–32	Similar to B_{21} but very slightly calcareous.
C_{ca}	32+	Yellowish-brown (10YR 5/6) sandy loam till; highly calcareous.

than the next two most common rock types present (Table 3). The high degree of variation (11–75 per cent) is partly explained by the fact that samples containing the lower percentages of limestone were obtained at localities where the gray till is closely associated stratigraphically with limestone-deficient brown till and is presumably contaminated. As noted earlier, the only known source of limestone is the Paleozoic carbonate terrane of southern Manitoba and the northwestern corner of Minnesota.

The Upper Wisconsin Keewatin drifts of Minnesota are commonly characterized by a concurrence of fragments of Paleozoic limestone and gray to green-gray Cretaceous shale. In fact, the clayey character of most of these deposits is generally attributed to the incorporation of shale derived largely from formations that underlie western Manitoba and the Red River Valley of the Dakotas and western Minnesota (Fig. 4). This limestone-shale or limestone-clayey till association is mentioned in many reports concerning the Pleistocene geology of the state. (See Winchell and Upham, 1888, pp. 294, 541–42; Upham, 1900, pp. 283–84; Leverett, 1915, p. 33; 1932, p. 65; Leverett and Sardeson, 1917, p. 15; 1919, p. 12; Allison,

TABLE 3. SUMMARY OF PEBBLE ANALYSES OF THE GRAY, RED, AND BROWN DRIFTS
(Average percentage of each rock type)

Rock Type	Gray Drift (10 samples)	Red Drift (3 samples)	Brown Drift (17 samples)
Granitic	21.6	12.0	27.2
Gabbroic	7.1	7.7	11.6
Felsite	5.3	12.3	12.5
Basalt	13.9	26.0	15.1
Chert	1.0	0.3	0.6
Sandstone and siltstone	0.3	22.3	0.8
Limestone	38.0	1.7	0.0
Quartzite	2.4	1.0	1.4
Graywacke	4.9	9.0	15.1
Slate and schist	1.8	2.0	6.0
Greenstone	3.2	4.3	5.0
Iron formation	0.5	1.3	4.9

1932, p. 6; Cooper, 1935, p. 16; Thiel, 1944, p. 79; 1947, p. 32; Ruhe and Gould, 1954, p. 789.)

Unlike most of the Keewatin glacial deposits of Minnesota, however, the Wadena till is virtually destitute of Cretaceous shale. Wright (1954, 1957c) notes that Cretaceous shale is not well represented and offers this as partial evidence that the Wadena lobe came from the northwest rather than from the southwest. In the drift of Morrison and eastern Todd counties very few fragments of shale were observed and none could be positively identified as Cretaceous. Of the 10 pebble samples of Wadena drift analyzed, not one was found to contain a single fragment of shale. The absence of shale might be explained in either of two ways:

(1) The rock was completely pulverized during glacial transport and its ground-up products incorporated into the matrix of the till. Holmes (1952) has cited evidence to show reduction by crushing and abrasion of pebbles and cobbles of shale to fine particles over short distances of transport. It seems unlikely, however, that attrition of Cretaceous shale was so thorough as to erase all traces of its presence. Some fragments should have survived, as they did in other Keewatin drifts over comparable distances of transport. If, on the other hand, pulverization *was* as complete as is indicated by the lack of shale, then the matrix of the till should be clayey. But the till of the Wadena lobe is predominantly sandy and contains only a small proportion of clay. This explanation, therefore, is rejected.

(2) The ice did not pass over an area in which shale constitutes a significant part of the bedrock. This explanation meets with no apparent objections and is considered more acceptable than the first. It appears likely that in its advance across southern Manitoba the Wadena lobe followed the Paleozoic limestone lowland east of the Cretaceous escarpment, yet entered Minnesota without crossing the Cretaceous shale belt of the Red River Valley.

Stone counts show that granitic rocks rank second to limestone, averaging 22 per cent of the pebble content of the gray drift (Table 3). Granite is the predominant rock type of this group but the category also includes small percentages of quartz, microgranite, gneissic granite, and syenite (Table 2). The abundance of granitic pebbles is in accord with the known distribution of bedrock types in northern Minnesota and east of the limestone belt in southern Manitoba and western Ontario.

Following limestone and granite, the more common rock types represented are basalt, gabbro, felsite, and graywacke. Some of the gabbro was locally derived from the vicinity of Philbrook in northern Todd County; the majority of the gabbroic pebbles, however, are texturally unlike the coarse-grained gabbro and anorthosite described by Harder and Johnston (1918, pp. 49–50) that outcrop near Philbrook and must have been derived from farther north.

Stratified Keewatin Drift. Sorted and stratified deposits of the Wadena lobe range in texture from silty clay of lacustrine origin to coarse sand

and gravel. Where uncontaminated they are easily recognized by their light color and by their reaction to hydrochloric acid. In the case of gravel deposits, limestone pebbles are very abundant (see samples PG37–52 and PG83–53, Table 2), and all stones are commonly coated with secondary calcium carbonate.

"PATRICIAN" DRIFT

General. The "Patrician red drift" of eastern and central Minnesota was considered by Leverett (1932) to have been deposited by an ice sheet that entered the state from the north-northeast, i.e., from the general direction of the Patrician "center" of glaciation south of Hudson Bay. The Patrician drift is commonly described as a red to reddish-brown loose-textured sandy to gravelly till, characterized by a general absence of limestone but by an abundance of basalt, gabbro, granite, felsite, and sandstone pebbles.

The Patrician till of central Minnesota as mapped by Leverett is here subdivided into two lithologic types, red sandy till and brown sandy till. According to Wright (1952; 1953, p. 469; 1955, p. 407; 1956, p. 10), the red sandy till was deposited by the Superior lobe, which moved out of the Lake Superior basin and spread southwestward to central and southeastern Minnesota. Brown sandy till was deposited by both the Pierz and Brainerd lobes, physiographic evidence for which has already been presented.

Red Sandy Till. Only two exposures of red sandy till have been discovered in the Randall region proper, where the dominant surface and subsurface drifts are gray and brown. To the south and east, however, exposures of red sandy till are more manifest and studies of the drift have been extended to northern Stearns, eastern Morrison, Benton, and Isanti counties. Superior-lobe deposits have been described from the Minneapolis vicinity and Stearns County (Wright, 1953) and from the region about the head of Lake Superior (Wright, 1955). Lithologic descriptions and stratigraphic relations of the Patrician till of Dakota County (Ruhe and Gould, 1954, pp. 784–88) strongly suggest that it is a Superior-lobe drift, at least in part.

Despite its thinness and irregular distribution, the Superior till of central Minnesota can usually be recognized easily by its lithologic characteristics. The most distinctive of these is color, the hue being median yellow-red (5YR). Chroma and value are not consistent, so that the over-all color of the till varies from yellowish red (5YR 4/6) to reddish brown (5YR 4/4) and dark reddish brown (5YR 3/4); these variations are ascribed mainly to contamination by other drifts and secondarily to differences in moisture content and intensity of oxidation.

The reddish color of the Superior till is primary and is attributed to the assimilation of red sandstones and shales of the Upper Keweenawan Fond du Lac beds and Hinckley sandstone of eastern Minnesota. The explanation by some authors (e.g., Allison, 1932, pp. 8, 53, 130, 193, 214; Ruhe and Gould, 1954, p. 784) that the red color is due principally to ferruginous materials derived from the iron-range regions is considered untenable. The following reasons are offered in support of this conclusion:

(1) The Superior lobe is believed to have advanced into the southeastern part of central Minnesota, and into adjoining regions farther south and east, from the northeast, flowing out of the Lake Superior basin as proposed by Wright. Iron formations have not been mapped between the head of the lake and the known distribution of red sandy till in central and southeastern Minnesota. On the other hand, much of this area is underlain by red clastics (Fig. 4).

(2) With certain local exceptions, deposits left by ice known to have traversed the iron districts did not acquire a red coloration: (a) Wright (1955, p. 408) has cited drift resting directly on iron formation in which only the basal few inches of the drift are colored red. (b) Materials deposited by the St. Louis sublobe of the Des Moines lobe show no apparent color contamination as the result of being transported by ice flowing across the iron-bearing rocks of the western end of the Mesabi district, but have retained their distinctive gray (buff where oxidized) color. The red Keewatin drift south of the Mesabi (Leverett and Sardeson, 1917, pp. 47–48; Leverett, 1932, p. 65; Thiel, 1947, p. 123) has recently been reassigned as Valders (Wright, 1955). (c) The Brainerd lobe followed the strike of the Deerwood iron formation for a known distance of 30 miles across Crow Wing County and into northwestern Morrison County; yet the till is not red, but distinctly brown. The possibility exists, of course, that the Brainerd brown and other non-red tills did not acquire a red color because of the presence of yet unidentified older drifts which served to protect the underlying iron-bearing rocks from glacial erosion. If the load of the Brainerd lobe was not colored red as the result of passing over drift-protected iron formations, then it seems probable that the Superior till should not be red for the same reason.

(3) A significant relationship exists between the color and the pebble content of the red sandy till. Sandstone fragments derived from the red clastic beds of eastern Minnesota are common and at several localities they occur in abundance. Some of the stones are firm, but a great many more are in a partial or advanced state of decay and can be crushed between the fingers. As one proceeds to pick out the disintegrating reddish fragments from the till, the source of its color becomes apparent. Hand-lens examination of the matrix of the drift indicates a high percentage of quartz grains coated either with hematite or hematitic clay.

Because of the manner of its occurrence (patchy distribution, thinness, association with other drifts) it is difficult to secure pebble samples from the red till of central Minnesota adequate for making analyses. For this reason only three samples were obtained. Sandstone is the dominant component of one (PT25–53, Table 2) and is nearly twice as abundant as the second most common rock type; 34 per cent of the pebbles are sandstone, of which 29 per cent are red to purple. The other two samples are lower in sandstone but the percentages are still significantly higher than in gray and brown drifts of the area, which rarely contain more than one or two sandstone pebbles in a hundred (Table 2). The exposures from which these two latter samples were obtained are about 30 miles west of the first and the lower sandstone content may partly reflect a greater distance of transport, which permitted more thorough crushing of the rock and incorporation of its mineral constituents into the matrix of the till. According to Ruhe and Gould (1954, p. 784), red sandstone of the variety that outcrops in the Lake Superior region is abundant in the red to reddish-brown Patrician till of Dakota County. Table 1 (p. 772) of their paper indicates that the average sandstone pebble content of eight samples is 12.5 per cent.

Whereas sandstone is a major constituent of the red sandy till, iron formation is not well represented. Counts of the three samples from central Minnesota average a little more than 1 per cent iron-formation pebbles (Table 3). In the eight samples analyzed by Ruhe and Gould from Dakota County iron-formation pebbles average about 0.5 per cent.

In addition to sandstone the red sandy till is characterized by an abundance of basalt and by lower but significant percentages of red to purplish-red felsite (including porphyritic rhyolite), acidic intrusive rocks, graywacke, and gabbro. Most of these rocks underlie extensive areas along the north and south shores of Lake Superior or between the head of the lake and southeastern central Minnesota (Fig. 4). Their plentiful occurrence along with red sandstone substantiates Wright's conclusion of a southwestward-advancing ice lobe from the Lake Superior basin. Other rock types represented in the red sandy till are shown in Tables 2 and 3.

The texture of the Superior red till commonly is a sandy loam. The degree of calcareousness and pH range from noncalcareous and slightly acid (pH 6.5) to distinctly calcareous and moderately alkaline (pH 8.0). This variation in calcareousness, and probably pH also, is the result of differential contamination by calcium carbonate derived from the gray drift of the Wadena lobe. In exposures showing gray till overlying red till it is apparent that the carbonate of the latter is largely, perhaps entirely, secondary, having been precipitated from saturated solutions originating in the upper till. The addition of carbonate has been sufficient in some cases to raise the pH of the red till to 8.0 and to alter its color from reddish brown (5YR 4/4) to yellowish red (5YR 4/6). However, the red till is locally calcareous where it does not underlie Wadena-lobe drift but occurs instead in contact with noncalcareous brown till of the Pierz lobe. Deposition by descending waters can not explain the presence of small amounts of carbonate at these exposures. It is concluded that the Superior lobe advanced over an area of limestone-rich drift, incorporating just enough carbonate to make its own deposits locally calcareous. Additional evidence for this conclusion is included in the section on stratigraphy.

Brown Sandy Till. The lithologic characteristics of the Pierz and Brainerd tills are so similar that they may be considered together. In fact, the two drifts are apparently identical and no satisfactory lithologic criteria have yet been found to aid in their differentiation. If it were not for discrete landforms (drumlins and eskers) trending at nearly right angles, assignment of the brown sandy till to two ice lobes would not be justified. It may be that the Pierz and Brainerd lobes actually represent protrusions of one ice mass, which gave birth to two sublobes that deposited lithologically similar drift.

The color of the Pierz and Brainerd tills is brown or dark brown (7.5YR 4/4). The drift is normally noncalcareous and slightly acid (pH 6.0–6.5). These characteristics are very uniform throughout the area studied, except locally where the brown till is highly contaminated or mixed with Wadena-lobe drift; at these localities the brown till is commonly calcareous, neutral to moderately alkaline (pH 7.0–8.0), and its hue may be altered to 10YR. Texturally, the till is a sandy loam. It contains an abundance of pebbles and the surface of the drift is characteristically marked by numerous cobbles and boulders.

The brown color, noncalcareous nature, and sandy texture of the Pierz and Brainerd tills appear to be due mainly to the incorporation of dark-colored igneous and low-rank metamorphic rocks derived from northeastern Minnesota. Stone counts were made on 17 pebble samples; 11 of these samples were collected from till and 6 from ice-contact gravel deposits. The results (Tables 2 and 3) show that granite, basalt, felsite, gabbro, and graywacke are well represented; greenstone, slate, schist, and iron-formation pebbles are less common. All of these rock types are more abundant in the brown drift than in the gray.

Neither limestone nor red sandstone pebbles are important constituents of the brown till. Not a single limestone fragment was found in any of the brown-drift pebble samples; sandstone or siltstone pebbles were present in only 6 of the 17 samples and their combined percentage averages less than 1 per cent (Table 3). The occurrence of limestone and sandstone, when present, appears to be due to contamination from the gray and red drifts, respectively. Iron-formation pebbles, on the other hand, are more abundant than in either of the other drifts; the brown drift averages nearly 5 per cent. Quartzite may be less common in the brown drift than in the gray.

It would seem reasonable to expect a somewhat higher percentage of granitic pebbles in the Pierz drift than in the Brainerd drift, inasmuch as the Pierz lobe crossed the central Minnesota granite terrane in its westward advance across northern Mille Lacs and eastern Morrison counties. Conversely, the Brainerd drift should contain a relatively greater proportion of slate, schist, and iron-formation pebbles acquired by following the strike of the Animikie series and the Deerwood iron formation across Crow Wing County. As yet, this writer has been unable to detect any significant difference in pebble content between presumed Pierz-lobe drift and probable Brainerd-lobe deposits. Additional pebble analyses, particularly of samples collected from the Pierz and Brainerd drumlin fields, are necessary before the expected relationship is confirmed (or rejected) as a criterion for differentiating between the two drifts.

The brown sandy till of central Minnesota appears to be lithologically similar to that of Cook County in northeasternmost Minnesota. The brown sandy till of this latter area was described by Sharp (1953, pp. 860–62) and attributed by him to the Rainy lobe of Elftman (1898), although Leverett (1932, pls. 1 and 3) apparently believed that it was deposited by the Superior lobe. Deposits of younger drift cover most of the intervening distance of 165 to more than 200 miles between Cook County and the central Minnesota exposures, and subsurface tracing of drifts has not been undertaken.

In Cook County the flow of the Rainy lobe was from north to south, except in the southern part of the county where it changed to a southeasterly direction (Sharp, 1953). The axis of the Rainy lobe, however, was northwest of Cook County, so that the central part of the lobe entered northern Minnesota with a heading of S. 40° W. (Elftman, 1898, p. 108; pl. 11). Evidence has already been introduced to show that the Brainerd lobe also flowed from northeast to southwest, in a direction of S. 40°–50° W. Both lithologic and physiographic evidence suggest, therefore, that the brown sandy tills of central and northeastern Minnesota may have been deposited by the same ice lobe, as inferred by Wright (1955, pp. 407–8). If this was the case, then the Pierz and Brainerd lobes might be considered sublobes of the Rainy lobe (Wright, 1956, p. 11).

Stratified Patrician Drift. Stratified deposits of the Superior, Pierz, and Brainerd ice lobes range from well-sorted clay of lacustrine origin to poorly sorted ice-contact gravel. Brown clay and silt are interpreted as glaciolacustrine and glacio-fluvial deposits derived from the Pierz and Brainerd lobes. Red clay has been identified only near Randall and is interpreted as a lacustrine sediment associated with Superior-lobe ice.

Most of the coarser stratified deposits are noncalcareous sand and gravel derived from the Pierz and Brainerd lobes; these are widely distributed throughout the Randall region and adjacent areas. The pebble assemblages (Table 2) are similar to those of the brown sandy till, characterized by an abundance of granite, basalt, felsite, gabbro and graywacke pebbles. Limestone fragments are rare or absent and, unlike the stratified drift of the Wadena lobe, a coating of secondary calcium carbonate on the pebbles is not characteristic. Locally, however, the gravel deposits may be slightly calcareous. No deposits of sandstone-bearing reddish-colored gravel are known to occur within or near the Randall region. Red Superior sand has been positively identified at only one locality, where it underlies and grades laterally into red sandy till.

6. PLEISTOCENE STRATIGRAPHY OF CENTRAL MINNESOTA

GENERAL STATEMENT

During the early stages of this investigation the author, following Leverett, classified the brown sandy till and associated glacio-fluvial sediments simply as "Patrician" of Middle Wisconsin age. Lighter colored limestone-rich deposits were thought to be part of the "young gray drift" (Late Wisconsin) and to represent a previously unrecognized eastward extension of the Des Moines lobe. Thus, the eastern brown drift was designated as Cary and the calcareous material was assigned to the Mankato.

It soon became apparent, however, that these assignments were not fully acceptable. Numerous exposures were discovered in which brown sandy till unmistakably overlies calcareous gray drift, indicating that the brown must be somewhat younger. Further search showed that, although the usual superposition is brown over gray, the two are locally interbedded.

As it became clear that the Patrician till could be subdivided into two lithologic types (brown sandy till and red sandy till), it also became apparent that the stratigraphic relations involving three till classes and four ice lobes are very complex. Exposures showing interbedding of red and brown, of gray and red, and of brown and gray tills are not uncommon in central Minnesota. Several sections illustrating the stratigraphic relationships of the various deposits are described below. Most of these are located within the Randall region proper.

SECTION DESCRIPTIONS

Irish Creek. Excellent stratigraphic sections attesting to the relative ages of the gray, brown, and red drifts occur in the south-central part of the Randall region on the slopes of the Irish Creek drainageway. The first exposure is located 0.6 mile west of the creek in a deep drainage ditch on the north side of Morrison County Aid Road 52 (S½SW¼SE¼ Sec. 31, T. 130 N., R. 31 W.), where Stratigraphic Section A is exposed (Fig. 8).

STRATIGRAPHIC SECTION A. WEST IRISH CREEK

	Thickness (feet)
2. Pierz till: sandy loam till, brown or dark-brown (7.5YR 4/4), noncalcareous, slightly acid (pH 6.5); pebbles of granite, red felsite, graywacke, basalt, and gabbro. Contact with underlying unit very sharp, rises westward from base of cut to surface with average apparent dip of 20° E. Samples T5–53 and PT5–53......	0–6
1. Wadena till: loam till, grayish-brown (2.5Y 5/2) when very moist to light olive-brown (2.5Y 5/3) when drier, with yellowish to white (limestone) and reddish (hematite) mottles, extremely calcareous, moderately alkaline (pH 8.0); limestone pebbles and granules exceedingly abundant. Texture is finer grained, limestone more abundant, and till less strongly oxidized than at most exposures of Wadena till. Depth of leaching shallow (2 inches), and till is highly calcareous 4–5 inches beneath surface but soil profile has been artificially removed. Samples T6–53 and PT6–53. Base concealed	0–6

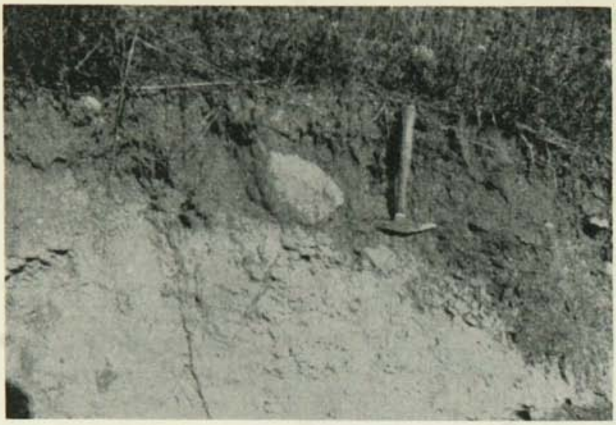

FIGURE 8. — Contact of brown Pierz till over gray Wadena till on west slope of Irish Creek drainageway. Soil profile has been artificially removed. SW¼SE¼ Sec. 31, T. 130 N., R. 31 W., Morrison County.

This is one of the very best contacts of Pierz brown over Wadena gray in the entire Randall region. The two tills are dissimilar in all important lithologic characteristics — color, texture, degree of calcareousness, pH, and pebble content. Stone counts indicate that 75 per cent of the gray-till pebbles are limestone whereas no limestone was present in the brown-till pebble sample (Table 2). Another but less obvious contact of these two drifts is located 0.3 mile east near the bottom of the Irish Creek channel (SE cor. Sec. 31, T. 130 N., R. 31 W.).

One-quarter mile east of Irish Creek there are two fine ditch exposures on opposite sides of the road. The main section on the north side (SW cor. SE¼ Sec. 32, T. 130 N., R. 31 W.) shows gray till overlying red (Section B).

Except for calcareousness and pH values, the contrast between the gray and red drifts here is as striking as that of the gray and brown tills west of Irish Creek. The color difference is very pronounced and the gray till is

STRATIGRAPHIC SECTION B. EAST IRISH CREEK

	Thickness (inches)
3. Wadena till: loam or sandy loam till, yellowish-brown (10YR 5/4), mottled with white (limestone) and rust (limonite), highly calcareous, moderately alkaline (pH 8.0); limestone pebbles abundant, granite and basalt pebbles common. Contact with underlying units generally very sharp but basal 2–3 inches of till locally contain laminae of underlying red till; contact dips gently eastward from near surface to base of ditch. Samples T19–53 and PT19–53	13–34
2. Fine pebble and sand lag: discontinuous, not readily apparent	0–1
1. Superior till: sandy loam till, yellowish-red (5YR 4/6), distinctly calcareous, moderately alkaline (pH 8.0); disseminated carbonate appears to be largely secondary, deposited by descending solutions from upper till; red sandstone, basalt, gabbro, granite, and red felsite pebbles common; some limestone. Contact with overlying units sharp, rises westward. Samples T18–53 and PT18–53. Base concealed	0–17

distinctly finer grained than the red. The Wadena till contains 36 per cent limestone pebbles, the Superior only 5 per cent (Table 2). Although the percentage of sandstone pebbles in the red till is not high (10 per cent), the presence of sandstone, as opposed to its apparent absence in the gray till, is significant.

Twenty feet west of this section a 12-inch layer of red till definitely underlies gray till, and appears in turn to overlie more gray till. About 30 feet farther west, at a point where the red till reaches the surface, 15 inches of light-colored calcareous sand separate two red-till units from each other. The intervals between the three exposures in the north ditch are largely covered, so the sections can not be correlated.

In the ditch on the south side of the road (NW cor. NE¼ Sec. 5, T. 129 N., R. 31 W.) three drifts occur in stratigraphic superposition (Fig. 9). Section C describes the sequence at the eastern end of the cut.

STRATIGRAPHIC SECTION C. EAST IRISH CREEK

	Thickness (inches)
4. Noncalcareous brown sandy Pierz-lobe till	18
3. Calcareous Wadena-lobe till	9
2. Red sandy Superior till	4
1. Red Superior sand. Base concealed	2

The contact between the Pierz and Wadena tills, which is less sharp here than on the western slope of the drainageway, rises westward, the brown till gradually thinning to zero thickness 8 feet from the eastern end of the cut. The Wadena-Superior contact is slightly irregular, characterized by several thin tongues of red till extending into the overlying limey drift. A few thin lenses of red till occur in the lower 3–4 inches of the gray; these may also be tongues continuous with the main mass of red beneath the

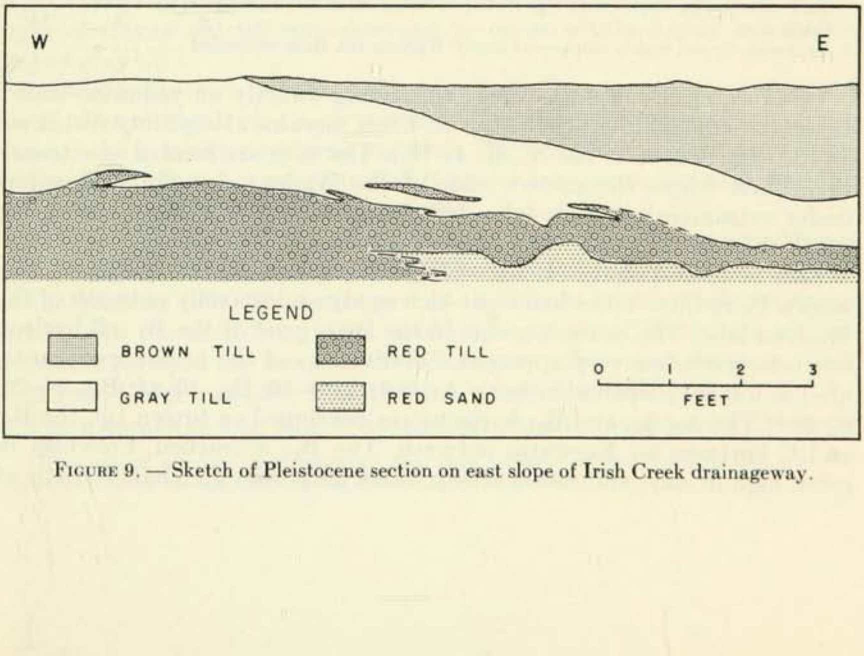

FIGURE 9. — Sketch of Pleistocene section on east slope of Irish Creek drainageway.

face of the cut. The contact rises to the west but at a lower angle than the Pierz-Wadena contact, so that the thickness of the Wadena till increases to 18 inches near the western end of the exposure. The red drift thickens to 15 inches on the west where it consists entirely of till, the sand grading into till near the middle of the cut.

Stratigraphic superposition of drifts at the Irish Creek exposures shows that the Wadena lobe entered this area after the Superior lobe and prior to the advance of the Pierz lobe. The absence of soil or weathering profiles between the tills suggests short time intervals between advances. Thin interbeds of red drift at the base of the gray and of light-colored calcareous sand (interpreted as proglacial Wadena outwash) in the upper part of the red till suggest that Superior ice was still present when the Wadena lobe advanced. The presence of limestone in the red till can be adequately explained only by contamination resulting from an advance of the Superior lobe over gray drift. This may partly account for the calcareous nature of the red till, although much of the carbonate was probably deposited by descending solutions originating in the gray till.

Lake Beauty. Numerous exposures of Wadena and Pierz drifts occur near Lake Beauty (Todd County) in the southwestern part of the Randall region. Contacts of brown over gray have been found at a few localities in this vicinity and several more are inferred from physiographic evidence.

Near the center of the SW¼ Sec. 35, T. 130 N., R. 32 W. the materials described in Section D were exposed after a heavy grass cover had been stripped from the face of a drainage ditch on the east side of the road.

STRATIGRAPHIC SECTION D. LAKE BEAUTY

	Thickness (inches)
3. Noncalcareous brown Pierz till	27
2. Interbedded brown clay and brown sandy Pierz till: till bands redder colored than intervening clay layers; clay beds 1–2 inches thick, till layers each ½–1 inch thick	12
1. Yellowish-brown highly calcareous sandy Wadena till. Base concealed	3

Good exposures of dark-brown till resting directly on yellowish-brown till occur immediately west of the St. Croix moraine along State Aid Road 18 (N edge Sec. 6, T. 129 N., R. 32 W.). The sites are located in a transitional belt where the eastern edge of the Wadena drumlin field passes under extramorainic Pierz-lobe drift before completely disappearing beneath the moraine.

East of Lake Beauty (E edge SE¼SE¼ Sec. 3, T. 129 N., R. 32 W.), brown Pierz till overlies limestone-rich sandy and gravelly outwash of the Wadena lobe. The contact occurs in the lower part of the B_2 soil horizon but is nevertheless very apparent. Subdivisions of the profile were measured as follows (depth in inches): A_1, 0–2; A_2, 2–10; B_{21}, 10–24; B_{22}, 24–28; C, 28+. The A_1, A_2, and B_{21} horizons are developed on brown till, the B_{22} and C horizons on Keewatin outwash. The B_{22} is leached, brownish in color, high in clay, and rather sticky; these properties are characteristic of the B_2 horizon at most localities where gravelly Wadena outwash acts as soil parent material. Carbonate starts at the top of the C.

A significant exposure of gray and red tills is located one-quarter mile west of the north end of Lake Beauty (NW cor. NE¼NE¼ Sec. 3, T. 129 N., R. 32 W.). Because of its proximity to the road the cut is subject to frequent regrading, so that individual sections are sometimes destroyed between successive visits. At the time of the first two visits (1952) slightly calcareous gray till, about 4 feet thick, was observed to overlie red sandy till with knife-edge sharpness. A ¾-inch lighter colored band at the base of the gray was interpreted as the less strongly oxidized and unleached equivalent of the upper till. Both drifts, particularly the gray, were noted to be atypically high in clay and to contain few pebbles, most of which were small. Samples T46–52 and PT60–52 were collected from the red till. Analysis of the latter sample shows that 18 per cent of the pebbles are sandstone, thus confirming the provenance of the drift. This section was destroyed before the cut was revisited in 1953.

A few yards east of the contact the two tills were found to be interbedded. This part of the cut was better exposed the following year (1953) and is described in more detail in Section E.

STRATIGRAPHIC SECTION E. LAKE BEAUTY

	Thickness (inches)
3. Wadena till: clay loam till, dark yellowish-brown (10YR 4/4), slightly calcareous; pebbles small and not abundant	52
2. Superior till: clay loam or sandy clay loam till, reddish-brown (5YR 4/4), very slightly calcareous; disintegrated red sandstone pebbles	5
1. Wadena till: clay loam till, olive-brown (2.5Y 4/4), slightly calcareous; not as oxidized as uppermost till; pebbles small and not abundant. Base concealed	14

When revisited in 1954 the cut had again been modified by grading operations and as a result the materials were somewhat fresher. A 3- to 5-inch layer of clayey red till was observed to occur within highly calcareous clayey gray till.

Stratigraphic evidence afforded by the Lake Beauty exposures substantiates that of the Irish Creek sections. The general superposition of the three drifts is brown over gray over red. The occurrence of the red-till interbed within the gray suggests that Superior-lobe ice persisted during the early period of Wadena-lobe advance.*

Lake Alexander. Deep road cuts south of Lake Alexander along Morrison County Aid Road 69 show dark-brown till above yellowish-brown till of the Wadena lobe. The basal part of the brown is commonly contaminated with the underlying drift, probably because of glacier overriding. Contacts between the two, therefore, are generally not so sharp as those near Irish Creek and Lake Beauty but are instead gradational.

The presence of two tills is clearly indicated by contrasting lithologic

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* The red-till interbed may represent the main advance of the Superior lobe and the gray-till units the two advances of the Wadena lobe (see p. 100ff.).

characters; the highly calcareous Wadena till is lighter or more yellowish in color (10YR 5/4) and in most cuts is sandier than the noncalcareous brown (7.5YR 4/4) till. The latter is interpreted as a Pierz-lobe deposit. It is possible, however, that it may be Brainerd brown because the exposures occur near the western limit of the northeast-southwest topographic lineation attributed to the Brainerd lobe.

Similar stratigraphic relations of the gray and brown drifts have been noted at the following sites near Lake Alexander in T. 131 N., R. 31 W.:

(1) NW cor. NE¼ and NE cor. NW¼ Sec. 2.
(2) SE¼NE¼NW¼ Sec. 2; samples T41–52 and PT42–52.
(3) NW cor. SW¼NW¼ Sec. 11.
(4) SE cor. Sec. 10.

Fawn Lake. Brown Pierz till is known to overlie calcareous Wadena drift at a number of localities in Fawn Lake Township, in and adjoining the northwestern part of the Randall region. Identification of the brown till in this area is made difficult by its thinness (0–3 feet thick) and erratic surface distribution. At most sites where brown till lies at the surface, soil development has extended downward into the underlying gray drift, obscuring the brown till and giving rise to "two-storied" soil profiles. The similarity in color and texture of the Pierz till and the B horizon on the Wadena till complicates the identification. Several cuts were examined in which a thin cap of Pierz till, probably about 2 feet thick, was suspected but could not be verified. Where the brown-till cap is thicker (2–3 feet) it can be recognized by the presence of eastern pebbles and by a slightly greater depth to carbonate than that which characterizes unburied Wadena till.

Definite Pierz-Wadena contacts in Fawn Lake Township (T. 132 N., R. 32 W., Todd Co.) occur at the following localities (listed in approximate order of clarity):

(1) Middle of E edge Sec. 7 and W edge Sec. 8; yellowish-brown sandy Wadena till capped by brown sandy Pierz till of variable thickness (approximately 1–3 feet); excellent "two-storied" soil profiles.
(2) S edge SW¼SE¼ Sec. 20; knife-edge contact of noncalcareous brown sandy till, 30 inches thick, overlying highly calcareous gray till.
(3) Sec. 21, just north of center; approximately 3 feet of brown till overlying calcareous Keewatin till.
(4) N edge NW¼NW¼ Sec. 28; 3–5 feet of noncalcareous dark-colored sandy gravel of eastern origin overlying highly calcareous light-colored sandy gravel of northwestern source.
(5) SW¼NE¼ Sec. 20, immediately north of Rat Lake.
(6) E edge NW¼NE¼ Sec. 16; light-brown sand of eastern origin overlying calcareous Wadena outwash.
(7) SW¼NW¼ Sec. 17; 3 feet of brown till overlying clayey calcareous gray till (auger boring).
(8) SW¼SW¼ Sec. 20.

Stratigraphic superposition of brown drift over calcareous gray drift has been described in considerable detail. However, local modifications of this relationship have been observed at some localities. Section F is exposed in a fresh road cut near the center of Sec. 8, T. 132 N., R. 32 W., 2 miles southwest of Philbrook.

Stratigraphic Section F. Philbrook

	Thickness (feet)
4. Sand and sandy gravel of eastern origin. Thickness somewhat variable, averages about	3
3. Upper till: sandy loam till, dark yellowish-brown (10YR 4/4), noncalcareous, slightly acid (pH 6.5); granite, graywacke, basalt, gabbro, felsite pebbles common. Samples T93–53 and PT93–53	3
2. Middle till: sandy loam till, yellowish-brown (10YR 5/4), extremely calcareous, moderately alkaline (pH 8.0); limestone and granite pebbles abundant; basalt, graywacke, and gabbro pebbles also present. Samples T94–53 and PT94–53	3
1. Lower till: sandy loam till, brown (10YR 5/3), noncalcareous, neutral (pH 7.0); pebbles similar to those of unit 3. Base concealed, exposed thickness of unit estimated as	6

The lithologic characteristics of the lower and upper tills are so similar as to preclude the possibility of deposition by different glaciers. Those of the middle till, on the other hand, are significantly different. Pebble counts (Table 2) attest to this difference; the sample from the middle till contains 27 per cent limestone, whereas that from the upper till shows no limestone. The lower and upper tills are classified as Pierz, the middle till as Wadena.

Although the color of the Pierz till is lighter than typical, it is definitely darker than that of the Wadena. The 10YR hue is apparently due to contamination by Keewatin drift, yet the till is almost barren of limestone and the matrix is noncalcareous. Auger borings disclose the presence of carbonate 2–3 feet beneath the base of the cut, but it could not be determined if this material was calcareous Pierz till or a second unit of Wadena drift.

The stratigraphic relations at this exposure imply the following sequence of events: (1) deposition of brown till by the Pierz lobe, (2) temporary withdrawal of Pierz ice, allowing the Wadena lobe to advance and deposit its limestone-rich till, (3) retreat of the Wadena glacier and readvance of the Pierz lobe, and (4) final withdrawal of the Pierz lobe and attendant deposition of eastern gravel and sand.

Lincoln. One of the best and most accessible exposures of interbedded drifts is located along U.S. Highway 10, one-half mile southeast of the Lincoln post office (SW¼NE¼NW¼ Sec. 31, T. 132 N., R. 31 W., Morrison Co.). A large knob of the St. Croix moraine, capped by eastern gravel, contains several feet of Pierz-lobe till draped over calcareous Wadena drift which appears to form the core of the knob. A thick contact zone in which the Pierz and Wadena drifts are complexly interbedded is partly exposed near the southern end of the cut; this is described (Section G) and figured (Figs. 10 and 11) in some detail.

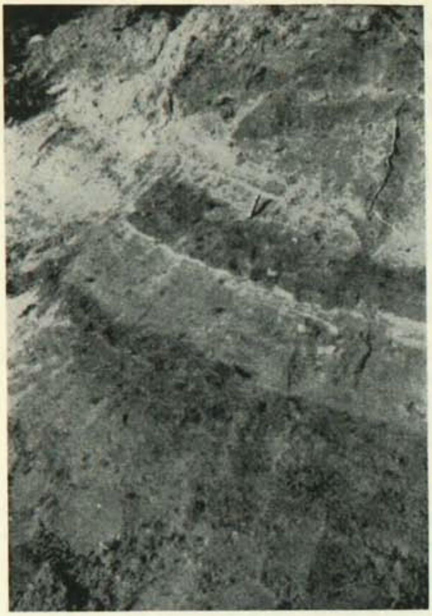

FIGURE 10. — Interbedded Wadena and Pierz drifts at Lincoln. Note the occurrence of laminated interlayers within the thicker interbeds of gray and brown till. Scale is shown by pocket knife. NE¼-NW¼ Sec. 31, T. 132 N., R. 31 W., Morrison County.

FIGURE 11. — Sketch of interbedded drifts at Lincoln.

STRATIGRAPHIC SECTION G, LINCOLN

	Thickness (feet)	(inches)
11. Gravel: poorly sorted cobbles, pebbles, and sand of eastern origin; noncalcareous. Base concealed, thickness indeterminate, probably about...	3–8	
10. Pierz till: sandy loam till, brown or dark-brown (7.5YR 4/4), very slightly calcareous to distinctly calcareous and moderately alkaline (pH 8.0) at base of unit. Largely covered, thickness indeterminate, possibly..	20–25	
9. Sand: light-colored (white), slightly calcareous, very well sorted, well stratified, quartzose; bedding planes distinct; mostly well-rounded fine-grained sand but with interbeds of medium- to coarse-grained sand. Locally deformed, marked by a series of small normal faults and one or two less distinct reverse faults of somewhat greater displacement	2	
8. Gravel: numerous cobbles and pebbles of eastern origin contained in a matrix of calcareous sand similar to overlying unit; not well sorted; basalt and schist pebbles abundant, limestone apparently absent	1–2	
7. Gray (yellowish-brown) till lens		0–6
6. Sand: well-sorted, fine- to medium-grained, calcareous, quartzose; subrounded to rounded grains		3
5. Wadena till with interbeds of sand: sandy loam till, yellowish-brown (10YR 5/4–10YR 5/6), extremely calcareous, moderately alkaline (pH 8.0); granite, limestone, basalt, gabbro, and graywacke pebbles. Samples T38–52 and PT39–52. Sand similar to unit 6. Entire unit subdivided as follows (from top to bottom):		
Till		3
Sand		1
Till	1	8
Interbedded sand and till: 4 layers of sand, 3 layers of till; bedding planes distinct and regular		3
Till		3
4. Brown Pierz till with lenticular interbeds of darker brown till and thin lenses of lighter colored drift		5–7
3. Gray (yellowish-brown) Wadena till containing very thin interbeds of sand in upper part and numerous ⅛- to ½-inch lenses of brown till throughout		10
2. Brown Pierz till with highly contorted laminae of yellowish-brown till..		10–12
1. Gray (yellowish-brown) Wadena till containing lenses of brown till. Base concealed		7

Two kinds of till interbeds are recognized, based upon the thickness of individual layers. Interbedding of thicker units of Wadena and Pierz tills (Figs. 10 and 11) can be seen many feet away from the face of the cut. The layers are typically 8–12 inches thick, ranging from about 4 to 30 inches. Thinner or laminated interbeds (Fig. 11, inset) which occur within the thicker layers are not so apparent from a distance but are striking upon close inspection of the cut. The beds are usually less than 1 inch thick, commonly discontinuous, and in some cases are difficult to trace because of their extreme thinness (as fine as ⅛ inch thick). Nearly all of them are different in color and texture from the thicker till layers in which they occur.

Aside from the inclusion of brown-till laminae in the gray till and vice versa, the thicker units are relatively pure. Some contamination is evidenced by pebble anomalies and other lithologic discrepancies but the degree of contamination is not great. The individuality of the tills can not be questioned and attests to their deposition by different ice lobes. Interbedding of the thicker units implies intermittent deposition by confluent ice lobes alternately advancing over the site as the other receded.

The laminated interbeds of till, however, may not be actual glacier deposits by the parent ice mass. Two alternative hypotheses are offered, either of which might explain their occurrence in the thicker layers: (1) The laminae may represent thin mud flows, which originated in rapid succession off the front of the parent ice mass and flowed into a zone of marginal deposition of the second ice lobe. (2) Following deposition by the parent ice mass, layers of till may have been eroded by the second ice lobe and injected into the load of the latter by thrusting along closely spaced shear planes.

The two layers of sand that occur in the upper part of the gray till (Fig. 11, inset) are definitely water deposited, as indicated by good sorting. Their light color, calcareous nature, and high quartz content suggest a Wadena-lobe origin. A similar association seems to apply to the four sand beds in the lower part of the gray till but the thinness of the beds makes it difficult to obtain pure samples of sand for hand-lens examination. Alternating layers of till and sand are explained by intermittent glacier and meltwater deposition occasioned by fluctuations in the frontal position of the Wadena lobe.

The gravel unit apparently received contributions from both the Wadena and Pierz lobes. Many of the stones have a definite eastern source; limestone pebbles, which are very abundant in uncontaminated Wadena gravel, are rare or absent but the sandy matrix of the gravel is calcareous and appears to have been washed out from the Wadena lobe. The well-sorted, well-stratified sand that overlies the gravel is also interpreted as mixed, although the majority of the grains probably came from the receding Keewatin ice.

The uppermost unit of Pierz till appears to have been deposited after complete withdrawal of the Wadena lobe from this vicinity. Unlike the underlying layers of brown till, it does not contain thin interbeds of gray drift. At its base the till is distinctly calcareous and alkaline but this is more likely due to overriding and assimilation of Wadena drift than to direct contributions from Keewatin ice. The irregular and unconformable contact of the brown till with the subjacent units (Fig. 11) is more apparent than real, at least in part. As seen from the front of the exposure, the contact has an apparent dip to the southeast; however, the till is draped over the underlying deposits in such a way that a second component of dip is to the southwest — or toward the reader. Thus, the position of the contact is partly determined by the amount of brown drift removed from the face of the cut.

Contacts of noncalcareous brown (7.5YR 4/4) Pierz till overlying calcareous yellowish-brown (10YR 5/4) Wadena till occur along the Morrison-Todd county line road in the first half mile south of Lincoln (W edge Sec. 31, T. 132 N., R. 31 W., Morrison Co., and E edge Sec. 36, T. 132 N.,

R. 32 W., Todd Co.). One exposure (SE¼NE¼ Sec. 36) shows a buried hill of Wadena drift draped over by 3–5 feet of Pierz till, with the contact closely paralleling the present slope. At the northern end of this cut the upper till is nearly obscured by soil development. Identification of the younger deposit is further complicated by a 6- to 9-inch transitional zone in which the Pierz till is highly contaminated with calcareous Wadena drift. Soil Profile 2 illustrates these relationships.

Soil Profile 2

Location: SE¼NE¼ Sec. 36, T. 132 N., R. 32 W., Todd Co.; road cut through knob of St. Croix moraine, about 15 feet north of crest.

Conditions: Strongly rolling topography, C slope, red oak and silver poplar abundant, moisture at field capacity.

Horizon	*Depth (inches)*	*Description*
A_1	0–1	Very dark gray (10YR 3/1) sandy loam; granular structure.
A_2	1–22	Light-gray (10YR 7/2) loamy fine sand; weakly platy structure.
B_2	22–40	Reddish-brown (5YR 4/3) sandy clay loam; blocky structure.
C_2	40–50	Brown or dark-brown (7.5YR 4/4) sandy loam; noncalcareous Pierz till.
C_3	50–56	Dark yellowish-brown (10YR 4/4) sandy loam, slightly calcareous; zone of mixed Pierz and Wadena tills.
D_{ca}	56+	Yellowish-brown (10YR 5/4) sandy loam; highly calcareous Wadena till, secondary carbonate stringers. Samples T55–52 and PT56–52.

Center Valley. Thin layers of red sandy till occur as interbeds within the brown at several localities in the Pierz drumlin field of eastern Morrison County. The finest known exposure of this nature is located 3 miles southwest of Center Valley, or 4 miles southeast of Pierz, on the northern flank of a brown-till drumlin (NW cor. Sec. 25, T. 40 N., R. 30 W.). The deposits described in Section H are exposed here (Fig. 12).

Stratigraphic Section H. Center Valley

	Thickness (inches)
4. Grassed-over colluvium and soil	36
3. Pierz till: similar to unit 1. Contact with unit 2 rises abruptly and is truncated by unit 4 near north end of cut, so that thickness decreases to zero	24
2. Superior till: loam till, dark reddish-brown (5YR 3/4), slightly calcareous; red sandstone pebbles very abundant, basalt and gabbro common. Texture is distinctly more silty than usual but becomes sandier in upper 4 inches. Unit has apparent dip of 10°–15° S. Contacts with underlying and overlying units sharp. Samples T25–53 and PT25–53	20
1. Pierz till: sandy loam till, brown or dark-brown (7.5YR 4/4), noncalcareous; basalt, gabbro, and granite pebbles common. Texture is definitely more silty than normal. Samples T24–53 and PT24–53. Base concealed	22

The lithologic characteristics of the two tills are so different that the identity of the deposits is readily apparent. The color difference is much more striking than is indicated by the color names. Pebble counts of the red till show 34 per cent sandstone, of which 29 per cent are red, whereas only 2 per cent of the brown-till pebbles are sandstone (Table 2). The brown till is definitely coarser grained than the red; the abnormally high

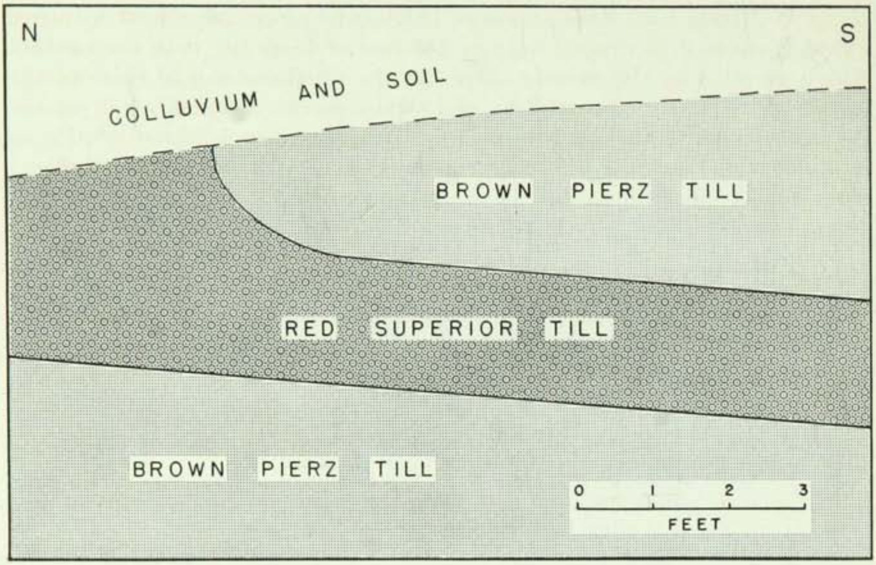

FIGURE 12. — Sketch of brown and interbedded red tills near Pierz.

silt content of both drifts is not understood but is possibly due to incorporation of soft local bedrock.

The stratigraphic relations at this exposure indicate the following sequence of events: (1) advance of the Pierz lobe, (2) temporary withdrawal of the Pierz ice and encroachment of the Superior lobe, (3) retreat of the Superior glacier and readvance of the Pierz lobe.

One mile northeast of Center Valley, on the south side of State Aid Road 18 (NW cor. Sec. 9, T. 40 N., R. 29 W.), three drifts are exposed. Noncalcareous brown sandy Pierz till, 5–8 feet thick, overlies calcareous red sandy till near the base of which are faint interlaminations of calcareous gray sandy till. The contact of the brown drift with the underlying deposits is strikingly shown on the road cut by differential erosion, the red till being marked by deeper and wider rills than the Pierz till. Pebbles of both limestone and red sandstone may be found on the surface of the cut. Samples 53–192A and 53–192C were collected here.

The stratigraphic position of the Pierz till indicates that it is younger than the Wadena and Superior drifts. In general, the gray till appears to be somewhat older than the red, but interbedding of these deposits suggests that the Wadena and Superior lobes were confluent. Superposition of brown over red is further shown approximately 2 miles east of here (NW¼ Sec. 10, T. 40 N., R. 29 W.).

Camp Ripley. Stratigraphic sections attesting to the age of the Brainerd drift are not abundant and the chronological position of the Brainerd lobe is interpreted mainly from geomorphic evidence. In the Camp Ripley area the drift consists principally of eastern-source gravel and brown sandy till. The surficial occurrence of these deposits and their association with the northeast-southwest topographic lineation are consistent with physiographic relationships which indicate that the Brainerd lobe was the last Wisconsin ice lobe to enter the Randall region.

Superposition of Brainerd-lobe gravel over Wadena outwash sand near Lake Alexander has previously been cited. At a few localities in and adjoining Camp Ripley, eastern-source gravels sharply overlie brown sandy till. The geomorphic relations indicate that the gravels are Brainerd-lobe deposits, at least at the first three localities cited below. The underlying till might be classified as either Pierz or Brainerd; definite assignment is not possible until some satisfactory method is found to differentiate between the two brown tills. Analyses of pebbles from till and gravel show no significant differences (see samples PT66–53, PG67–53, PT71–53, and PG72–53, Table 2).

Eastern gravel overlies noncalcareous brown sandy till (color 7.5YR 4/4, pH 6.0) at the following localities:

(1) SW cor. Sec. 11, T. 131 N., R. 30 W.; 3½ feet of gravel over till; excellent contact; stratification in gravel apparent.
(2) SW cor. Sec. 9, T. 131 N., R. 30 W.; 15 inches of gravel over till.
(3) Near NW cor. Sec. 36, T. 132 N., R. 30 W.; approximately 4 feet of gravel over till.
(4) SE¼NE¼SW¼ Sec. 1, T. 130 N., R. 30 W.; two exposures showing 4 feet of sand or sandy gravel over till.
(5) Near NE cor. NW¼ Sec. 10, T. 130 N., R. 30 W.; 3 feet of gravelly sand over till.

Glacial Lake Randall. Additional evidence indicating contemporaneity of ice lobes is found in the deposits of Glacial Lake Randall. Auger borings in the lacustrine plain 1½ miles north of Randall (center Sec. 31, T. 131 N., R. 30 W.) disclose two distinct types of well-sorted lake sediments. One is a calcareous yellowish-brown (10YR 5/4) very fine silt or silty coarse clay. The other is a noncalcareous brown or dark-brown (7.5YR 4/4) clay. Except for sorting and for the lack of coarse particles, the materials are nearly identical to the gray and brown tills of the area, respectively. The occurrence of the two types, in the same physiographic environment and at the same elevation, suggests simultaneous contributions to the lake from more than one source. Only one definite contact of the two sediments was located; in this case, the yellowish-brown overlies the brown.

Interbedded lake sediments similar to the above occur in the abandoned Gorman iron-ore pit, 1 mile north of Randall (SE¼SE¼ Sec. 31, T. 131 N., R. 30 W.). They are reported to reach a thickness of 50 feet.

Several kinds of lake sediments were penetrated by auger holes in the eastern half of Sec. 12, T. 130 N., R. 31 W., three-quarters of a mile west of Randall. Contributions from at least three sources are clearly implied. The deposits include brown silt, calcareous brown silt, brown clay, red clay, and calcareous light-colored clay. One boring (NE¼SE¼) showed interbedded red clay and brown clay overlain by 3 feet of brown silt.

Western Randall Region. Within and beyond the outer (western) margin of the St. Croix moraine the Pierz and Wadena tills are overlain by fine-grained to gravelly outwash sand. The pebble assemblage, noncalcareous nature, and physiographic occurrence of most of these outwash deposits point to a Pierz-lobe derivation. Till-outwash contacts of this type in eastern Todd County are indicated below.

(1) Near SW cor. SE¼ Sec. 21, T. 132 N., R. 32 W.; drainage ditch; 3 feet (minimum thickness) of well-sorted sand overlying noncalcareous brown sandy Pierz till.

(2) NW¼NE¼ Sec. 17, T. 132 N., R. 32 W.; auger boring below base of drainage ditch at northeast corner of T-intersection.

	Thickness	
	(feet)	(inches)
3. Sand: light-brown, noncalcareous, quartzose, medium-grained	3	3
2. Sandy gravel		6
1. Till: light-colored, noncalcareous, mildly alkaline (pH 7.5), sandy	3	6

(3) Near center Sec. 8, T. 132 N., R. 32 W.; 3 feet of sand and sandy gravel overlying 12 feet of interbedded Pierz and Wadena tills. (See p. 56 for complete section description.)

(4) SW¼NW¼ Sec. 20, T. 132 N., R. 32 W.; auger boring northwest of western tip of Rat Lake; thin sand cap overlying probable Pierz till.

(5) NW cor. SE¼ Sec. 21, T. 132 N., R. 32 W.; auger boring; probable 2-foot cap of sand overlying Pierz till.

(6) Near NW cor. SW¼ Sec. 25, T. 132 N., R. 32 W.; road cut; 5 feet of sand overlying gravelly Pierz till.

(7) N edge NE¼NW¼ Sec. 17, T. 131 N., R. 32 W.; pit and auger boring below base of road cut along drainage ditch.

	Thickness	
	(feet)	(inches)
3. Sand: light-brown, noncalcareous, fine-grained. Contact with underlying unit sharp	3	6
2. Till: sandy loam till, brown (10YR 5/3), noncalcareous, slightly acid (pH 6.5). Interpreted as contaminated Pierz-lobe deposit	3	
1. Sand: well-sorted, medium-grained. Reached by augering		3

(8) SE cor. SW¼ Sec. 8, T. 131 N., R. 32 W.; 5-foot road cut; till, similar to that at above locality, grading upward into poorly sorted sand and interbedded gravel layers overlain by light-brown fine pebbly sand.

(9) NW¼SW¼ Sec. 32, T. 131 N., R. 32 W.; northeast corner of Y-intersection south of Thunder Lake; 3 feet of sand overlying Pierz till.

(10) NW¼SE¼ Sec. 32, T. 131 N., R. 32 W.; first cut east of Thunder Lake; 2 feet of sand overlying Pierz till.

(11) NW cor. NE¼SE¼ Sec. 32, T. 131 N., R. 32 W.; road cut; 2–4 feet of light-brown noncalcareous fine- to medium-grained sand overlying noncalcareous brown Pierz till and interbedded sand units.

(12) Near NW cor. SW¼ Sec. 26, T. 131 N., R. 32 W.; first road cut east of side road; 4 feet of sand overlying Pierz till.

(13) SE cor. SW¼ Sec. 18, T. 130 N., R. 32 W.; road cut.

	Thickness (feet)
2. Pierz-lobe outwash: sandy gravel, noncalcareous; basalt, granite, felsite, and gabbro pebbles common. Sample PG28–53	5
1. Wadena-lobe till: sandy loam till, yellowish-brown, extremely calcareous; granite and limestone pebbles common. Upper foot of unit may possibly represent a thin cap of contaminated Pierz-lobe till. Base concealed	2½–3

(14) N edge NE¼ Sec. 19, T. 130 N., R. 32 W.; road cut.

	Thickness (feet)	(inches)
3. Pierz-lobe outwash: sandy gravel, light-brown, noncalcareous, poorly sorted	4	2
2. Pierz till: sandy loam till, brown, noncalcareous		8
1. Wadena till: yellowish-brown, highly calcareous, sandy. Contact with overlying till indistinct and upper part of unit may actually be mixed Pierz and Wadena tills. Estimated exposed thickness	1	2

(15) NW¼NE¼ Sec. 20, T. 130 N., R. 32 W.; gravel pit; 7–10 feet of well-stratified sand and gravel overlying reddish-brown noncalcareous clayey till.

Southeastern Randall Region. In the southeastern part of the Randall region the brown Pierz till is overlain by fine-grained to gravelly outwash sand. Because of low relief good exposures are not abundant and much of the stratigraphic data was obtained from auger borings.

West of the Mississippi valley train the thickness of the sand cover is variable; it probably does not exceed 4–5 feet throughout most of the area and locally the sand is absent or very thin. This is indicated by the surficial occurrence of sand and till within a few yards of each other and by the discovery of several probable sand-till contacts at shallow depths. Definite contacts of outwash over till are known, however, and the age relationship is substantiated by geomorphic evidence.

No occurrences of till were discovered between the Mississippi River and the mapped western border of the valley train, which is here called the Green Prairie terrace. All definite and probable contacts of outwash over till were found west of the terrace border, many of them within 1 mile. This suggests that the sand deposits thicken considerably (eastward) at or near the mapped border.

These relationships may be illustrated by reference to specific areas where short detailed auger traverses were undertaken. Sixteen auger holes were drilled in the S½ Sec. 30, T. 130 N., R. 29 W., all to a depth of 3–3½ feet. Seven of these borings were in brown Pierz till and seven in sand. The other two holes disclosed excellent contacts of well-sorted sand over brown till, each at a depth of 30 inches. In addition, three exposures were discovered in this half-section: a gravel pit, a shallow road cut in till, and a second cut showing 2 feet of sand resting on 6 inches of till(?) overlying sand.

One of the two 30-inch contacts was found at the southwestern corner of the lot occupied by School No. 117. Most of the schoolyard is obviously underlain by sand and immediately in front of the schoolhouse the till could not be reached with the auger, but a few yards west of the contact hole the sand cover is absent. The total distance between these points is approximately 100 feet. The second 30-inch contact was discovered about one-half mile west of the first. Both of these contacts are located very close to the mapped border of the Green Prairie terrace (Pl. 1).

Nine auger holes were drilled in the NW¼ Sec. 7, T. 129 N., R. 29 W. The southeasternmost three holes are located just within the border of the Green Prairie terrace; all ended in sand at depths of 3–3½ feet. Each of the other six holes is no farther than one-quarter mile from this border. Two of these ended in brown Pierz till and one in calcareous Wadena till. Two of the remaining holes disclosed definite contacts of sand over Pierz-lobe till, at depths of 18 and 30 inches. The ninth boring showed a probable cap of sand, 18 inches thick, above brown till.

A good contact of sandy gravel, 4 feet thick, overlying brown sandy Pierz till occurs near the SE cor. NW¼ Sec. 27, T. 130 N., R. 30 W. along the Northern Pacific railroad tracks. Just northwest of here brown till is continuously exposed for many yards along the tracks but the outwash cap is apparently absent. Twelve auger holes and one additional exposure within 0.6 mile of the contact locality show till at three places, sand or gravelly sand at seven, and probable contacts of sand over till at three. At two of these contact locations (SW cor. NW¼ Sec. 26 and NW cor. SE¼NW¼ Sec. 27, T. 130 N., R. 30 W.) the probable sand cap was recorded as 2 feet thick.

Elk River. One locality in the southeastern part of the Randall region (NW¼NE¼ Sec. 6, T. 129 N., R. 29 W.) offers additional evidence concerning the sand-cover sediments of this area. Here several other lithologic units as well are discontinuously displayed along the valley of the Elk River for 800 feet or more, downstream from where the creek is crossed by Morrison County Aid Road 45. The exposed materials include a postglacial alluvial fill, at least three outwash units, Pierz-lobe till, and Wadena-lobe till unconformably overlying weathered and unweathered Precambrian phyllite. The physiographic and general stratigraphic relations are shown in Figure 13.

Section I was measured on the northeast side of the river, approximately 75 feet downstream from the concrete highway bridge.

STRATIGRAPHIC SECTION I. ELK RIVER

	Thickness (feet)	Thickness (inches)
6. Sand: pale-brown (10YR 6/3), noncalcareous, well-sorted, fine-grained . . .	2	8
5. Gravel: strong-brown (7.5YR 5/6), noncalcareous, poorly sorted, sandy;		

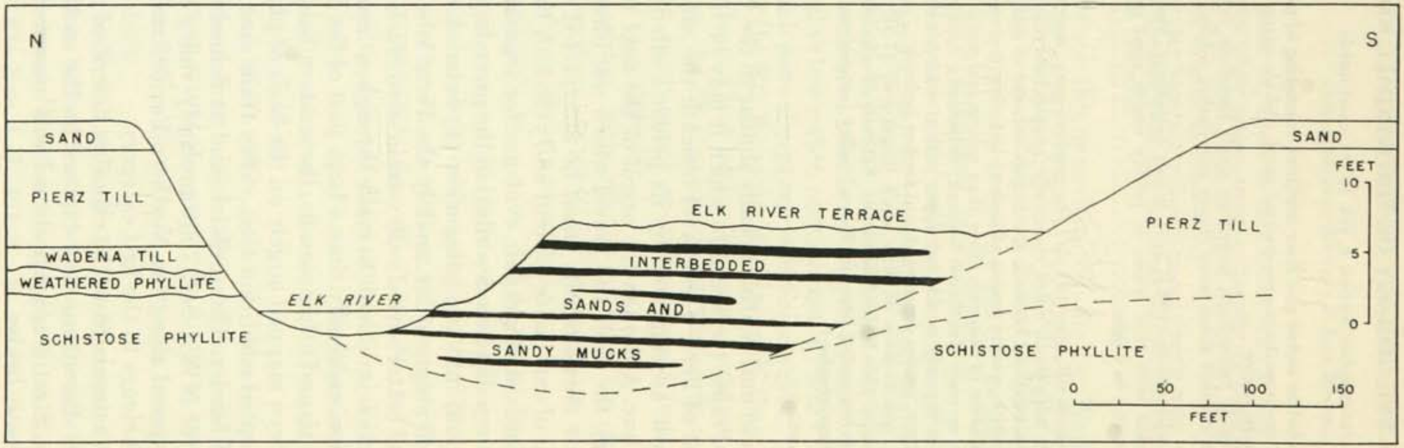

FIGURE 13. — Cross-section showing physiographic and general stratigraphic relations at the Elk River locality.

Stratigraphic Section I. Elk River (continued)

	Thickness (feet)	Thickness (inches)
lower 9 inches becomes better sorted and finer textured, consisting of pebbly very coarse sand and medium- to coarse-grained sand. Pebble assemblage indicates a general eastern source	6	6
4. Pebbly coarse sand: highly calcareous; numerous small limestone pebbles; upper and lower 1-inch contact zones more clayey and darker colored than rest of unit		8
3. Sand and gravel: yellowish-brown (10YR 5/4), highly calcareous. Medium-grained sand interbedded with thin lenses of pebbly coarse sand or fine gravel. Distinctly Keewatin in origin		9
Unconformity.		
2. Weathered bedrock: coarse silt, gray (5Y 5/1) to greenish-gray, noncalcareous, very soft, highly micaceous; color commonly approaches yellowish-green when fragments are rubbed between the fingers because of numerous flakes of altered muscovite; quartz grains abundant but silty texture precludes positive identification of minerals other than quartz and mica. Contains inclusions of less severely weathered bedrock. Schistosity moderately well preserved except in severely weathered upper part of unit; lower part not so weathered as upper, grades downward into fresher bedrock	1	10
1. Precambrian bedrock: quartz-mica phyllite, dark bluish-gray (7.5R 4/0), noncalcareous, fine-grained, thin-bedded, schistose. Attitude of schistosity is N. 45° E., 72° SE. Base concealed beneath floor of valley, approximate exposed thickness (not stratigraphic)	1	3
Total thickness of section	13	8

The uppermost sand unit is lithologically similar to the valley-train sediments of the Green Prairie terrace, into which it may be traced one-fourth to one-half mile east of here. The gravel beneath the sand is interpreted as Pierz-lobe outwash, as suggested by its pebble content, noncalcareous nature, and 7.5YR hue. Although the origin of the next subjacent unit is not so clear (mixed?), the sand and gravel which rest directly on the Precambrian-Pleistocene unconformity must be interpreted as Wadena-lobe outwash on the basis of carbonate content and yellowish-brown color.

This exposure affords stratigraphic evidence for separation of the noncalcareous sand-cover sediments described in the preceding section (southeastern Randall region) into two categories: (1) outwash sand and gravel derived directly from stagnant ice, mainly the Pierz lobe, and (2) generally finer grained and better sorted valley-train sand. Such a lithologic and stratigraphic distinction is difficult to make throughout much of the southeastern Randall region, especially since a large part of the data comes from auger borings. For this and other reasons, the western border of the Green Prairie terrace has been mapped largely on the basis of physiographic evidence, with the accepted condition that valley-train sand locally extends west of the mapped border. The surficial sand at School No. 117, for example, and that in the NW¼ Sec. 7 are probably valley-train sediments. The sandy gravel exposed along the Northern Pacific tracks, on the other hand, undoubtedly belongs to the first category.

Several yards downstream from the exposure described above, the Pierz and Wadena tills are discontinuously exposed on the northeastern side of the Elk River valley. Stratigraphic Section J was measured about 175 feet southeast of the highway bridge.

Stratigraphic Section J. Elk River

	Thickness (feet)	Thickness (inches)
2. Pierz till: sandy loam till, brown or dark-brown (7.5YR 4/4), noncalcareous; basalt, granite, felsite pebbles common. Locally the basal part of unit is highly contaminated with masses of weathered phyllite and some Wadena till. Thickness variable, averages about	6	
1. Wadena till: silty clay loam till, yellowish-brown (10YR 5/6), highly calcareous; limestone pebbles, fresh and weathered phyllite pebbles abundant. Maximum exposed thickness	1	2

At several points in this immediate vicinity the Wadena till very sharply overlies weathered phyllite. Locally the gray till is absent and weathered bedrock is directly overlain by brown Pierz till. The latter in turn appears to be overlain by a thin cap of eastern gravel, as suggested by an abnormally stony A_2 soil development, 20 inches thick.

Several hundred yards still farther downstream Pierz-lobe till and sand to sandy gravel are exposed on the western and southern slopes of the valley. Superposition of sand over till is strongly implied but the actual contact could not be located because of a covered interval of many feet. Just above creek level at low water, noncalcareous Pierz till overlies calcareous Wadena till, which rests sharply on weathered schist.

The terrace of the Elk River lies slightly more than 5 feet above normal water level, or about 8 feet below the upland surface. As examined along the stream banks, the fill consists of well-sorted fine-grained quartz sand interbedded with sandy muck containing wood fragments. Both terrace and fill are dated as postglacial.

Additional Localities. Although the following list of drift contacts is not complete, the locations are cited for the purpose of supplementing the stratigraphic evidence already presented.

(1) E edge SE¼SE¼ Sec. 27, T. 131 N., R. 31 W., Morrison Co.; deep railroad cut; crossbedded light-colored fine-grained calcareous Keewatin sand sharply overlain by brown (7.5YR 4/4) silt which grades upward into brown sandy Pierz till; sample PT45–53.

(2) NW cor. SW¼SW¼ Sec. 28, T. 131 N., R. 31 W., Morrison Co.; drainage ditch; 4 feet of Pierz till overlying Wadena till.

(3) SW¼SE¼ Sec. 5, T. 130 N., R. 31 W., Morrison Co.; road cut; very clayey, highly calcareous Keewatin till capped by eastern-source gravel; sample T45–52.

(4) NE cor. Sec. 10, T. 130 N., R. 31 W., Morrison Co.; drainage ditch; noncalcareous brown Pierz till overlying calcareous sand.

(5) W edge SW¼NW¼ Sec. 18, T. 131 N., R. 31 W., Morrison Co.; road cut; brown Pierz till with 1- to 4-inch interbeds of light-colored Wadena drift.

(6) SW cor. Sec. 8, T. 131 N., R. 30 W., Morrison Co.; road cut, contact destroyed in 1953; 5 feet of brown sandy till (Brainerd?) overlying yellowish-brown Wadena till; sample T100–53.

(7) Center NE¼ Sec. 5, T. 131 N., R. 30 W., Morrison Co.; first road

cut north of schoolhouse; probable cap of brown till (Brainerd?) resting on calcareous Keewatin outwash.

(8) NE cor. Sec. 26, T. 130 N., R. 32 W., Todd Co.; deep drainage ditch; calcareous yellowish-brown Wadena till overlying and interbedded with noncalcareous dark-brown Pierz till; samples T86–53 and T87–53.

(9) NE cor. Sec. 12, T. 130 N., R. 32 W., Todd Co.; auger boring below bottom of drainage ditch; 54 inches of Pierz till overlying Wadena till.

(10) SE¼ SW¼SW¼ Sec. 6, T. 130 N., R. 31 W., Morrison Co.; auger boring beneath base of road cut; brown Pierz till resting on sandy Wadena-lobe till.

(11) NE cor. SE¼NW¼ Sec. 19, T. 39 N., R. 29 W., Morrison Co.; road cut; 6-inch interbed of red Superior till within brown Pierz till.

(12) SW cor. NW¼ Sec. 18, T. 130 N., R. 31 W., Morrison Co.; auger boring; 40 inches of Pierz till overlying Wadena till.

(13) NW cor. SW¼SW¼ Sec. 28, T. 130 N., R. 31 W., Morrison Co.; auger boring; 32 inches of Pierz till overlying Wadena till.

(14) SE cor. NE¼NE¼ Sec. 11, T. 130 N., R. 32 W., Todd Co.; road cut; 40 inches of Pierz gravel resting on Wadena till.

(15) SE¼NE¼ Sec. 12, T. 129 N., R. 32 W., Todd Co.; auger boring; 3 feet of probable Pierz till overlying Wadena till.

OTHER EVIDENCES OF INTERBEDDED DRIFTS AND CONFLUENT ICE LOBES

The interbedded drifts described above are interpreted, for the most part, as the result of intermittent deposition by confluent or nearly confluent ice lobes. Occurrences of interlayered tills and lake deposits are not unique to the area studied during this investigation, however, and previous workers have found evidence attesting to deposition by confluent ice currents in other areas of the state. This evidence is reviewed below.

The concept of confluent ice lobes from two centers of radiation was inferred for Minnesota about 75 years ago by T. C. Chamberlin (1883, p. 384), who stated: "When glaciation was at its height it seems almost necessary to suppose that these two lobes crowded upon each other with some force . . . It seems quite possible that the Leaf Hills are the result of this conflict, their course being such as might be produced by the crowding of the Red River glacier against the Lake Superior protrusion."

Interbedded red and gray tills were mentioned by Winchell (Winchell and Upham, 1888, pp. 276, 293–94) from the area southeast of Lake Harriet in southern Minneapolis. Although "their relative position shows a somewhat later deposition of the gray," according to Winchell (p. 293), "this difference of time . . . seems not to have been great" and "the origination and transport of the two tills may be considered practically contemporary . . ."

The existence of confluent ice masses in central Minnesota was postulated by Upham in the same report. In his discussion of the drift of Wadena and Todd counties, Upham (Winchell and Upham, 1888, p. 570) writes: "When this ice-sheet of the last glacial epoch attained its greatest extent, and while its earlier moraines of recession were being accumulated, the ice-current upon this district was doubtless from the northwest and north, being confluent a little farther east with an ice-current that came from the region of lake Superior on the northeast."

Upham's opinion that these two lobes were in actual contact with each other is further indicated in his analysis of the glacial history of Stearns County (Winchell and Upham, 1888, p. 463): "The ice from the northwest and west, becoming relatively thicker, pushed back that from the northeast upon a large area . . ."

Berkey (1897, p. 363) postulated the existence of confluent ice masses in the St. Croix Dalles area of western Wisconsin: "The western ice lobe advanced spreading the western drift to the very position now occupied by the central plain. Here it was met and energetically opposed by a northeast lobe carrying much debris and rapidly accumulating the thicker eastern drift deposits. The eastern advance was even energetic enough to override the edge of the western lobe, and left a few patches of characteristic material within western territory."

A few years later Upham (1900, pp. 284–88; pl. 7) described in detail six sections of interbedded red and yellow (gray) tills in western Minneapolis; five of these were figured. The close similarity of Upham's exposures to those described in this report is well illustrated by the following description of one of the six sections (Upham, 1900, pp. 286–87): "Red till forms all the upper part, to a maximum depth of nearly 20 feet, having the obscurely laminated or foliated structure before noted, although it is an indiscriminate mixture of clay, sand, gravel and boulders, a typical till. Near the center of the section, it includes a shred of yellow till, a foot thick and six feet long. In the lower part of the section . . . the red till is underlain by a layer of yellow till, 2 to 6 feet thick, partly contorted, bounded above and below at irregular but well defined lines; and beneath this the base of the whole section is again reddish till. The two kinds of till are plainly distinct and unmixed, excepting for an extent of about 50 feet on the upper boundary of the yellow till near the deepest part of the excavation. In the yellow till limestone fragments are frequent, but in the red till they are wanting or very rare."

A second exposure was described by Upham as follows (Upham, 1900, p. 287): "The next section observed . . . showed much interstratification, confused and contorted, of the yellowish gray and the red till, in layers and streaks sometimes no more than 1 to 3 inches thick, with distinctly contrasted coloration. Much limestone gravel was noted in the yellow till, but none in the red."

Still another section was characterized in this way (Upham, 1900, p.

288): "Yellow till, 3 to 6 feet thick, forms the surface and lies on a very thin, but continuous layer of red till, 1 to 1½ feet thick, which curves in parallelism with the smoothly rounded surface. Under this layer is a similar layer of yellow till, also a foot thick, or slightly more; and this . . . is underlain by red till, . . . seen to the thickness of 8 feet and continuing below."

Interbedded red and gray tills were explained by Upham in these words (Upham, 1900, p. 285): "How we should account for the intercalation of the thin yellow till layers in the red till . . . is a most difficult problem. It seems to me probable that wavering of the belt of confluence between the ice flowing from the northeast and that from the northwest, one side repeatedly pushing back the other in alternation with being itself similarly displaced, may best supply the clue for the interpretation of the history of these sections. The whole deposit, in all its complications, I believe to have existed as englacial and finally superglacial drift, being amassed somewhat as I would explain the accumulation of drumlins, and falling together and settling to the subglacial ground while the ice-sheet at this place was being melted above and beneath its inclosed drift."

In 1911 Upham once again cited evidence to show that "Keewatin and Labradorean currents were confluent," or "met and opposed each other on a belt that extends from St. Paul and Minneapolis northward and northwestward through Minnesota to the vicinity of Winnipeg" (Upham, 1911, p. 467).

Wright (1953) has described and figured in detail interbedded red and gray drifts west of Minneapolis and cites other localities in Minneapolis, Stearns County, and Isanti County that show similar relationships. The exposure west of Minneapolis is described as follows (Wright, 1953, pp. 467–468): "The locality is in the midst of the St. Croix moraine. A large kame of red sand has a cap of a few feet of gray till. The contact zone, a few feet thick, shows intricate interbedding, in which laminae of red till or outwash a few millimeters thick alternate with laminae of gray till or outwash. The individual laminae are remarkably pure — either gray (oxidized buff) calcareous drift with pebbles of limestone, shale, granite, and schist from northwestern Minnesota and Manitoba, or red noncalcareous drift with pebbles of basalt, rhyolite, gabbro, and red sandstone and shale from the Lake Superior Basin." *

The Minneapolis exposure is interpreted "as a product of initial deposition by confluent ice lobes" * (Wright, 1953, p. 468). Interbedded red and buff lacustrine silts in the Wrenshall clay pits south of Duluth are cited by Wright (1955, p. 410) as evidence of two contemporaneous ice lobes supplying meltwater sediments to a proglacial lake. The nature of the interlayering at Wrenshall is similar to that of the Glacial Lake Randall deposits.

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CLASSIFICATION OF THE DRIFTS

The Patrician drift was dated by Leverett (1929, 1932) as Middle Wisconsin, which is now called Cary. The approximate terminus of Leverett's Patrician ice sheet is marked in eastern and central Minnesota by the St. Croix morainic system. Part of this moraine was described and mapped about 75 years ago by T. C. Chamberlin (1883, pp. 382–88; pls. 31, 35) and correlated with the Kettle or Interlobate moraine of eastern Wisconsin. Subsequent investigations by Leverett (1929, pp. 18–19; pl. 1) and others have shown that the Patrician drift may be traced eastward into the deposits of the Chippewa and Green Bay lobes, and thence southward into those of the Lake Michigan lobe to the type locality of the Cary in northeastern Illinois (see Flint and others, 1945). The Cary age of Leverett's Patrician drift, therefore, appears to be well established.

Assignment of the Patrician drift to the Cary substage is substantiated by its relationships to the "young gray drift" of Leverett's Keewatin ice sheet and to red clayey till of the Lake Superior region. The "young gray drift," according to Leverett (1932), was deposited by the Des Moines lobe and by two major protuberances from its eastern edge, the St. Louis sublobe in northern Minnesota and the Grantsburg sublobe in east-central Minnesota. This drift was dated by Leverett as Late Wisconsin on the basis of (1) stratigraphic superposition above the Patrician drift and (2) truncation of Patrician moraines, including the St. Croix, by moraines of young gray drift correlated with those of the Lake Superior, Michigan, and Huron basins (Leverett, 1929). The Late Wisconsin drift of southern Minnesota is now termed Mankato, the type locality being located in the middle of the Des Moines lobe.

When traced northeastward from central Minnesota toward the head of Lake Superior, the red sandy till and stratified drift of the Superior lobe are found to be overlain by red clayey till deposited by a later advance of the Superior lobe (Wright, 1953, pp. 469–70; 1955, p. 407). This red clayey till was formerly correlated as Late Wisconsin (Leverett, 1929, 1932) or Mankato (Sharp, 1953, pp. 865–66; Wright, 1953, pp. 469–70; 1955, pp. 410–11). Most recently it has been correlated as Valders (Wright, 1955; 1956, pp. 19–20) on the basis of lithologic similarity to the red Valders till of eastern Wisconsin (Thwaites, 1943), which overlies the Two Creeks forest bed along the western shore of Lake Michigan north of Manitowoc, Wisconsin. West of the head of Lake Superior the red clayey till is overlain by and interbedded with calcareous gray silty till of the St. Louis sublobe (Leverett, 1932, p. 65; Wright, 1953, pp. 469–70; 1955, p. 410). This gray till was assumed to be Mankato, suggesting equivalence of Valders and Mankato. When Mankato drift was found by radiocarbon dating to be older than the Two Creeks interstadial (Wright and Rubin, 1956), this correlation was abandoned, and the Mankato is now considered by Wright (1957a) to represent a separate substage following the Cary and preceding the Two Creeks interstadial.

The brown sandy till of the Brainerd drumlin field has been traced eastward into the Mille Lacs moraine by Weis (written communication). Noncalcareous brown till and associated ice-contact gravel, dated as Cary, are exposed at many places on the west side of Mille Lacs Lake, where the moraine is capped by a veneer of red clayey till deposited by the Valders Superior lobe (Wright, 1955, p. 409). Red clayey till is known to overlie Cary brown sandy till west of Duluth (Wright, 1955, p. 407) and at numerous localities in Cook County (Sharp, 1953, pp. 860–66, figs. 4 and 5). Thus, the brown sandy till of central Minnesota appears to be correlative with that of the Rainy lobe on the basis of stratigraphic position as well as lithologic similarity and physiographic evidence.

The calcareous gray drift of the Wadena drumlin field was tentatively dated by Leverett (1932, p. 63) as Iowan. This assignment is here rejected in favor of a Cary date. The shallow depth of leaching and lack of well-drained topography on the Wadena till suggest that it is no older than Cary, by comparison with leaching depths and drainage development on other Cary, Mankato, and Valders drifts. Detailed stratigraphic evidence has been introduced to show that the Wadena drift is essentially the same age as the red sandy and brown sandy tills of Leverett's Patrician drift. It may, therefore, be firmly dated as Cary.

In general, the calcareous Wadena till is somewhat older than the noncalcareous brown tills of the Pierz and Brainerd lobes. West of the Mississippi River, in the southern part of the Randall region, the gray sandy till appears to be slightly younger than the red sandy till of the Superior lobe but east of the river the red till appears to be younger. These reverse relations are explained in the section on Pleistocene history.

The exact relationship of the Wadena drift to the calcareous gray till deposited by the Cary advance of the Des Moines lobe (Ruhe, 1950b, 1952a; Ruhe and Gould, 1954, pp. 780–83) in southwestern Minnesota and northern Iowa or to that of the James lobe in eastern South Dakota (Flint, 1950, 1955) has not been determined. However, since the red sandy till of the Superior lobe is known to be interbedded with both Wadena-lobe till (this report) and Des Moines-lobe till (Wright, 1953), the two gray drifts are probably correlative.

The outwash sand along the Mississippi River has been demonstrated to overlie brown Pierz-lobe till. It may be dated, therefore, as no older than late Cary. This interpretation agrees with that of Cooper (1935, p. 20), who concluded that deposition of the valley train took place during the late Middle Wisconsin (Cary) and Late Wisconsin (Mankato) subages: "The section of the Mississippi from Brainerd to St. Cloud, initiated during the earliest stage of decline of the Patrician ice and first nourished by meltwater derived from that sheet flowing into it from east and north, thus came later to receive the greater part of its volume from the Keewatin ice lying to the west. This phase came to a rather abrupt end when the

Keewatin ice, in further recession, shrank away from its great submarginal moraine."

Cooper thus implies that deposition of the valley train was continuous throughout the Cary-Mankato interstadial. Leverett's interpretation that the Middle Wisconsin subage was distinctly "set off from a later one known as the late Wisconsin by a marked recession of the ice front, followed by a distinct readvance" (Leverett, 1932, p. 51) is apparently not accepted by Cooper (1935, pp. 18–20), who cites evidence to show that stagnant remnants of Patrician ice were buried by outwash sand from the Des Moines lobe during the Mankato maximum. If Cooper's interpretation is correct, the Cary-Mankato interstadial interval in central Minnesota was relatively short. This author discovered no indications of weathering either within or immediately below the outwash sand suggestive of any significant time break. Independent evidence that the Cary-Mankato interval was of relatively brief duration in other parts of Minnesota, Iowa, and South Dakota has been presented by Ruhe (1950a, 1952b), Sharp (1953, pp. 865–66), and Flint (1950; 1955, pp. 108–9).

7. AREAL GEOLOGY OF THE RANDALL REGION AND ADJACENT AREAS

GENERAL STATEMENT

The surface and subsurface drift of the Randall region consists principally of noncalcareous brown sandy till and related glacio-aqueous (glacio-fluvial and glacio-lacustrine) deposits. Calcareous gray (or yellowish-brown) drift, both stratified and nonstratified, is abundant in the subsurface but only locally acts as soil parent material. Deposits of red sandy till and outwash are known to occur at only two localities. Peat and other swamp deposits are widely distributed.

Most of the common landforms associated with continental glaciation are found within and adjacent to the Randall region: end moraines, ground moraine, drumlins, pitted and unpitted outwash plains, valley trains, eskers, kames, crevasse fillings, deltas, lacustrine plains, and meltwater drainageways. Except for the occurrence of glacial striae at two localities (see p. 29) and the general smoothing of a few rock outcrops, erosional bedrock features are absent.

The areal geology of the Randall region as mapped by this worker is shown in Plate 1. Discussion of the geology of the Randall region and adjacent areas is considered under five main headings: ground moraine, end moraine, outwash plains and valley trains, glacial lake plains and drainageways, and postglacial valley features.

Parts of Upham's county maps (Winchell and Upham, 1888, pls. 52 and 53; Winchell *et al.*, 1899, pl. 58) and of Leverett's state maps (Leverett and Sardeson, 1919, pl. 1; Leverett, 1932, pl. 2) have been redrafted to a common scale. They are reproduced here (Figs. 14 and 15) in order (1) that the reader might compare the recent mapping with that done by Upham and Leverett, and (2) to show the geology beyond the borders of the Randall region proper, as a more nearly complete basis for the interpretation of glacial history treated in the next chapter.

Information on drift thickness has been gathered from several published and unpublished sources. Upham (Winchell and Upham, 1888, pp. 574–75, 606–8) cites the locations and depths of many wells in his county reports but most of these wells are too shallow to have reached bedrock. Considerable data have been taken from the text, figures, and tables of Allison's (1932, pp. 128–35, 212–21) report on the geology and water resources of western Morrison and Todd counties and from Thiel's (1947, pp. 103–14, 176–87) chapters on the geology and underground waters of Crow Wing and eastern Morrison counties.

Mr. Ray Van Hercke, well driller at Little Falls, has confirmed generally

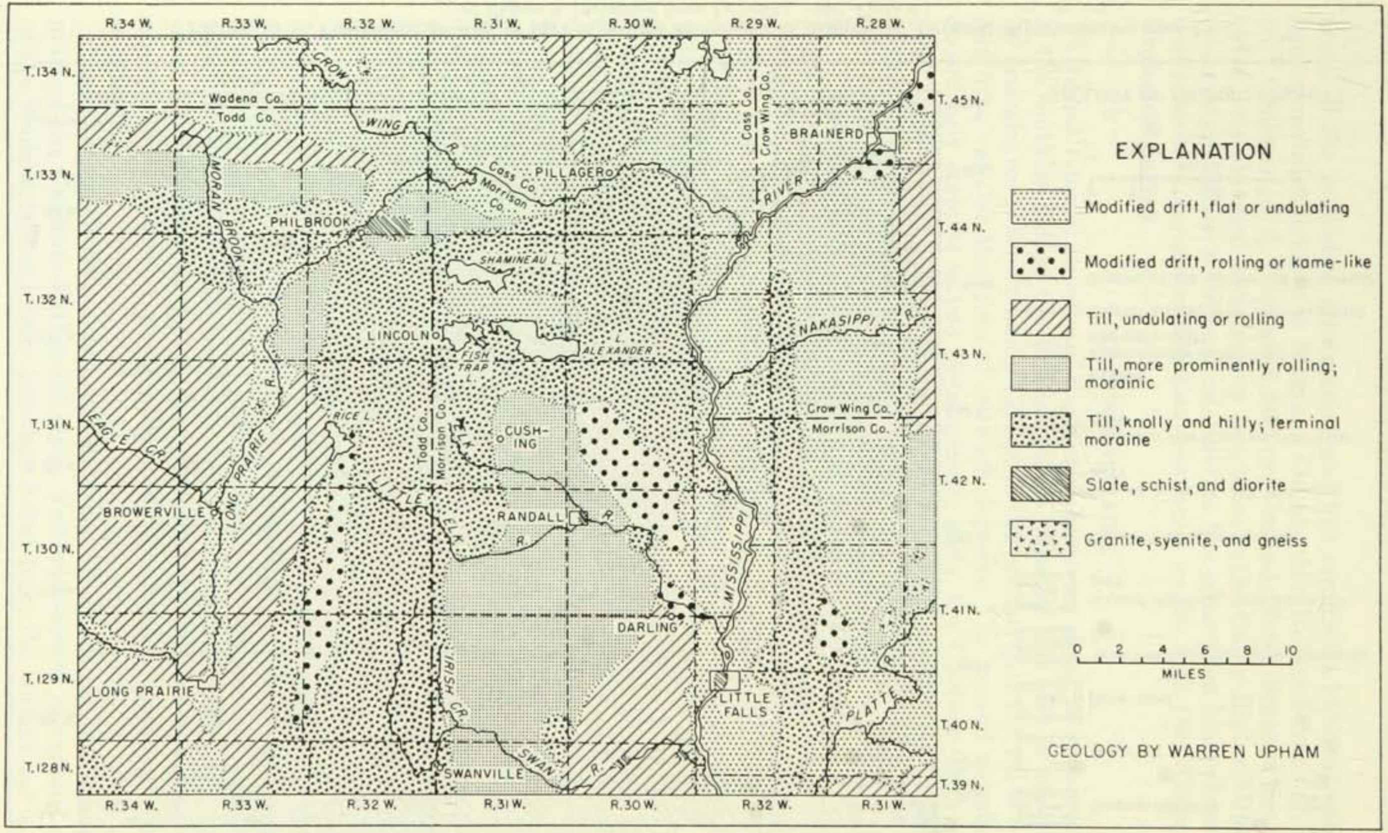

FIGURE 14. — Pleistocene geology of part of central Minnesota as mapped by Upham. Approximates area 1 of Figure 2. (Adapted from Winchell and Upham, 1888, Plates 52 and 53; Winchell *et al.*, 1899, Plate 58.)

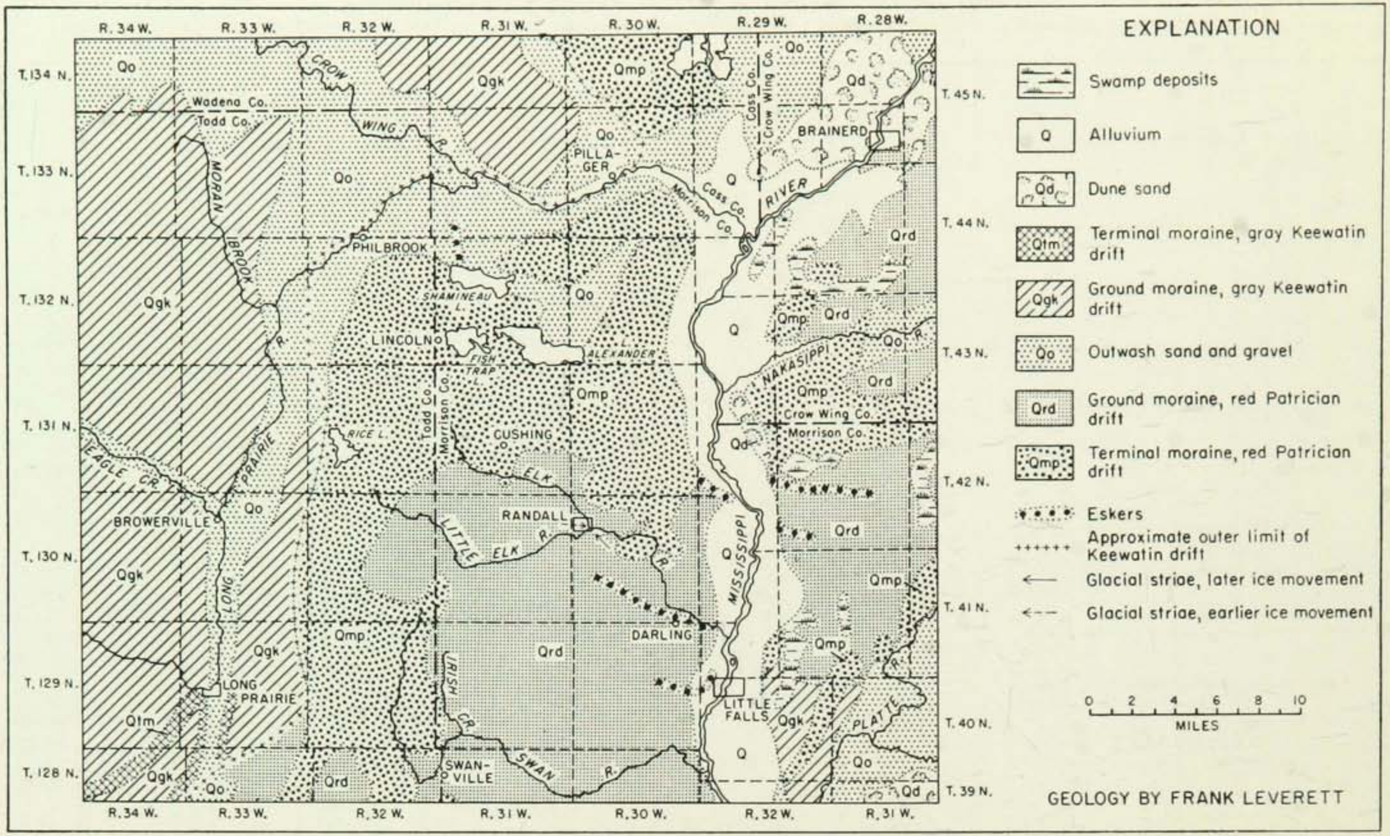

Figure 15. — Pleistocene geology of part of central Minnesota as mapped by Leverett. Approximates area 1 of Figure 2. (Adapted from Leverett, 1932, Plate 2.)

much of the published information and has supplied additional specific figures on drift thickness in Morrison County. Mr. Robert Schneider, District Geologist, U.S. Geological Survey, Ground Water Branch, has provided data obtained from Survey test holes in the Camp Ripley Military Reservation. Much additional information has come from blueprints and well records of various exploration companies on file with the Minnesota Geological Survey.

GROUND MORAINE

General. Ground moraine of the Pierz lobe covers about 65 square miles in the southern half of the Randall region. Most of this area is underlain by noncalcareous brown sandy till but in the eastern part the till is overlain by a variable thickness of outwash deposits. The ground moraine is accordingly mapped as two physiographic units, the Culdrum-Parker till plain and the East Darling plain. Upham (Winchell and Upham, 1888, pl. 53) recognized a similar separation and mapped the western part of the area as till and the eastern part as outwash. Leverett and Sardeson (1919, pl. 1), however, mapped the entire area as clayey till plain and Leverett (1932, pl. 2) later assigned the drift to his Patrician ground moraine.

Culdrum-Parker Till Plain. The topography of the Culdrum-Parker till plain is that of typical ground moraine. The area is an undulating swale-marked plain with average local relief of about 25–30 feet. Although much of the plain lies at a general elevation of 1200–1240 feet above sea level, the surface rises gradually westward and northward from less than 1140 feet near the Mississippi River to around 1280 feet along the irregular inner margin of the St. Croix moraine. A faint southeast-northwest fluting is visible on aerial photos (Fig. 7) and several small drumlins, described earlier in this report (see p. 24), have been mapped. The most conspicuous positive feature of the ground moraine is the Darling esker (see p. 26), whose western end rises more than 60 feet above the till plain.

Shallow depressions of the till plain locally tend to coalesce, so as to suggest incipient Pleistocene drainageways. One such channel originates just south of Parker Town Hall in a tiny subcircular ice-block pit (SE¼ Sec. 21 and SW¼ Sec. 22, T. 130 N., R. 31 W.) closed on all sides except for a narrow outlet to the southeast. This opening connects the pit with a larger depression, which in turn coalesces with a much larger swale apparently drained at its southern end by a channel-like series of elongated pits. Near the southern edge of the Cushing quadrangle the channel appears to split; the main branch is traceable into the Swanville quadrangle but a short distance south of the quadrangle border the channel form becomes obscure. Other incipient drainage lines on the upland till plain are similar to this one.

Noncalcareous brown sandy till underlies nearly all the 45–50 square miles of the Culdrum-Parker till plain. Yellowish-brown calcareous drift of the Wadena lobe is locally less than 3 feet from the surface but is nowhere important as soil parent material. A few areas of sand, generally too small to warrant mapping, are also included in the till plain.

Allison (1932, p. 130) indicates that the brown till (Allison calls it red drift, following Leverett) in this area is from 20 to 50 feet thick and that the total drift thickness, including the older gray drift (here called Wadena), probably averages about 95 feet. Two wells, whose precise locations are not cited but which are plotted on Allison's map (1932, fig. 22, p. 129) in Secs. 18 and 33, T. 130 N., R. 30 W., struck bedrock at depths of 65 and 70 feet, respectively. The locations of two additional wells (NE¼ Sec. 22, T. 130 N., R. 31 W.; SE¼ Sec. 16, T. 129 N., R. 31 W.) are given in Table 55 (p. 132) of his report; these wells ended in till at 87 feet and 58 feet, respectively. According to driller Van Hercke, the drift is 128 feet thick in the vicinity of Parker Town Hall (SW cor. NW¼ Sec. 22, T. 130 N., R. 31 W.).

East Darling Plain. The East Darling plain covers about 17 square miles in the southeastern part of the Randall region, mainly in the east half of Darling Township (T. 130 N., R. 30 W.). Most of the area was mapped by Upham (Winchell and Upham, 1888, pl. 53) as flat or undulating modified drift but was not differentiated by him from the generally finer grained and better sorted outwash sand that borders the Mississippi River to the east. Leverett and Sardeson (1919, pl. 1; Leverett, 1932, pl. 2), on the other hand, included the area with clayey ground moraine to the west and clearly distinguished the deposits from their Mississippi River alluvium.

The East Darling plain is a nearly flat to gently undulating plain at an average elevation of about 1140 feet. It is bordered on the east by the Green Prairie terrace (Fig. 20), and on the north by the St. Croix moraine or by steep 40- to 60-foot ice-contact slopes leading upward to the depositional surface of the Camp Ripley terrace. On the west and southwest the boundary is indefinite and the East Darling plain grades imperceptibly into the Culdrum-Parker till plain.

The plain is crossed in the south and west by the valley of the lower Elk River, generally 10–15 feet deep. The southern segment of the river nearly parallels the prominent Darling esker, whose eastern end rises more than 60 feet above the nearly level surroundings. Conical sand hills associated with the esker also attain a height of over 60 feet. Locally (e.g., W½ Sec. 14, T. 130 N., R. 30 W.) the sand deposits of the plain show a braided pattern similar to that of the Green Prairie terrace.

As viewed by this worker, the East Darling plain is Pierz-lobe ground moraine unevenly veneered with outwash deposits. The thickness of the outwash cover is variable but probably does not exceed 4–5 feet throughout much of the area. Several definite and probable contacts involving 1½ to 4 feet of sand or sandy gravel over till have already been mentioned (see p. 57). South of Fish Lake (SW¼ Sec. 18, T. 130 N., R. 29 W. and SE¼ Sec. 13, T. 130 N., R. 30 W.) the sand cap is 5–10 feet thick, according to Van Hercke. In some places the outwash cover is absent and inliers of noncalcareous brown till or locally of calcareous gray drift, representing the tops of incompletely buried swells, rise gently above the outwash level.

Total thickness of drift beneath the East Darling plain appears to be variable. According to Van Hercke, bedrock lies at a depth of 30 feet south of Fish Lake. Allison's map (1932, fig. 22, p. 129), however, shows the locations of two wells that struck bedrock at a depth of 85 feet each (specific locations not given but plotted on map as NE¼ Sec. 25, T. 130 N., R. 30 W. and NW¼ Sec. 7, T. 129 N., R. 29 W.).

END MORAINE

General. Three end moraines are recognized within and adjacent to the Randall region: the St. Croix, the Nakasippi, and the Fawn Lake. The St. Croix morainic system of Leverett (1932) is equivalent in this area to much of Upham's (Winchell and Upham, 1888) Fergus Falls moraine and to a small part of his Leaf Hills moraine. The nomenclature used in this paper follows that of Leverett, except that the segment of the St. Croix moraine east of the Mississippi River is called the Nakasippi moraine. Also newly named is the Fawn Lake moraine; this belt was not recognized by Leverett but had been mapped by Upham as weakly morainic.

St. Croix Moraine. The massive St. Croix moraine, which covers a little more than half the Randall region or about 180 square miles, is easily the most striking physiographic feature of the area. The main part of the moraine trends nearly north-south along the western side of the area, but in the north the moraine curves eastward to the Mississippi River. Its general outline is convex to the northwest.

The name St. Croix moraine was proposed by Berkey (1897, p. 360) for one of the nearly parallel morainic ridges comprising the Wisconsin Kettle moraine. Specifically, the name was applied to a strong morainic belt of eastern drift bordering the St. Croix River in the vicinity of St. Croix Falls, Wisconsin. The moraine was traced southwestward, first by T. C. Chamberlin (1883, pp. 382–83) and later by Leverett (1932, pp. 40–41), through St. Paul to northwestern Dakota County and thence northwestward through Hennepin County. In this latter county the moraine is buried, according to Leverett, by the "young gray drift" of the Grantsburg sublobe but he inferred that it probably continues northwestward across Wright County, to reappear beyond the outer limit of gray drift in southeastern Stearns County. From here northward into the Randall region the moraine is broken only by outwash gaps in southern Stearns County (see Cooper, 1935, pp. 19–23); the northernmost or Cold Spring gap, about 2 miles wide, is occupied by the Sauk Valley outwash train.

The configuration of the St. Croix moraine in the Randall region as mapped by this worker is basically the same as shown on Leverett's and Upham's maps. In order to minimize nomenclatural confusion, it seems best to retain the well-established name St. Croix for that part of the moraine west of the Mississippi River. The discarded names Fergus Falls moraine and Leaf Hills moraine used by Upham (Winchell and Upham, 1888, pp. 571, 605–6) for different segments of the St. Croix system in this region do have precedence, however, and, dependent upon future investigations of the central Minnesota Pleistocene, may yet prove to be useful terms.

Most of the St. Croix morainic belt in and adjoining the Randall region is very rugged. A fine example of knob-and-kettle topography, the belt is marked by thousands of ice-block basins and steep-sided knobs and ridges composed of till and ice-contact sand and gravel. Relief within the moraine averages about 100 feet but locally exceeds 200 feet. The crest of the moraine, at 1400–1500 feet above sea level, rises 200–300 feet above the general level of the enclosed ground moraine to the south and east. The highest known point is located about 2½ miles northeast of the eastern end of Lake Alexander (SE¼ Sec. 21, T. 132 N., R. 30 W.) where a bench mark records the elevation as 1535 feet, or about 380 feet above the surface of the Mississippi River 3 miles to the east.

The moraine is virtually undrained and is everywhere characterized by small- to medium-sized lakes and many marshes. In the southwestern part of the Randall region an impressive system of meltwater drainageways (Swanville spillways) splits the moraine into longitudinal ridges and interchannel morainic islands. In the north-central part of the area the continuity of the moraine is broken by the Scandia Valley outwash plain, and in the east-central part by the floor of Glacial Lake Randall.

Most of the drift in the St. Croix moraine consists of brown sandy till and eastern- or northeastern-source sand and gravel. Leverett (1932, pp. 39–42) apparently believed that the moraine was built entirely of noncalcareous eastern (Patrician) drift but the present study has disclosed that calcareous western (Keewatin) drift is also present. In fact, deposits of Wadena-lobe till and outwash are locally so abundant that it is hard to understand how they could have been overlooked in previous investigations, even if one allows for less satisfactory field conditions that probably prevailed at the time of Leverett's study. In some sections of the moraine western drift, although capped by a variable thickness of eastern drift, may actually form the core of the moraine. This appears to be the case particularly (1) in the southwestern part of the Randall region along the inner part of the moraine from the southern border of the Cushing quadrangle northward for a distance of about 4 miles, and (2) in the east-west segment of the moraine south of Fish Trap Lake and Lake Alexander. Contacts of brown sandy till with Wadena drift in these areas have been described or listed in the section on stratigraphy.

In the southwestern area exposures of Wadena drift (mainly stratified sand and gravel but also till) are commonly found on the slopes and at or near the tops of the interchannel islands. Four such islands have nearly accordant crests at 1310–1320 feet, the remainder 1275–1285 feet. At some localities the Wadena drift is overlain by brown Pierz till or noncalcareous eastern sand, but at other sites the younger drift is absent. These relationships are exemplified by the large morainic island (1.8 miles long by 0.8 mile wide) immediately east of Lake Beauty. The crest of the island reaches an elevation of 1317 feet, or about 110 feet above the bordering channel floors. Many road cuts expose Wadena drift, most of them (9 of 11 exposures) showing well-stratified calcareous sand and limestone-rich gravel (see sample PG83–53, Table 2). Brown sandy till and noncalcareous sand are also present (14 exposures and auger borings) and at three localities were found to overlie Wadena drift. In general, however, the distribution of the younger drift cover appears to be discontinuous.

Other spillway islands show similar relationships. Wadena drift is commonly exposed at or near the tops of the hills and also on the slopes; the Pierz drift seems to be thicker and its distribution more continuous on the slopes than over the crests. It appears that the Pierz lobe in this area may have been too thin or too feeble to demolish completely an older Wadena-drift topography — possibly either a moraine or an outwash plain (as suggested by the predominance of sand and gravel) at about 1310–1320 feet (as suggested by nearly accordant crests at this elevation).

Wadena-lobe drift (mainly till but including some stratified drift) is even more abundant south of lakes Fish Trap and Alexander. It is exposed in many cuts along the Todd-Morrison county line in the first mile south of Lincoln, along U.S. Highway 10 and the Northern Pacific tracks, along both the north-south and east-west sections of Morrison County Aid Road 69, along State Aid Road 6, and in the western part of Camp Ripley. Several of the morainic knobs show calcareous Wadena drift nearly to their crests. At a few localities brown till is draped over gray till in a fashion implying burial of Wadena-lobe drumlins. The evidence suggests that here also the present topography partly reflects a buried topography on Wadena drift.

Calcareous Wadena drift is well exposed 2½ miles south of Cushing along State Aid Road 7 (SW¼NW¼ Sec. 3 and SE¼NE¼ Sec. 4, T. 130 N., R. 31 W.). Nearly all the cuts in this segment of the moraine show noncalcareous brown till, but exposures of calcareous sand and gravel are again found near the crest of the moraine at elevations of 1295–1340 feet.

In addition to Wadena-lobe till and outwash deposits, calcareous lake sediments have been found at the crest of morainic hills. One of the best exposures is located in eastern Todd County, 0.7 mile south of Pine Island Lake on the south side of an incipient drainageway or small glacial lake plain (SE¼NE¼ Sec. 4, T. 130 N., R. 32 W.). The cut exposes a thick section of varved calcareous silt and fine sand (Fig. 16) at an elevation of 1320 feet.

A second fine exposure of western-source lacustrine sediments occurs at the 1220-foot crest of a morainic knob 2½ miles east-southeast of Randall. The exposure is located on the west side of Morrison County Aid Road 29 about 2500 feet south of Minnesota Highway 115 (SE cor. Sec. 9, T. 130 N.,

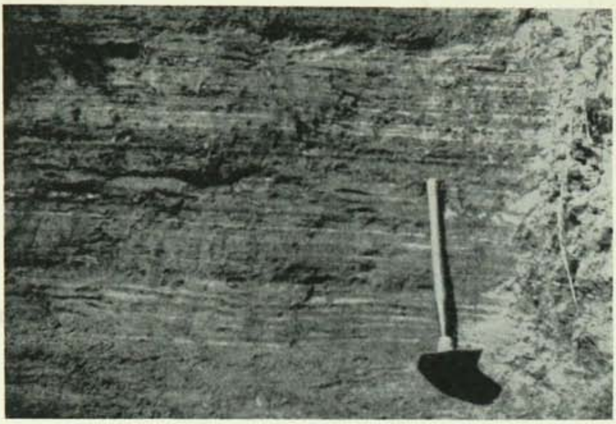

FIGURE 16. — Calcareous lacustrine sediments in the St. Croix moraine. SE¼NE¼ Sec. 4, T. 130 N., R. 32 W., Todd County.

R. 30 W.). It shows moderately well-sorted sandy gravel and gravelly coarse sand of eastern origin overlapping calcareous western lake beds on the north side of the hill (Fig. 17).

The lacustrine sediments at this locality consist of flat-lying, well-stratified, well-sorted, interbedded sand and silt. Individual layers vary in thickness but probably average 1½–2 inches thick. The sand is mostly fine grained, pale brown in color (10YR 6/3), calcareous, and highly quartzose (80–85 per cent subrounded quartz grains). The silt layers are darker in color, consisting of yellowish-brown (10YR 5/4) calcareous coarse silt.

Superior-lobe till and sand have been positively identified at only two localities in the Randall region, one of which is in the middle of the St. Croix moraine just west of Lake Beauty (see p. 47). The second exposure is located about 2 miles from the mapped inner border of the moraine (see p. 44). Although it is very possible that additional exposures of Superior drift may yet be discovered in the moraine, it is improbable that red till constitutes a significant fraction of the moraine's composition in the Randall region proper.

In addition to the deposits described above, the St. Croix moraine is composed of brown sandy till and noncalcareous sand and gravel. In fact, these materials form the bulk of the moraine and are exposed at many hundreds of localities throughout the Randall region. The moraine in the western part of the area (i.e., the north-south section, the arcuate part, and the western part of the east-west segment south of lakes Fish Trap and Alexander) is basically a till moraine, although deposits of stratified drift are also abundant. According to the present interpretation, this section of the moraine defines a long stillstand of the Pierz ice front, though not everywhere its farthest advance.

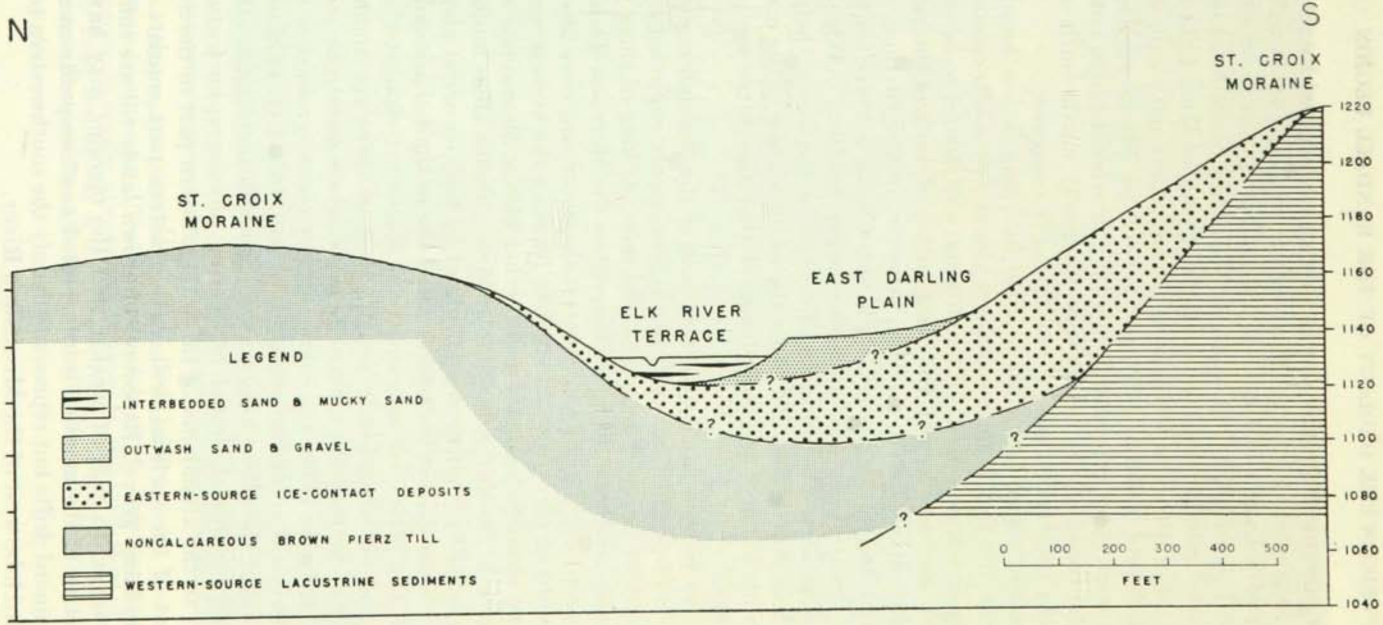

FIGURE 17. — Cross-section showing physiographic and stratigraphic relations near Randall.

The outer margin of the moraine in this area is marked by many short steep-sided ridges transverse to the moraine axis. The best examples are located near Mill Lake and Chain of Lakes (Fig. 18) in the western part of Little Elk Township (T. 130 N., R. 32 W.). They occur less well formed elsewhere in the moraine (e.g., south and southeast of Long Lake in T. 131 N., R. 32 W.; Fig. 19). The features were recognized and mapped by Upham (Winchell and Upham, 1888, pp. 571–72; pl. 52) as a belt of short ridges and kames 14 miles long and about a mile wide. Upham noted, however, that the trend of the ridges was commonly north-south or nearly parallel, rather than transverse, to the axis of the moraine.

The ridges are commonly 1000 to 2000 feet long, a few hundred feet across, and 75–100 feet high. Several are double- or multi-crested or are aligned along a common axis. Although some were found to be composed of ice-contact sand and gravel, the composition of most of the ridges was not thoroughly investigated. Upham, however, described them as "consisting of sand and coarse gravel, with water-worn cobbles up to a foot in diameter, occasionally also enclosing larger boulders" (Winchell and Upham, 1888, p. 572). The shape and lineation of the forms, their composition, and their general location along the outer margin of the moraine in association with kamic topography suggest that the ridges are probably crevasse fillings.

The St. Croix moraine in the western part of the Randall region is also marked by small perched outwash plains, commonly encircled by 40- to 60-foot ice-contact slopes. The largest and most striking of these plains is located 1½ miles south-southwest of Lincoln on the Morrison-Todd county line; it measures nearly a mile in greatest diameter and rises 50–100 feet above its base to an elevation of 1420 feet, forming the highest part of the moraine in the immediate area. Several other plains, all mapped as intramorainic outwash, are shown in Plate 1. Many similar areas undoubtedly exist, as suggested by topographic form and by tone on aerial photos, but escaped direct examination because of small size or limited accessibility.

In general, the plains are subcircular or somewhat elongated in plan, flat-topped, and not abundantly pitted. Most of them are underlain by well-sorted fine- to medium-grained noncalcareous quartzose sand (see sample S57–52, Table 7) or, less commonly, by coarse-grained or gravelly sand. The absence of accordant crests (1285 feet, 1350 feet, 1375 feet, 1420 feet) suggests that the plains have no special significance and are therefore considered only incidental, though interesting, physiographic features.

In contrast to the abundance of till in the western part of the St. Croix moraine, most of the surficial drift in the eastern part consists of noncalcareous sand and gravel. Exposures of brown sandy till are sufficiently common, however, to suggest weakly that the moraine may have a till core. This section of the moraine is interpreted as a composite moraine of Pierz and Brainerd drifts but represents mainly the southwestern terminus of the Brainerd lobe west of the Mississippi River.

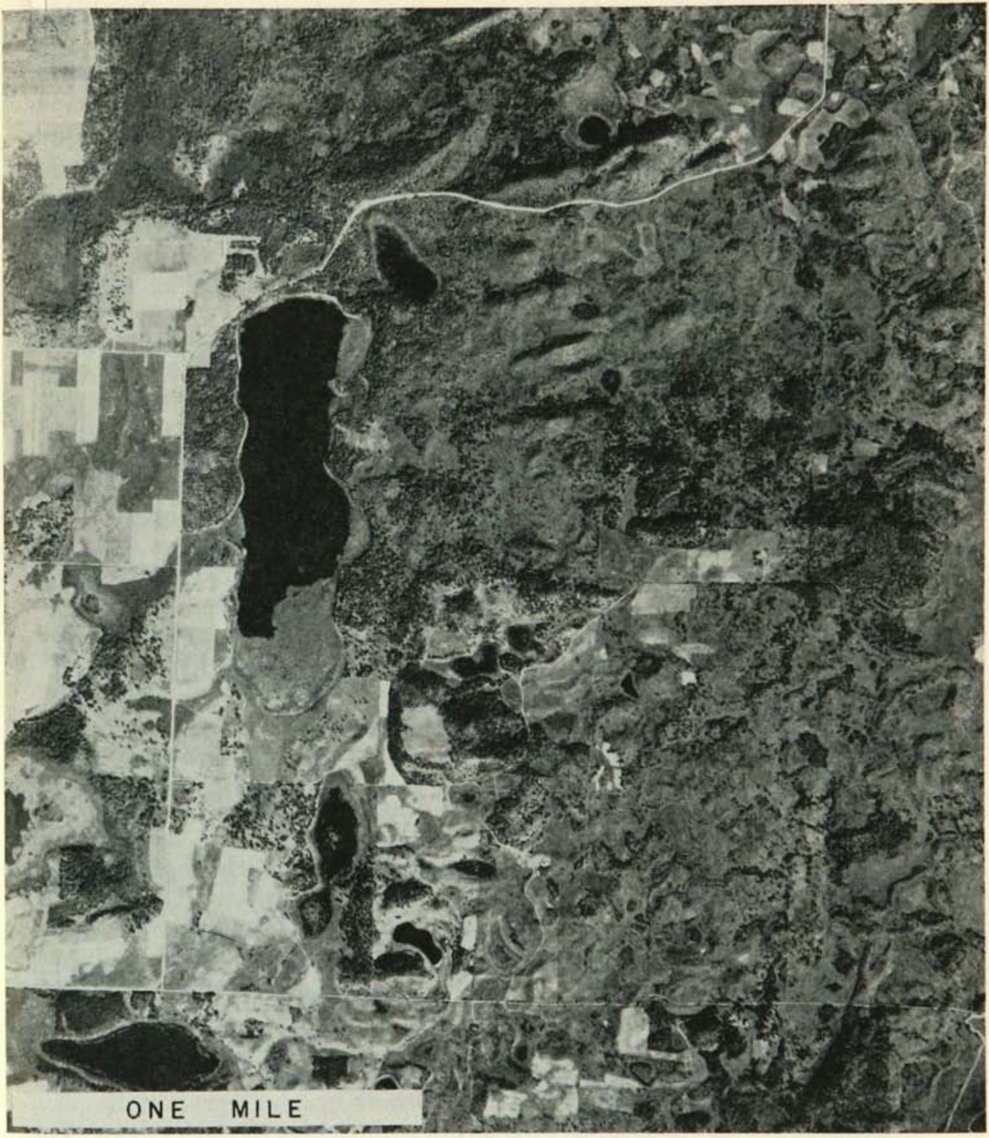

FIGURE 18. — Outer margin of the St. Croix moraine near Mill Lake. St. Croix moraine on right (east); outwash-veneered east margin of Wadena drumlin field on left. Note short steep-sided ridges (crevasse fillings) transverse to moraine axis east and northeast of Mill Lake. Head of western branch of Lake Beauty-Grey Eagle drainageway is in southeast corner. Location is eastern Todd County, 7 miles northeast of Long Prairie in Tps. 129–130 N., R. 32 W. (Photo by U.S.D.A., BYH 5-71, Sept. 16, 1939.)

A variety of topographic features appears to be present in the eastern morainic area, including kames, eskers, crevasse fillings, esker deltas, outwash fans, and similar features composed of stratified drift. Only a few have been studied, however. Some of the more linear forms have been described in the section on eskers (see p. 28). Good exposures of delta foreset beds are mentioned in the discussion of Glacial Lake Randall and a prominent marginal outwash plain (Camp Ripley terrace) is treated separately.

The discontinuous morainic belt along the northern edge of the Randall region, hereafter called the Shamineau Lake segment, is similar in topographic expression and composition (mainly ice-contact sand and gravel) to the area just described. The two segments merge just north of the Randall region at the head of the Scandia Valley outwash plain, thence continue northward to and beyond (north of) the prominent morainic gap 2 miles east of Pillager.

The western end of the Shamineau Lake segment is composed of outwash. Most of the deposits are well-sorted fine- to medium-grained sands with interbeds of coarse sand and gravel. The outwash has a distinctly eastern origin, as indicated by its noncalcareous nature and pebble content, and is lithologically indistinguishable from that of the Fawn Lake and Scandia Valley outwash plains. It was apparently deposited as part of an ice-cored outwash plain at about 1340 feet but much of the initial surface has been destroyed, so that only strongly pitted remnants remain. One of the best remnants (Secs. 13 and 14, T. 132 N., R. 32 W.) is at a general level of 1330–1350 feet above sea level but the surface locally rises from 1300 to 1380 feet. It is bounded on the west by a steep ice-contact slope exposing 50–80 feet of well-sorted fine- to medium-grained sand (see sample S62–53, Table 7).

Available data indicate that drift thickness in the Morrison County part of the St. Croix moraine probably averages about 200 feet. According to Allison (1932, p. 130), the mean thickness in parts of the moraine "is at least 200 feet, for several wells have entered the drift that far without striking rock." One well near the east end of Lake Alexander (NW¼ Sec. 5, T. 131 N., R. 30 W.) ended in till at a depth of 203 feet; two wells, one at Lincoln and the other about 3 miles northeast of Cushing, struck bedrock at 200 feet; a fourth well, at the inner margin of the moraine (probable location is Sec. 18, T. 130 N., R. 31 W.), entered bedrock at 90 feet (Allison, 1932, fig. 22, p. 129; table 55, p. 132).

Van Hercke reports that north of Cushing bedrock generally lies at a depth of 175–190 feet, the average depth approaching the latter figure. The surficial Pierz till in this area, according to Van Hercke, is about 30 feet thick and overlies no less than 115–120 feet of sand which extends down to bedrock. His recent drilling on the south shore of Fish Trap Lake indicates that the drift here is 175–180 feet thick, subdivided as follows: brown clay (Pierz till), 20 feet; sand, 15 feet; blue clay (unoxidized Wadena till), 50 feet; and quicksand, 90 feet.

The thickness of the drift is apparently greater in eastern Todd County than in Morrison County. Although no specific depths are cited, Allison (1932, p. 214) estimates that the maximum thickness is 350 feet.

Nakasippi Moraine. The name Nakasippi moraine is applied to that segment of the St. Croix morainic system east of the Mississippi River mapped by Leverett and Sardeson (1919, pl. 1; Leverett, 1932, pl. 2) along the Crow Wing-Morrison county line. It is separated from the main part of the St. Croix system by the Mississippi River and the Green Prairie terrace, whose combined width narrows to 1½ miles just north of the village of Fort Ripley. The composition of the Nakasippi moraine and especially its physiographic location at the southwestern end of the Brainerd drumlin field suggest that the moraine represents in part the southern terminus of the Brainerd lobe east of the Mississippi River. The moraine may be interlobate, however, as it also seems to represent a recessional stage of the Pierz lobe.

The topography of the Nakasippi moraine is similar to that of the St. Croix moraine in the northeastern part of the Randall region proper. Maximum relief is about 150 feet and much of the belt is extremely rugged. Deep ice-block depressions bordered by steep-sided knobs and ridges abound. The crest of the moraine generally attains an elevation of 1220–1250 feet but locally rises to over 1300 feet.

Reconnaissance studies indicate that the composition of the Nakasippi moraine is also similar to that of the eastern part of the St. Croix moraine west of the river. The drift consists predominantly of northeastern-source gravel and sand but brown sandy till is locally exposed in the less rugged parts of the moraine. Calcareous Wadena drift and red Superior-lobe deposits have not been found.

Little well information is available for this area. A shallow well in Sec. 27, T. 43 N., R. 31 W. passed through 21 feet of sand and coarse gravel beneath a 2-foot soil profile (Winchell and Upham, 1888, p. 606).

Fawn Lake Moraine. A weak but distinct belt of end moraine is located 5–7 miles west of Lincoln between the western border of the Randall region and the outwash train of the Long Prairie River. The belt appears to trend nearly north-south and has a maximum width of about 2 miles. Fawn Lake, Pine Island Lake, and Turtle Lake of southwestern Fawn Lake Township (T. 132 N., R. 32 W.) occupy ice-block depressions in the moraine, which is accordingly named the Fawn Lake moraine.

The several exposures of drift that have been examined in the Fawn Lake moraine reveal highly calcareous sand and gravel (see samples S35–52 and S36–52, Table 7) similar to that in the St. Croix moraine farther south and east. Limestone fragments ranging in size from sand to cobbles abound. A count of one pebble sample collected at the north end of Fawn Lake shows 57 per cent limestone (see sample PG37–52, Table 2).

The Fawn Lake moraine probably represents a northward continuation of the belt of gray drift mapped by Leverett (1932, pl. 2) along the base of the St. Croix moraine. It almost certainly is equivalent to the incompletely buried moraine or outwash plain of Wadena drift in the southwestern part of the Randall region described above as part of the St. Croix moraine. The Fawn Lake morainic area was previously recognized by Upham (Winchell and Upham, 1888, pl. 52), who mapped it as intermediate in relief between terminal moraines to the east and northwest and rolling till plains south of the (Fawn Lake) moraine and west of the Long Prairie outwash train. Leverett and Sardeson (1919, pl. 1; Leverett, 1932, pl. 2), however, mapped the morainic area as part of the Long Prairie outwash gravel plain. When the moraine is traced northeastward from Fawn Lake, its identity becomes obscure in the complex physiographic relationships that exist in and adjoining the northwestern corner of the Randall region. In this area calcareous Wadena drift is largely buried by thin extramorainic brown Pierz till or by younger outwash and peat deposits.

Three test holes drilled in 1910 by the Crosby Exploration Company entered bedrock (green schist) at depths of 165 feet, 174 feet, and 180 feet about a mile west of the southern end of Fawn Lake (SW¼SE¼SE¼ Sec. 25, T. 132 N., R. 33 W.).

OUTWASH PLAINS AND VALLEY TRAINS

General. Outwash sand and gravel are widely distributed in and adjacent to the Randall region. Some of the smaller or apparently less significant outwash areas were considered in connection with the St. Croix moraine, and the outwash-veneered East Darling plain has been discussed as part of the ground moraine. The more important outwash plains and valley trains are treated here as distinct physiographic areas; these include the Fawn Lake outwash plain in the northwestern part of the Randall region, the Camp Ripley terrace in the east-central part, the Scandia Valley outwash plain along the northern edge of the area, the Long Prairie valley train located a few miles west of the Randall region proper, and the Green Prairie terrace which borders the Mississippi River.

Fawn Lake Outwash Plain. The Fawn Lake outwash plain is named from Fawn Lake Township (T. 132 N., R. 32 W.) in the northwestern part of the Randall region. Physiographically, it is situated beyond the outer (western) margin of the St. Croix moraine and east of the Fawn Lake morainic belt.

The outwash surface is best preserved at an elevation of about 1280 feet, immediately west of a linear ice-block trough located along the toe of the St. Croix moraine. Rogers (Slough) Lake, Long Lake, Beck Lake, Rice Lake, and Thunder Lake occupy the deeper depressions in this trough, the continuity of which is locally broken by outwash fanheads or fan "handles" rising eastward into the moraine. One of the frontal fans, weakly dissected by narrow valleys draining northwestward to the floor of Glacial Lake Wadena (Fig. 19), is crossed by State Aid Road 7; the "handle" of this fan is located between Rogers and Long lakes. Most of the plain,

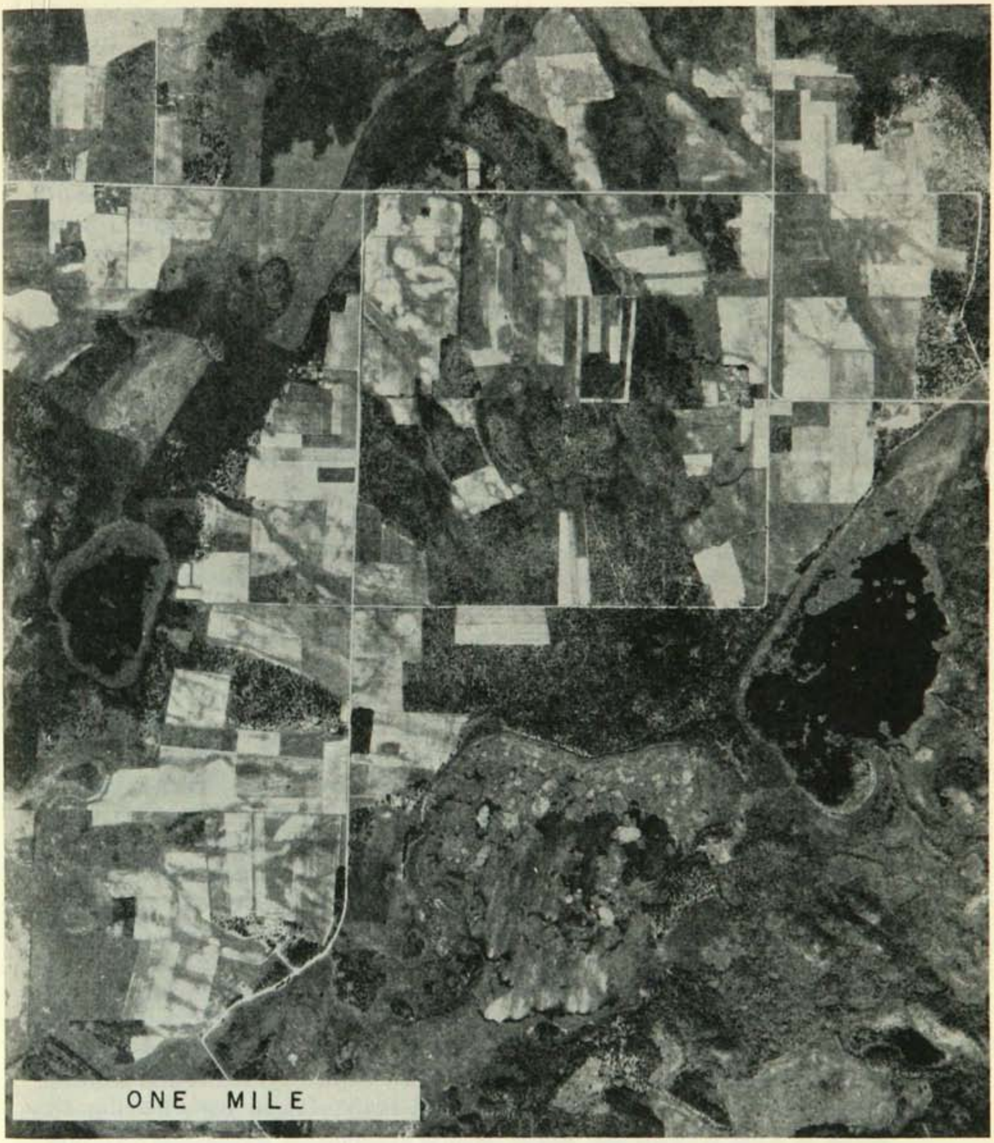

FIGURE 19. — Weakly dissected frontal fan of Fawn Lake outwash plain. Slope of fan is accentuated by shallow valleys which drain northwest toward narrow plain of Glacial Lake Wadena. Head of lake plain is at north end of ice-pit lake (Little Fish Trap Lake) on left (west-center). Handle of fan is between Rogers Lake and Long Lake (nearly dry) on right. Note steep morainic ridges (probably crevasse fillings) southeast of these lakes. Location is eastern Todd County, just west of Lincoln in Tps. 131–132 N., R. 32 W. (Photo by U.S.D.A., BYH 4-75, Sept. 14, 1939.)

however, is still undrained and is marked by small ice-pit lakes (Jaeger Lake, Little Fish Trap Lake, Sackmeister or Little Rice Lake) in addition to the larger lakes east of the ice-contact slope that borders the western edge of the trough.

The Fawn Lake plain is underlain generally by noncalcareous well-sorted sand, which is commonly fine grained (see sample S98–53, Table 7). Pebbles from gravelly interbeds are similar to those of the Pierz-lobe till and point to a source in northeastern Minnesota. Limestone pebbles and granules have not been noted in the outwash deposits.

Extramorainic Brown Till: Brown sandy till has been identified at several localities beyond the outer margin of the St. Croix moraine, notably within and adjacent to the area mapped as the Fawn Lake outwash plain. This extramorainic till is difficult to identify because of its thinness (0–3 feet thick) and patchy surface distribution. Where it reaches the surface, the brown till is usually found in contact with the underlying Wadena drift (see p. 48); commonly, however, it is overlain by outwash deposits (see p. 56).

Brown sandy till has also been observed at a number of points west of the Long Prairie River in the eastern part of the Wadena drumlin field. A veneer of brown till resting atop a Wadena-lobe drumlin was discovered by I. G. Bue as far northwest as Leaf River, about 4 miles north of Wadena, or about 25 miles beyond the outer margin of the moraine. Extramorainic eastern drift was also noted by Leverett (1932, p. 40), who recognized "an admixture of rocks that seem to have been brought in from the borders of the Lake Superior Basin" in the surface portion of his Keewatin or gray-drift ground moraine in Todd, Wadena, and Cass counties.

Camp Ripley Terrace. Several disconnected outwash surfaces, ranging in area from a few hundred square feet to about 3 square miles, have been mapped in the region north and east of Randall. The surfaces are of nearly equal elevation and are interpreted as remnants of a collapsed outwash plain, here named the Camp Ripley terrace.

The largest and best preserved remnant of this depositional surface is located about 4 miles east of Randall, in and adjoining the southwestern corner of the Camp Ripley Military Reservation (mainly in Secs. 34 and 35, T. 131 N., R. 30 W. and Secs. 2, 3, and 11, T. 130 N., R. 30 W.). The terrace tread is a smoothly graded outwash plain pocked by several ice-block depressions, the largest of which are occupied by Kraft and Johnson lakes. The surface of the plain drops from 1250 feet above sea level on the north to 1200 feet on the south with a gradient of 20–25 feet per mile. Where best defined, the northern and southern margins of the terrace are sharply bounded by steep ice-contact slopes, 40–50 feet high. The southern margin has been considerably modified by stream erosion, so that several rolling valleys, now dry, extend headward (northward) from the edge of the escarpment between level-crested spurs.

A second fine remnant of the depositional surface is located northwest of Fish Lake in Secs. 13 and 14, T. 130 N., R. 30 W. It is a nearly level pine-covered sand plain at about 1200 feet, traversed along its entire length (1 mile) by Minnesota Highway 115. At its eastern end the surface attains an elevation of 1217 feet (B.M.), or about 80 feet above the immediate surroundings. The northern edge of the terrace is a very steep undissected ice-contact slope that drops 40–80 feet to the adjoining marsh. The southern and western slopes are less steep than the northern and the descent to the East Darling plain is interrupted by small outliers of the depositional surface.

Other excellent remnants of the Camp Ripley terrace are crossed by County Aid Road 4 and State Aid Road 6 north of Randall and east of Cushing. In the vicinity of Betesta Church and Rosenlund Cemetery (Sec. 25, T. 131 N., R. 31 W. and Sec. 30, T. 131 N., R. 30 W.), 2½ miles north of Randall, the elevation of the plain is 1220–1240 feet, rising locally to 1251 feet. The surface slopes southward to 1200 feet 1½ miles north of town, where it is interrupted by an arm of the Lake Randall plain (Sec. 31, T. 131 N., R. 30 W.). South of the lake plain the terrace can again be recognized at an elevation of 1180–1200 feet. The gradient of the plain in this region decreases southward but averages about 25 feet per mile.

In the vicinity of Round and Three Finger lakes (Secs. 27 and 28, T. 131 N., R. 30 W.) isolated remnants of the Camp Ripley terrace are mapped at elevations above 1260 feet. The sand plain immediately south of Three Finger Lake at 1272 feet undoubtedly represents part of the uncollapsed surface. Small sand plains east of this lake and south of Round Lake, two of which rise to an elevation of 1277 feet, represent the highest probable remains of the terrace that have been mapped. Additional remnants of the uncollapsed outwash surface probably occur elsewhere in the area mapped as St. Croix moraine.

The over-all slope of the Camp Ripley terrace, therefore, descends from about 1280 feet on the north to about 1200 feet on the south. The average gradient is approximately 25 feet per mile.

Camp Ripley terrace deposits consist of medium- to coarse-grained sediments. The main outwash surface east of Randall and the outwash apron east of Cushing are underlain principally by gravelly sand and sandy gravel derived from source regions in northeastern Minnesota. The surface materials of the elongated plain northwest of Fish Lake and of the depositional surfaces north of Randall are generally better sorted and finer grained, consisting mainly of sand.

Little information is available regarding the thickness of drift beneath the Camp Ripley terrace. Allison's small-scale map (1932, fig. 22, p. 129) shows the locations of two wells which were probably drilled on the outwash surface, but the specific sites are not given and can only be implied (SE¼ Sec. 2, T. 130 N., R. 30 W.; NE¼ Sec. 27, T. 131 N., R. 31 W.). The first well struck bedrock at 48 feet and the second ended in drift at a depth of 105 feet.

Scandia Valley Outwash Plain. The Scandia Valley outwash plain covers about 12 square miles along the northern border of the Randall region. The plain is underlain by noncalcareous well-sorted fine- to medium-grained sand (see sample S76–53, Table 7) which, according to Van Hercke, overlies bedrock at a depth of 175–190 feet in the vicinity of Ham Lake (NE¼ Sec. 29, T. 132 N., R. 31 W.). Northeast of Lake Alexander the thickness of the drift is reported by Allison (1932, fig 22, p. 129) to be at least 175 feet.

The Scandia Valley outwash surface heads in the St. Croix moraine 1½ miles north of the Randall region, or about 4 miles south-southeast of Pillager, at an elevation of 1350 feet. After sloping steeply to about 1300 feet, the plain broadens and slopes more gently southwestward to the east end of Lake Alexander. North of Lake Alexander and Fish Trap Lake the surface is nearly level at 1280–1290 feet and exhibits no apparent gradient for a distance of 8 miles. The western end of the sand plain, northwest of Lincoln, appears to coalesce with the frontal-fan sediments of the Fawn Lake outwash plain and to pass beneath the peat-covered floor of Glacial Lake Wadena. At one locality (SW¼NE¼ Sec. 23, T. 132 N., R. 32 W.), however, 6-inch layers of fine sand (Scandia Valley or Fawn Lake outwash?) are interbedded with 9-inch layers of noncalcareous clay of possible lacustrine origin.

Except along the morainic borders to the north and south, the Scandia Valley plain is not deeply pitted. It becomes somewhat swampy near its western end, suggesting that the filling may not have been so complete as farther east.

Long Prairie Valley Train. Outwash deposits along the lower Long Prairie River (downstream from the village of Long Prairie) were mapped by both Upham and Leverett. "At Long Prairie the outwash floor of the valley is about one mile wide, but toward the north the width increases to three miles at Browerville and to eight miles beyond Philbrook. . . . Most of the surface of the outwash is a smooth plain, but locally hills rise from 20 to 40 feet above the general surface" (Allison, 1932, p. 215). North and east of Philbrook the sand and gravel coalesce with that of the Crow Wing drainage basin to form the extensive outwash plain west of Pillager gap.

Upham (Winchell and Upham, 1888, p. 573) recognized two distinct levels along the valley: (1) an inner flat tract of gravel, sand, and silt, ½ to 1 mile wide, 5 to 15 or 20 feet above the river, which he considered postglacial floodplain, and (2) an outer undulating glacial outwash plain, 20 to 40 feet above the river. Leverett apparently did not make this distinction.

The three principal tributaries of the Long Prairie River between Long Prairie and Philbrook (upper Long Prairie River, Eagle Creek, Moran Brook) flow in a general southeasterly direction; all empty into the northward-flowing Long Prairie River at obtuse angles (Fig. 2). Upham's map

(Winchell and Upham, 1888, pl. 52) shows sand and gravel deposits bordering the upper Long Prairie River and Moran Brook but not along Eagle Creek (Fig. 14). Leverett (Leverett and Sardeson, 1919, pl. 1; Leverett, 1932, pl. 2), on the contrary, mapped outwash deposits along Eagle Creek but not along the upper Long Prairie River or Moran Brook (Fig. 15).

South of Long Prairie the main outwash belt, as mapped by both Upham and Leverett, continues on to the vicinity of Little Sauk, about 9 miles south-southwest of Long Prairie.

Most of the wells located on the Long Prairie valley train are shallow driven wells, usually less than 25 feet deep. All pass through interbedded sand and gravel. According to Allison (1932, p. 214) the drift in the valley of the Long Prairie River at Long Prairie is about 200 feet thick. Four exploration holes drilled near Philbrook (S½NW¼SE¼ Sec. 32, T. 133 N., R. 32 W.) by the Crosby Exploration Company in 1909 and 1910 encountered bedrock at 140–146 feet. Outcrops of syenite occur near the western edge of the valley train about 5 miles northeast of Browerville (NE¼ Sec. 15, T. 131 N., R. 33 W.) and several exposures of gabbro and anorthosite occur at and above the mouth of Fish Trap Creek near Philbrook (Sec. 34, T. 133 N., R. 32 W.) (Winchell and Upham, 1888, pp. 567–69; Harder and Johnston, 1918, pp. 49–50).

Green Prairie Terrace. Between Brainerd and St. Cloud the Mississippi River is bordered by a prominent terraced valley train 30–50 feet above the present river gradient (Cooper, 1935, p. 68; pl. 4). North of Little Falls only one terrace level can be positively identified; it has been partly mapped by this author as the Green Prairie terrace, named from the township of Green Prairie (T. 130 N., R. 29 W.) which adjoins the Mississippi River in the southeast part of the Randall region. The terrace sand was mapped by both Upham (Winchell and Upham, 1888, pl. 53) and Leverett (Leverett and Sardeson, 1919, pl. 1; Leverett, 1932, pl. 2), but neither of these workers differentiated the terrace from recent alluvium or from a second terrace level south of Little Falls recognized by Cooper (1935, p. 68). Inspection of the Little Falls quadrangle topographic map suggests that this second and lower terrace probably heads at Blanchard Dam, about 8 miles downstream from Little Falls; it has not been studied in the present investigation.

The Green Prairie terrace is commonly from 2½ to 3 miles wide, including the width of the narrow trench occupied by the modern Mississippi River and recent alluvium, and is usually present on both sides of the river. It has an average height of about 25 feet above the river and exhibits a uniform gradient of about 3 feet per mile to the south.

Perhaps the outstanding feature of the Green Prairie terrace is its conspicuous braided pattern, indicative of an overloaded stream. The anastomotic system of channels and bars is especially striking on aerial photos (Fig. 20) but can be identified locally in the field as well.

In the southeastern part of the Randall region the terrace sand grades

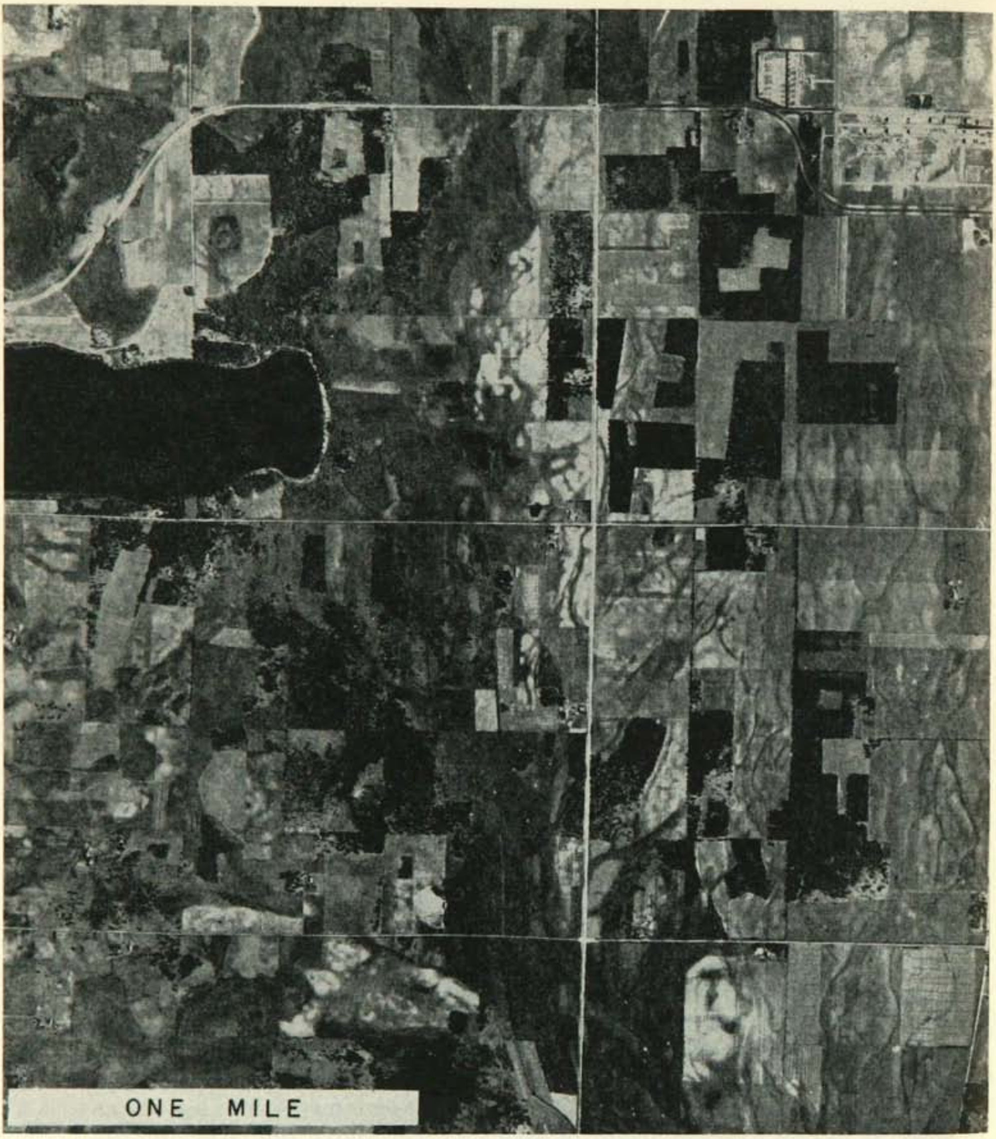

FIGURE 20. — Green Prairie terrace and East Darling plain near Fish Lake. Note contrast between braided pattern of Green Prairie terrace on right (east) and pitted pattern of outwash-veneered ground moraine (East Darling plain) on left. Location is just west of Mississippi River, 6 miles north of Little Falls in T. 130 N., Rs. 29–30 W. (Photo by U.S.D.A., BYA 12-35, July 8, 1940.)

westward with little apparent topographic and lithologic change into the outwash sand of the East Darling plain. As previously mentioned, the distinction between these deposits is a difficult one to make, especially because a large part of the data comes from auger borings. The boundary between the Green Prairie terrace and the East Darling plain (Fig. 20) is mapped along the western border of the braided pattern with the qualification that valley-train sand locally extends as much as half a mile west of this boundary.

Farther north, however, in the Camp Ripley Military Reservation, the terrace is bordered on the west by a prominent east-facing escarpment, 50–80 feet high, locally capped by deltaic sediments deposited at the head of Glacial Lake Randall. As the terrace passes upstream through the gap at Fort Ripley, its width narrows to 1½ miles and the western scarp attains a height of 140 feet. North of Fort Ripley gap the terrace broadens into an abundantly pitted outwash plain at 1175 feet; this plain, which is located mainly on the east side of the river, has been previously described by Cooper (1935, pp. 18–20, 67–68). When traced northeastward, the plain appears to grade upstream into the ground moraine of the Brainerd drumlin field.

Well data indicate that the thickness of the drift beneath the Green Prairie terrace between Little Falls and Fort Ripley is variable. At Little Falls the drift is 0–50 feet thick. Several exposures of metasedimentary and igneous rocks occur in the city, chiefly along the Mississippi River at and below the dam (Harder and Johnston, 1918). Upham stated that "wells in the town are 15 to 25 or 30 feet deep, all sand and gravel in the west part, but in the east part they go about ten feet into slate rock . . ." (Winchell and Upham, 1888, p. 607). Wells from which the city now obtains part of its water supply encounter bedrock at about 47 feet, but in the southern part of the city bedrock (slate, schist, and other crystalline rocks) is only 12–20 feet deep (Thiel, 1947, pp. 184–85). The overlying deposits consist of outwash sand and gravel.

Driller Van Hercke reports that the well at his home (SW¼SE¼ Sec. 7, T. 129 N., R. 29 W.) just north of the city limits passes through 10 feet of sand underlain by 3 feet of gravel which rests on bedrock. Outcrops of finely crystalline phyllite occur along the Little Elk River about 500–1200 feet above its mouth in Sec. 5, T. 129 N., R. 29 W. (Harder and Johnston, 1918, p. 59). The exposures are largely restricted to the stream valley, however, so that the rock is generally overlain by 5–15 feet of sand beneath the terrace tread. Wells along the Mississippi River road in eastern Green Prairie Township (T. 130 N., R. 29 W.) go 15–25 feet in stratified sand and gravel (Winchell and Upham, 1888, p. 607). Recent drilling by Van Hercke indicates that 40 feet of sand overlie bedrock in this area.

The Ground Water Branch of the U.S. Geological Survey has drilled 10 test holes in the southeastern corner of the Camp Ripley Military Reservation (Secs. 8, 9, and 17, T. 130 N., R. 29 W.). Average depth to bedrock in these 10 holes is 73 feet, but the depths range regularly from 44 to 108 feet (R. Schneider, written communication).

Well records of the Hale-Bradley Exploration Company of Deerwood, dated September 15, 1918, show data obtained from 13 drill holes located on the Green Prairie terrace at Fort Ripley gap (NE¼NE¼ Sec. 7, T. 131 N., R. 29 W.). The drift thickness in 12 of these holes averages 87½ feet, ranging from 78 to 94 feet; the remaining hole ended at 70 feet, apparently without reaching bedrock.

On the east side of the Mississippi River the drift may be thicker. Wells in the vicinity of Fort Ripley (Sec. 34, T. 43 N., R. 32 W.) average about 100 feet in depth and do not enter bedrock (Thiel, 1947, p. 114). Although all the wells may not be on the terrace, one well at the south edge of the village that does appear to be located on the valley train goes down 110 feet without encountering bedrock (Thiel, 1947, fig. 18, p. 105; p. 114).

About 2 miles south of Fort Ripley (Sec. 10, T. 42 N., R. 32 W.) Upham (Winchell and Upham, 1888, p. 607) reports the occurrence of "very hard gray till" (Wadena?) beneath 16 feet of sand and gravel. Shallow wells 8–15 feet deep at the village of Belle Prairie (Sec. 14, T. 41 N., R. 32 W.) are wholly in sand and gravel (Upham, id.). None of the latter reached bedrock.

Available information suggests, therefore, that the thickness of the drift beneath the Green Prairie terrace generally increases upstream from bedrock outcrops at Little Falls northward to the vicinity of Fort Ripley. Virtually no significant data are available concerning drift thickness under the outwash plain north of Fort Ripley gap. At Brainerd, however, bedrock appears to lie at a depth of about 160 feet. Thiel (1947, pp. 107, 111–12) reports four deep wells in the city; three terminate in drift at depths of 107, 120, and 124 feet but the fourth reaches bedrock at 157 feet.

GLACIAL LAKE PLAINS AND DRAINAGEWAYS

General. As indicated by physiographic and sedimentologic evidence, many square miles of the Randall region were formerly occupied by small proglacial lakes and meltwater streams. The areas are expressed as poorly drained lowlands or marshes underlain by swamp deposits, fine-grained lacustrine sediments, sand and gravel, and locally by till. These areas are considered under the following headings: Lake Randall plain, Lake Wadena plain, miscellaneous lake plains, and Swanville spillways.

Lake Randall Plain. Several square miles of the Randall region have been mapped as the site of Glacial Lake Randall, an irregularly shaped proglacial lake marked by promontories and islands of gravelly moraine and sandy outwash surfaces bounded by ice-contact slopes. Most of the area covered by Lake Randall is represented by an undrained morass floored by several feet of peat (Figs. 7 and 21). In the better drained part of the plain near Randall, however, definite lacustrine sediments have been identified at several localities.

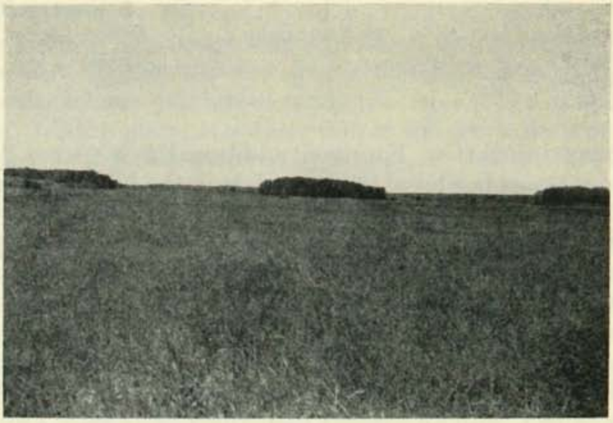

FIGURE 21. — Featureless topography of the Lake Randall plain. View is westward, SE¼ Sec. 12, T. 130 N., R. 31 W., Morrison County.

The bottom of the lake rises from 1175–1180 feet above sea level at and west of Randall to about 1200 feet at its margins north and northeast of Randall, except in the extreme northeastern part where it attains an elevation of 1220 feet. Shoreline features have not been recognized; the lake apparently was not long in existence. Topographic and sedimentologic evidence indicates that the deepest part of the lake was located at Randall, though much of the town itself is built on an island of Precambrian chloritic schist veneered with a variable thickness of brown Pierz till.

Physiographic evidence suggests that the lake sediments were derived principally from the wasting margins of the Brainerd and Pierz ice lobes. Lithologic and stratigraphic evidence indicates, however, that the lake received simultaneous contributions from several sources (see p. 55). Other important evidence relating to the source of the lake sediments occurs at the head of the lake area about 1½ miles west of the Mississippi River. Two deep road cuts (SE¼SE¼ Sec. 12 and NE¼NW¼ Sec. 25, T. 131 N., R. 30 W.) near the top of the escarpment that borders the Green Prairie terrace show excellent exposures of westward-dipping sand with interbedded gravel layers. These are interpreted as delta foreset beds, dropped by meltwater distributaries as they entered the lake from the east.

Data on the thickness of the drift beneath the lake plain are limited to the vicinity of Randall. A well at the Randall creamery (NE cor. NW¼ Sec. 7, T. 130 N., R. 30 W.) struck slate at 70 feet (Allison, 1932, p. 131). The lacustrine sediments in the abandoned Gorman iron-ore pit a mile north of town are reported to reach a thickness of 50 feet and to rest directly on bedrock. Numerous exploration holes have been drilled near the mine and furnish much information on drift thickness in this area. The data for 12 holes in Sec. 31, T. 131 N., R. 30 W. are summarized in the

Location of Holes	*No. of Holes*	*Thickness of Drift (feet)*	
		Range	*Average*
NE¼NE¼SE¼	5	63–89	73
SE¼NE¼SE¼	5	55–62	59
SW¼SE¼SE¼	2	40	40

accompanying tabulation. Fourteen additional holes were drilled very close to the mapped border of the lake plain in the NW¼NE¼NE¼ Sec. 6, T. 130 N., R. 30 W. The thickness of the surface materials in these 14 holes averaged about 42½ feet and had the limited range of 38 to 48 feet.

Well records of the Crosby Exploration Company suggest that the drift may be somewhat thicker west of Randall than it is north of town. A single exploration hole about 75 feet west and 550 feet north of the SE cor. Sec. 1, T. 130 N., R. 31 W. entered bedrock at 78 feet. Five holes at the NW cor. NE¼NE¼ Sec. 12, T. 130 N., R. 31 W. reached schist at depths ranging from 70 to 86 feet, with an average drift cover of 77 feet. Two additional holes in Sec. 12 (E½NW¼NE¼) encountered bedrock at 84 and 103 feet. The latter figure represents the greatest known thickness of drift beneath the Lake Randall plain.

Lake Wadena Plain. Leverett (1932, pp. 43–44) believed that the plain of sandy gravel which he mapped along the Crow Wing and Long Prairie rivers was the site of a large glacial lake, which he named Lake Wadena. A small area of poorly drained land in the northwestern part of the Randall region appears to represent an arm of this lake (Fig. 19).

The area mapped as part of Glacial Lake Wadena covers a few square miles in Fawn Lake Township (T. 132 N., R. 32 W.) along Fish Trap Creek and its intermittent tributaries. It is a level lowland or swamp mainly below 1260 feet, situated physiographically beneath the Fawn Lake outwash surface. Most of the plain is floored with peat. Around the margins of the lake the organic deposits overlie well-sorted sand of the outwash plain. Clastic lake sediments have not been positively identified but local occurrences of silt and clay may be of lacustrine origin.

Miscellaneous Lake Plains. Poorly drained areas of little or no relief along the inner margin of the St. Croix moraine have been locally mapped as lake plains. Some of the flats were thought at first to represent floors of meltwater channels, but failure to identify an integrated drainage pattern favors the conclusion that the areas were occupied by shallow glacial lakes. The lakes probably originated from the melting of large masses of stagnant ice left behind as the glaciers retreated eastward. As the climate ameliorated, the basins were partially filled with vegetation and the waters evaporated or were slowly and incompletely drained through narrow obscure outlets.

The largest of these lake plains is located southwest of Cushing at an elevation of about 1230 feet. Irregular in outline, the plain is enclosed by knobby morainic topography, except on the northeast where it appears to grade into the western end of the Camp Ripley terrace. Several knolls and ridges, commonly composed of sand and gravel, rise above the general level of the plain to an average height of about 20 feet. A limited number of auger borings suggest that the area is underlain largely by sand and peat but locally by clay and brown sandy till.

A second striking plain, less than a mile square, is located 3½ miles west of Randall (E½ Sec. 9 and W½ Sec. 10, T. 130 N., R. 31 W.). It is crossed in its central part by State Aid Road 7. A third impressive plain (Secs. 6 and 7, T. 130 N., R. 31 W.), somewhat larger than the last, is crossed by State Aid Road 8 just east of the Todd-Morrison county line. These two lakes, at one stage, were probably confluent and the water may actually have breached the low divide to the north to join that of the larger lake near Cushing.

Swanville Spillways. An anastomotic network of glacial drainageways is one of the most interesting physiographic features of central Minnesota. The system originates along the inner margin of the St. Croix moraine 5–9 miles west of Randall in the southwestern quarter of the Cushing quadrangle. It is traceable southward through the western part of the Swanville quadrangle at least as far as the Todd-Stearns county line, or to about the outer limit of Keewatin gray drift as mapped by Leverett (1932, pl. 2).

North of the latitude of Swanville the drainageways are well defined and have been studied in some detail, particularly within the Randall region proper. South of Swanville the drainage pattern becomes partially obscure and only a limited amount of field work has been done. For these reasons the two areas are treated separately.

Northern Area: North of Swanville the drainageways occur as broad, flat-bottomed north-south valleys locally occupied by underfit streams (e.g., Spring Branch, Swan River, Pillsbury Creek, Irish Creek) or by ice-block lakes (e.g., Lake Beauty, Wolf Lake, Little Rice Lake, Little Swan Lake). The channels are generally floored with several feet of undrained peat that supports a luxuriant growth of tall marsh grass, only locally encroached upon by forest vegetation along the edges of the channels. Morainic islands, ranging in height from less than 20 feet near the northern end of the drainageways to more than 120 feet farther south, rise abruptly above the spillway floors.

Some of the channels or segments thereof appear to be largely erosional valleys, as indicated by scarped slopes and by till floors covered with boulder lags (Fig. 22). Many of the channels, however, seem to represent intramorainic depressions partially filled with unknown thicknesses of outwash and peat, as suggested by the abrupt change in slope at the apparent bases of the moderately steep ice-contact slopes as they meet the flat peat-filled channel bottoms (Fig. 23), and by the occurrence of isolated islands of sand and gravel fill in the midst of the channels.

Although the general characteristics of the Swanville spillways may be observed along many of the gravel roads in western Morrison and eastern Todd counties, an excellent and easily accessible view is afforded by Minnesota Highway 27 on the Swanville quadrangle between Little Falls and Long Prairie. Four north-south drainageways are crossed in a distance of 5½ miles, 5–11 miles east of Long Prairie, namely the Irish Creek drainageway (the easternmost), the Swan River drainageway, and two branches of the Lake Beauty-Grey Eagle drainageway. The valleys are ½–1½ miles broad in this area. They are on the average about 80 feet deep but the floor

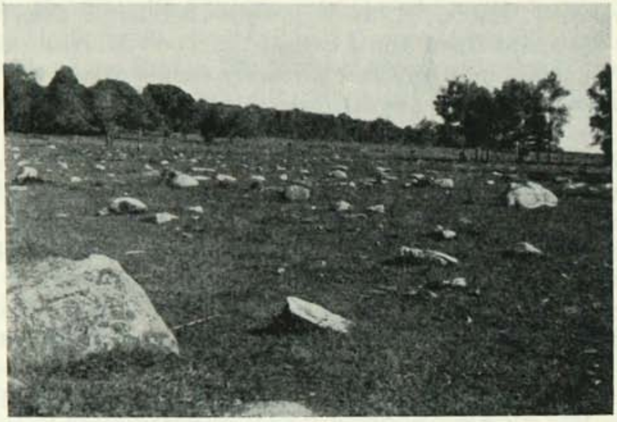

FIGURE 22. — Lag boulders on drainageway floor. Boulders range in size from 1 to 9 feet; average diameter is 2–3 feet. Drainageway is underlain by till, which is locally capped by 2–2½ feet of sand. View is southward. NE¼ Sec. 23, T. 130 N., R. 32 W., Todd County.

FIGURE 23. — Peat-floored drainageway. Near head of western branch of Lake Beauty-Grey Eagle drainageway. Note abrupt change in slope where peat fill meets 50-foot till knob. View is southeastward. NW¼ Sec. 3, T. 129 N., R. 32 W., Todd County.

of the westernmost spillway locally lies more than 240 feet below the crest of the St. Croix moraine. In general, the channel floors decrease in elevation from west to east. Where the spillways are crossed by Highway 27, for example, the bottom elevations are about 1215, 1200, 1180, and 1175 feet above sea level, respectively.

Within the Randall region proper two divisions of the Swanville spillway system may be recognized: (1) a western group of channels originating within the St. Croix moraine and (2) a single eastern drainageway that heads in the western part of the Culdrum-Parker till plain. South of the Cushing quadrangle, however, the spillways are so closely associated that this distinction is not apparent.

The western division consists of several intramorainic channels that branch and reunite to form an anastomotic pattern resembling that of a braided stream. Elongated islands of till and/or sand and gravel rise above the featureless spillway floors to a maximum height of more than 90 feet. When traced upstream (north), the channels are found to originate in subcircular to irregularly shaped ice-block pits. Similar in physiographic expression to the miscellaneous lake plains described above, the depressions are typically flat bottomed and peaty. (Good examples on the Cushing quadrangle occur in the NW¼ Sec. 19, T. 130 N., R. 31 W.; SE¼ Sec. 1, Sec. 10, and SE¼ Sec. 12, all T. 130 N., R. 32 W.; SW¼ Sec. 3 and SE¼ Sec. 4, T. 129 N., R. 32 W.)

The eastern or Irish Creek drainageway heads about 6 miles southwest of Randall at the western end of the Lake Randall plain. No apparent physiographic difference between drainageway and lake plain exists in this area, so the head of the spillway probably extended farther east along the valley of the underfit Little Elk River after the lake was partially drained. However, the occurrence of clay deposits in Sec. 20, T. 130 N., R. 31 W. suggests that ponded waters of Lake Randall, rather than a meltwater stream, initially occupied the lowland. The lake waters entered the Irish Creek channel via the narrow gap now used by Ted Brook Creek in the NE¼ Sec. 30, T. 130 N., R. 31 W. A second outlet, apparently utilized only during an ephemeral high-water stage, trends southwestward through the S½ Sec. 20 and the NW¼ Sec. 29, T. 130 N., R. 31 W.

Although the spillway floors are apparently flat, definite southward gradients can be detected. The best defined gradient is that of the Swan River drainageway whose eastern branch originates in ice-block pits at 1230–1240 feet above sea level. The channel descends southward from about 1220 feet in Sec. 24, T. 130 N., R. 32 W. to 1175–1180 feet west of Swanville. Near its head the spillway floor has a slope of about 10 feet per mile, but the gradient decreases rapidly downstream so that the over-all slope is less than 5 feet per mile.

The gradient of the Irish Creek drainageway is considerably lower. In the southern part of the Randall region the channel bottom lies at an elevation of 1180–1200 feet, or 15–20 feet below that of the Swan River spillway at the same latitude. West of Swanville, however, the two drainageways grade together, so that the floor of the Irish Creek channel drops only 20 feet in a distance of 10 miles.

Southern Area: South of the latitude of Swanville on the Swanville quadrangle the drainage pattern deteriorates. The southward gradients are difficult to follow or are reversed, and the spillways generally become constricted in width and/or disintegrate into strings of elongated ice-block lakes, most of which appear to be blind at either end. The number of apparent channels increases, however.

Constriction of the Swan River and Irish Creek drainageways is especially striking. One mile west of Swanville the two spillways unite and thence continue southward as a single valley, which is now occupied by underfit north-flowing Molly Creek. The valley bottom narrows from a width of 1.7 miles where the two drainageways become confluent to less than 100 feet at the north end of Molly Lake. South of Molly Lake the channel widens to a few hundred feet but has a steep northward gradient of about 50 feet per mile. South of the drainage divide at a point about 2 miles south-southeast of the lake the valley is joined by a channel from the northeast (occupied by Pine and Long lakes) and thence continues southwestward in the linear lowland occupied by Cedar Lake and Two Rivers River. A branch of this channel extends southwestward via Mary Lake and thence westward to enter the Grey Eagle valley at the southeast end of Big Birch Lake. Another branch, marked by Schreiers and Lovell lakes, diverges southward from the eastern side of the channel and appears to continue southward beyond the southern boundary of the Swanville quadrangle.

Two additional lake-and-valley chains originate west of Pillsbury in Little Swan Lake. Both appear to be southward continuations or branches of well-defined northern-area channels. The eastern chain is represented by Little Swan Lake, Moose Lake Creek, Moose Lake, Buck Lake, and Mound Lake. The western channel is occupied by Little Swan Lake, Mons Lake, Bass Lake, Long Lake, Mountain Lake, and Twin Lakes, where it joins the Grey Eagle drainageway.

The only apparent through channel in the southern area is the Grey Eagle drainageway, located along the western edge of the Swanville quadrangle, but even this is marked by ice-block depressions: Big Swan Lake, Lady Lake, Twin Lakes, Trace Lake, Bass Lake, and Big Birch Lake. This spillway occupies a prominent linear depression in the St. Croix moraine, mapped by Leverett (1932, pl. 2) as red-drift ground moraine. Limited reconnaissance studies suggest, however, that much of the valley may be underlain by outwash, and the plain is clearly continuous with the westernmost channels of the northern area near Lake Beauty. The total length of the system from its origin 7 miles west of Randall to the southern end of Big Birch Lake is about 27 miles.

POSTGLACIAL VALLEY FEATURES

General. Postglacial erosion and deposition have not significantly modified the glacial topography of the Randall region. Only a few valley features can be attributed to stream activity during the short time interval that has elapsed since the late Wisconsin. Three items are given brief consideration: postglacial erosion features, Elk River terrace, and Mississippi River alluvium.

Postglacial Erosion Features. Valley development has barely begun throughout most of the Randall region and has nowhere progressed beyond the youthful stage of the erosion cycle. The postglacial Mississippi River has downcut its valley to approximately 25 feet below the general level of the Green Prairie terrace, and the lower Elk River (downstream from Randall) has incised itself about 12 feet below the upland surface.

Most of the drainage lines are intermittent and even the few permanent streams, except the Mississippi and lower Elk rivers, are still in the infant stage. These streams (Fish Trap Creek, upper Elk River, Little Elk River, Swan River, Irish Creek) have no true valleys of their own but occupy instead the floors of meltwater channels and glacial lakes, which they have scarcely started to dissect and which serve as floodplains during periods of heavy surface runoff.

Locally, however, the streams occupy short gullies or ravines, the larger of which are up to 25 feet deep. Most of these valleys occur close to the inner margin of the St. Croix moraine near the headwaters of the Elk and Little Elk rivers, breaching local divides between lake-plain segments or drainageway heads (e.g., SE¼ Sec. 19, NW¼ Sec. 29, SW¼ Sec. 28, T. 131 N., R. 31 W.; NE¼ Sec. 12, T. 130 N., R. 32 W. and NW¼ Sec. 7, T. 130 N., R. 31 W.). The problem of determining whether these ravines were cut by glacial meltwaters or by postglacial streams has not been fully resolved but the latter interpretation is favored for most of the gullies. Ordinarily, the valleys are narrower than those definitely known to have been occupied by glacial waters, and there is some evidence to suggest that swamp deposits may be thinner than in the glacial valleys or absent. It seems probable that the ravines were formed as the postglacial Elk and Little Elk rivers extended themselves headward from one flat-floored basin to the next and in doing so downcut through local divides. The valleys seem to represent, therefore, an early stage in the formation of an integrated drainage system.

Elk River Terrace. A low alluvial terrace borders the lower Elk River below the confluence of the Elk and Little Elk rivers at Randall. The terrace has been studied at several localities where the stream is crossed by county roads. It has been only partly traced between these points, however, and mapping of the terrace was accomplished in part by inspection of aerial photos. The terrace could not be definitely identified, either in the field or on the photos, for about a mile above the mouth of the stream.

The Elk River terrace is 4–6 feet above normal midsummer stream level, or 7–8 feet below the upland surface (East Darling plain and Green Prairie terrace). Terrace deposits consist of well-sorted fine- to medium-grained light-brown sand interbedded with dark bluish-gray mucky sand to sandy muck containing wood fragments. Individual beds average about 1½ inches in thickness although some sand layers are thicker. The physiographic relations of the Elk River terrace 2 miles north of Little Falls (NW¼NE¼ Sec. 6, T. 129 N., R. 29 W.) and 2½ miles east of Randall (SW¼ Sec. 10, T. 130 N., R. 30 W.) are shown in Figures 13 and 17.

As indicated by the lithology and by artificial lateral cuts, the terrace deposits are dated as younger than the drift exposed along the valley slopes. The absence of lag gravel suggests that the tread is a depositional rather than an erosional surface. The abundance of organic matter in the alluvium and the failure to correlate the fill with any sediments of known glacial origin lead to the conclusion that the fill is postglacial. Failure to trace the terrace to the mouth of the Elk River where the Elk enters the Mississippi River (SW¼ Sec. 5, T. 129 N., R. 29 W.) makes it difficult to correlate the episode of filling with the postglacial history of the master stream.

Mississippi River Alluvium. Many small tracts of alluvium have been mapped along the Mississippi River downstream from the Fort Ripley gap. These areas have been plotted largely from aerial photos and the deposits have not been studied in the field. Most of the tracts are associated with the braided pattern of the modern river and represent an incipient floodplain. A few, however, may be low terrace levels of recent age; if so, their significance is unknown.

8. PLEISTOCENE HISTORY OF THE RANDALL REGION AND ADJACENT AREAS

PRE-CARY

Positive evidence bearing on the pre-Cary Pleistocene history of central Minnesota is meager. Although glacial deposits older than Cary (excluding Leverett's incorrect assignment of the Wadena drift to the Iowan) have been reported from the northern two-thirds of the state, these deposits have not been studied in detail and their pre-Wisconsin age must be considered tentative. Drifts assigned to the Nebraskan, Kansan, and Illinoian stages and to the Iowan and Tazewell substages of the Wisconsin stage have been mapped, however, in southeastern and southwestern Minnesota (Leverett, 1932; Flint *et al.*, 1945; Ruhe, 1952b; Ruhe and Gould, 1954).

It seems unlikely that central Minnesota could have escaped glaciation until the Cary subage, inasmuch as pre-Cary deposits are known from southern Minnesota and inasmuch as the sequence of glaciation in eastern and central Minnesota during Cary and post-Cary time was extremely complicated. On the other hand, the occurrence of brown Pierz till resting directly on bedrock at Randall and especially the several contacts of Wadena and Pierz drifts overlying weathered Precambrian phyllite at the Elk River locality suggest that pre-Cary drift may be absent in central Minnesota. It seems improbable that an ice sheet (of pre-Wadena age) would eradicate older drifts without also removing the soft weathered phyllite, or without leaving some deposit of its own. Descriptions of well cuttings from test holes drilled by the U.S. Geological Survey in the Camp Ripley Military Reservation suggest that here also the oldest material above bedrock is Wadena drift.

It is possible, of course, that weathering of the phyllite took place during an interglacial age (rather than during the Tertiary), after erosion of older drift and before deposition of the Cary deposits (e.g., deposition of Nebraskan and/or Kansan drifts atop fresh phyllite, removal of these drifts by an Illinoian ice lobe, weathering of the phyllite during the Sangamon, and deposition of Wadena and Pierz drifts during the Wisconsin). This explanation would account for the occurrence of Cary drifts above weathered phyllite as well as or better than one involving a period of weathering followed by incomplete erosion of the weathered product by a Nebraskan, Kansan, Illinoian, or pre-Cary Wisconsin ice sheet.

It is also possible that the gray drift at the Elk River locality is not Cary (i.e., not Wadena) but is instead pre-Cary in age, and belongs to the "old gray drift" of the Kansan stage recognized by Allison (1932, pp. 6,

130) in the subsurface of western Morrison County. If the drift is of pre-Wisconsin age, it probably should be leached, but the matrix is highly calcareous and the drift contains abundant limestone pebbles. It seems more likely that the Kansan drift of Allison is actually the Wadena drift of Cary age.

In brief, there is no direct evidence of the pre-Cary Pleistocene history of the Randall region and adjacent areas.

CARY

General. During the Cary subage of the Wisconsin, central Minnesota was invaded by the Wadena, Superior, Pierz, and Brainerd ice lobes. The order of advance of these lobes is disclosed by general stratigraphic superposition of drifts and by geomorphic relations. Interbedding and reverse superposition of the drifts indicate, however, that the lobes were in part concurrent and locally occurred in juxtaposition. Directions of movement of the Cary ice lobes into and across central Minnesota are indicated by lithologic characteristics of the drifts, by morphologic features of end moraines, and especially by drumlin fields and eskers.

The Cary history of the Randall region and adjacent areas involves not only the complex movements of these four ice lobes, but also the formation of glacial lakes and meltwater streams accompanying the retreat of the ice and leading to the establishment of the present course of the Mississippi River in this area during the late Cary and the Cary-Mankato interstadial.

Wadena-Lobe Advance. Because of its high limestone content, the Wadena lobe is presumed to have crossed the Paleozoic carbonate terrane of southern Manitoba and adjacent northwestern Minnesota. It entered central Minnesota from the northeast, however, heading about S. 50° W., and then spread radially to the west, southwest, south, and southeast to form the Wadena drumlin field.

The terminal position of the Wadena lobe has not been firmly established. Wright (1954) suggests that the western and southern terminus of the lobe may be represented by the Altamont-Gary moraine, because much of the drift of both the Bemis and Altamont-Gary moraines is lithologically indistinguishable from that of the Wadena drumlin field. If this is correct, the Bemis moraine may mark a recessional stage of the Wadena lobe.

As indicated by the orientation of drumlins adjacent to the lower Long Prairie River, the Wadena ice lobe entered the Randall region from the northwest, flowing about S. 35°–40° E. Its terminus east of the St. Croix moraine has not been determined because here the Wadena drift is nearly everywhere buried by younger deposits. Near the southeastern border of the drumlin field the calcareous drift passes beneath the western edge of the St. Croix moraine. It has been traced eastward through the moraine and beneath the brown sandy till of the Pierz ground moraine to the

Mississippi River (Elk River locality). In its eastward advance the ice may have produced the older set of striae (S. 86° E.) at Randall mentioned and plotted by Leverett (1932, pp. 44–45; pl. 2), although the scratches could have been engraved by a later readvance of the Wadena lobe into this area.

East of the Mississippi River the distribution of Wadena drift is not well known. An exposure about 18 miles east of the river (1 mile northeast of Center Valley) was described above. Wadena drift has been identified by Wright (1956, p. 10) to the north in the Mille Lacs moraine west of Mille Lacs Lake and also to the southeast at Milaca.

Superior-Lobe Advance. By the time the Wadena lobe had reached its terminal position, the Superior lobe was flowing southwestward across eastern Minnesota from its source in the Lake Superior basin. As the eastern edge of the Wadena lobe receded northwestward, the deglaciated area was partly re-covered by the expanding Superior lobe. It seems probable that the margins of the two lobes locally occurred in juxtaposition and produced the interbedding of gray and red drifts described earlier in this paper.

The limit of the Superior lobe in central Minnesota is difficult to trace because the red sandy till in this area is thin, irregularly distributed, and is everywhere buried by younger drift. At its maximum stage the ice appears to have reached the St. Croix moraine in the southern part of the Randall region, as suggested by the two exposures of red till in this area and by the local occurrence of red lacustrine clay beneath the Lake Randall plain.

Wadena-Lobe Readvance. Investigations by Wright in east-central Minnesota have disclosed that the general stratigraphic arrangement of the Superior and Wadena drifts east of the Mississippi River is red over gray. This has led to the conclusion that the Wadena lobe reached central Minnesota before the Superior lobe. West of the river, however, the superposition of these two drifts is reversed, as shown by the fine contacts of gray over red on the eastern slope of the Irish Creek drainageway. This anomalous relationship is explained if the Wadena and Superior ice lobes are considered contemporaneous; it suggests that the Wadena lobe readvanced during or shortly after withdrawal of the Superior lobe from the area west of the Mississippi River.

Additional evidence favoring readvance of the Wadena lobe is the superposition of Wadena and Pierz drifts in the Randall region. If the succession of ice lobes were simply Wadena, Superior, and Pierz, then brown sandy till of the Pierz lobe should be found in contact with red sandy till. The fact that it commonly overlies yellowish-brown Wadena till, rather than Superior drift, indicates that the Wadena lobe was the immediate precursor of the Pierz lobe in the Randall region.

The limit of the Wadena-lobe readvance has not been determined. The ice probably did not extend far beyond (east of) the Mississippi River, however, because Wright has found that east of the river, particularly in the Pierz drumlin field, the brown Pierz till rests directly on red Superior drift.

Pierz-Lobe Advance. As the Wadena lobe was readvancing west of the Mississippi River and the northwestern margin of the Superior lobe was retreating east of the river, probably to the southeast, the Pierz lobe entered central Minnesota from the east. In its westward advance across eastern Morrison and Benton counties the ice spread radially to the northwest and southwest, depositing brown sandy till and shaping the Pierz drumlin field. The advance of the Pierz lobe was apparently interrupted, however, by a temporary withdrawal and by a simultaneous readvance of the Superior lobe, as evidenced by interbedding of red and brown tills 3 miles southwest of Center Valley and at other localities in the drumlin field.

The northern part of the Pierz lobe crossed the present course of the Mississippi River, formed the low drumlins and the Darling esker in the southern part of the Randall region, and striated the bedrock at Randall. Its direction of flow in this area was N. 50°–55° W.

By this time the Wadena lobe was again in retreat, and as the Pierz lobe continued its northwestward penetration it encountered the edge of the receding Wadena lobe. To-and-fro fluctuations along the margins of both lobes resulted in alternate deposition of gray and brown drifts, as attested by the interbedded relationships near Lincoln and Philbrook. The lobes may have remained in actual juxtaposition, or at least near to each other, for some time before full retreat of the Wadena lobe from this area. A final stand appears to have been made by the Wadena lobe along the Fawn Lake moraine and its probable equivalent in the southwestern part of the Randall region; the latter was soon overridden, though not completely destroyed, by the more active ice from the southeast.

The terminal position of the Pierz lobe is represented generally by an arcuate segment of the St. Croix moraine between Pillager gap on the north and Cold Spring gap (?) on the south. The occurrence of extramorainic brown till indicates, however, that the ice front actually extended a little beyond the St. Croix moraine, as concluded initially by Leverett (1932, p. 40). In fact, a tongue of Pierz ice which overrode the northern end of the Fawn Lake moraine (north of Fawn Lake) may even have reached the vicinity of Wadena, as suggested by the distribution of extramorainic brown till in Fawn Lake Township and by its occurrence at Leaf River.

Development of Lake Wadena and the Long Prairie Drainageway. When the Pierz ice retreated to its morainic stand (Fig. 24, stage A), meltwaters spread their sandy load atop the gray and brown tills to build the Fawn Lake outwash plain in the northwestern part of the Randall region. Leverett (1932, pp. 43–44) believed that the extensive outwash plain along the Long Prairie and Crow Wing rivers was deposited at this time in Glacial Lake Wadena, a proglacial lake along the western edge of his

Patrician ice sheet. The lake drained southward, according to Leverett, around the edge of the moraine through a pass south of Long Prairie at about 1350 feet, but its outlet is now concealed by younger (Mankato) Keewatin drift. The present writer is not prepared to confirm or reject the existence of Lake Wadena on the basis of his own investigations; there is little doubt, however, that meltwaters at this stage drained southward via the Long Prairie valley train and that the course of the lower Long Prairie River was later reversed. These facts are clearly indicated by barbed tributaries (upper Long Prairie River, Eagle Creek, Moran Brook) of the modern Long Prairie River and by the distribution of outwash deposits between Long Prairie and Little Sauk.

It appears certain, therefore, that when the Pierz lobe attained its morainic stand, an ice-marginal river followed the outer margin of the moraine at least as far south as Little Sauk. The stream was fed from the east by Pierz-lobe meltwaters and from the northwest by waters derived from the wasting Wadena lobe. Rate of meltwater supply may have exceeded the rate at which the pass south of Long Prairie was lowered, thereby causing the waters to pond and give birth to Leverett's Lake Wadena. South of Little Sauk the discharge probably entered the Sauk Valley lowland via the Sauk Lake channel, followed the Sauk River outwash train southeastward, passed through the moraine or around the edge of the ice at Cold Spring gap, and joined the present course of the Mississippi River near St. Cloud.

Formation of the Swanville Spillways. As the Pierz lobe withdrew southeastward, the meltwaters found additional routes of southward escape around the western edge of the receding ice (Fig. 24, stage B; Fig. 25, stage C). North of Swanville the discharge rushed southward along the inner side of the St. Croix moraine over and around masses of stagnant ice, dropped some of its load in vacated ice-block basins, and locally cut away parts of the moraine to produce a striking anastomotic network of channels and elongated morainic islands. The progressive eastward drop in elevation of the flat channel floors, not everywhere recognizable, suggests that the Swanville spillways may have been successively formed from west to east as the margin of the ice retreated eastward. The western drainageways were not abandoned, however, as the more eastern channels came into existence; the braided pattern and the smoothly graded floors indicate that the valleys were simultaneously occupied as the discharge increased.

The cause for the apparent deterioration of the drainage pattern south of Swanville is not yet clear. Either of two reasons might explain this situation: (1) the discharge may have encountered an abundance of stagnant ice masses, over and around which it found its way southward, or (2) the area may have been covered by the Mankato Des Moines lobe which served to block and conceal segments of the late Cary drainageways. Further investigation in this area is necessary before more definite conclusions are drawn.

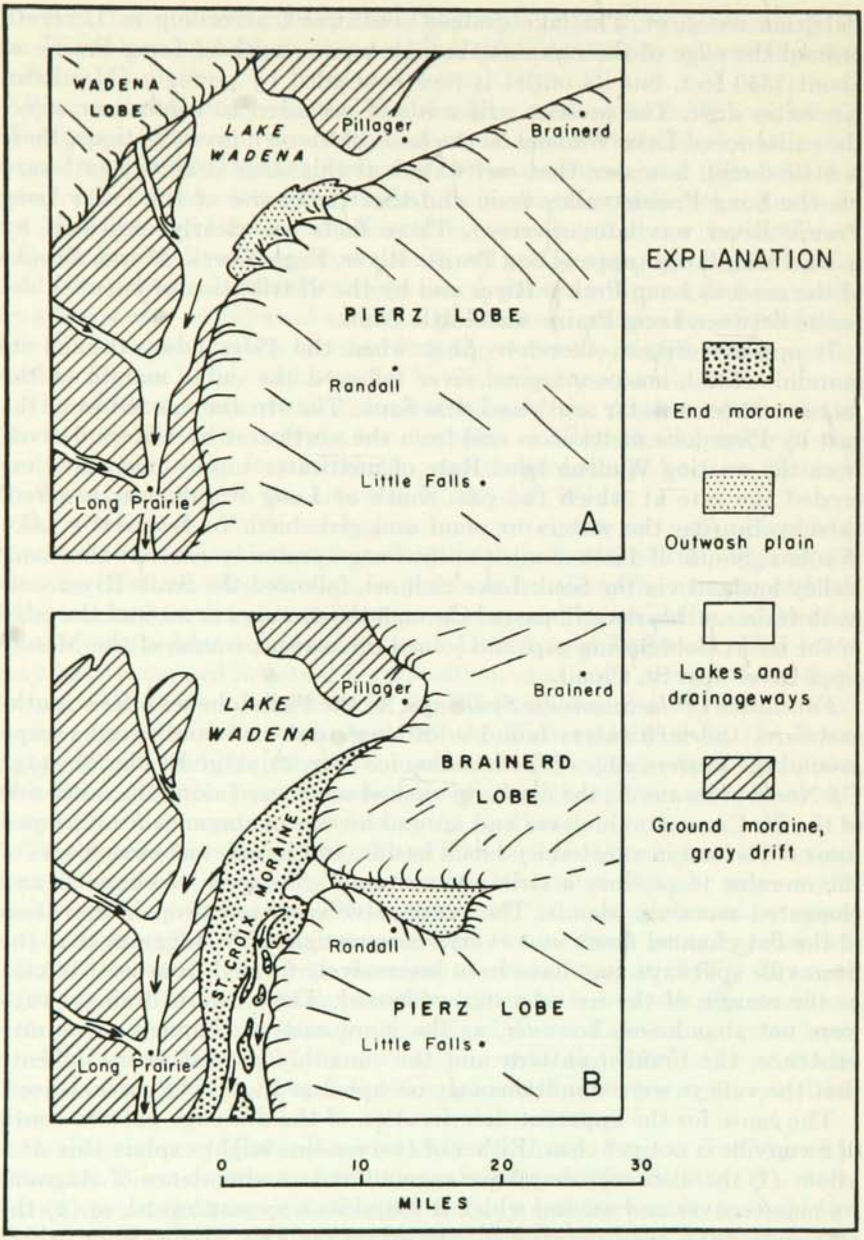

Figure 24. — Stages A and B of glacial history. See Figure 2 for area covered by diagrams. (Based partly on Leverett, 1932, Plate 2.)

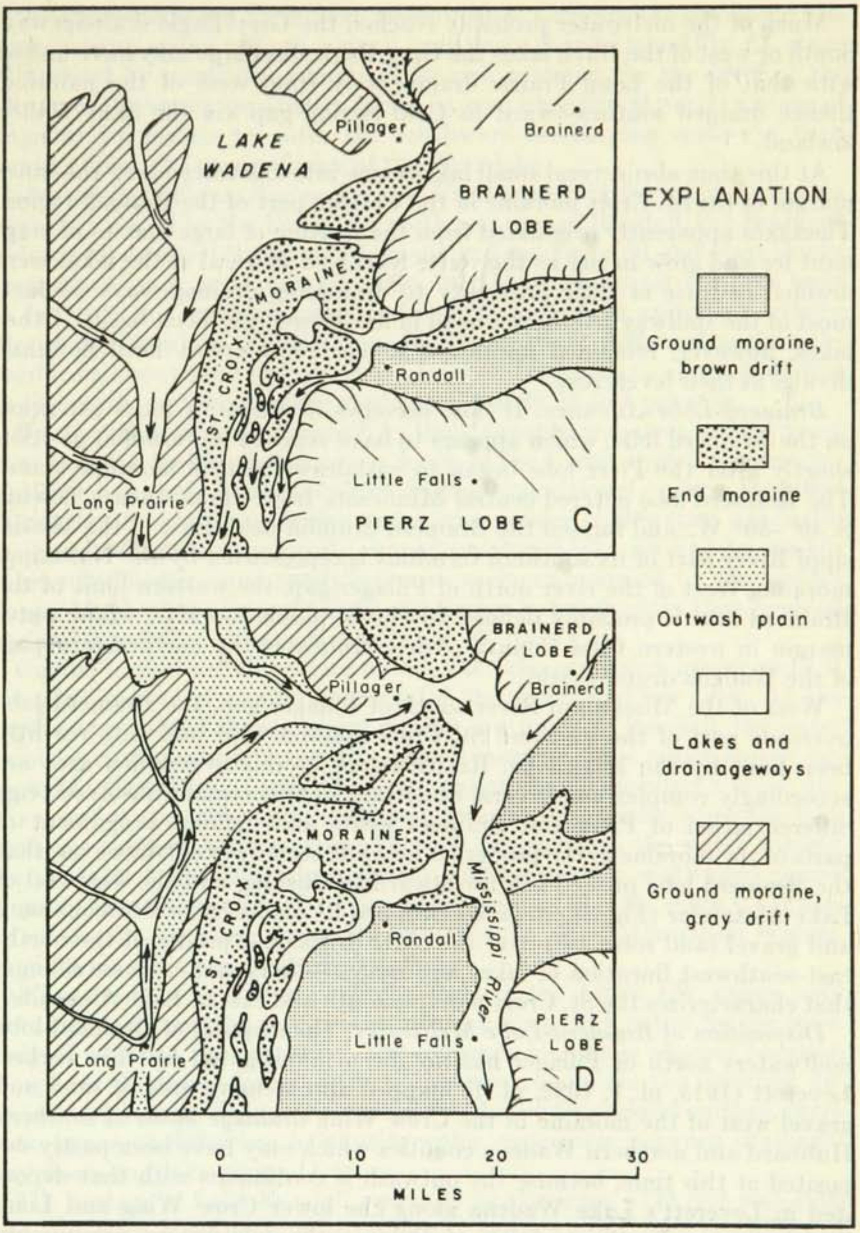

FIGURE 25. — Stages C and D of glacial history. See Figure 2 for area covered by diagrams. (Based partly on Leverett, 1932, Plate 2.)

Much of the meltwater probably reached the Grey Eagle drainageway. South or west of the Birch lakes the Grey Eagle discharge may have united with that of the Long Prairie drainageway from west of the moraine, thence drained southeastward to Cold Spring gap via the Sauk Valley lowland.

At this time also several small lakes came into existence along the inner margin of the St. Croix moraine in the western part of the Randall region. The lakes apparently originated from the melting of large masses of stagnant ice and grew in size as the water level rose. Several of the lakes were drained because of their proximity to expanding drainageways; in fact, most of the spillway tributaries head in flat-floored ice-block basins. Other lakes, however, remained undrained or coalesced across local morainic divides as their levels rose.

Brainerd-Lobe Advance. It now becomes desirable to focus attention on the Brainerd lobe, which appears to have reached its terminal position shortly after the Pierz lobe began to withdraw from its morainic stand. The Brainerd lobe entered central Minnesota from the northeast, flowing S. 40°–50° W., and formed the Brainerd drumlin field. East of the Mississippi River part of its southern terminus is represented by the Nakasippi moraine. West of the river north of Pillager gap, the western limit of the Brainerd lobe is probably defined by the St. Croix moraine, whose outer margin in western Cass County clearly truncates the northeastern part of the Wadena drumlin field.

West of the Mississippi River south of Pillager gap, the Brainerd lobe overrode part of the ice-cored St. Croix moraine that had only recently been built by the Pierz lobe. Relationships in this overridden area are accordingly complex and several important details remain unsolved (e.g., differentiation of Pierz and Brainerd drifts and definite assignment of parts of the moraine to the proper ice lobe). It seems certain, however, that the Brainerd lobe pushed southwestward to Cushing and the west end of Lake Alexander (Fig. 24, stage B), dropped its load of noncalcareous sand and gravel (and some till) over the older drifts, and produced the northeast-southwest lineation of lakes and ridges (eskers and crevasse fillings) that characterizes the St. Croix moraine south and east of Lake Alexander.

Disposition of Brainerd-Lobe Meltwater. The disposal of Brainerd-lobe meltwaters north of Pillager has not been investigated by this worker. Leverett (1915, pl. 1; 1932, pl. 1) mapped an extensive area of sand and gravel west of the moraine in the Crow Wing drainage basin of southern Hubbard and northern Wadena counties which may have been partly deposited at this time, because the outwash is continuous with that deposited in Leverett's Lake Wadena along the lower Crow Wing and Long Prairie rivers. In the vicinity of Pillager the meltwaters presumably drained westward directly into Lake Wadena.

South of Pillager, at the snout of the Brainerd lobe, the meltwaters were blocked on the west by the moraine and on the south by the northern edge of the slowly receding Pierz lobe. Southwest of Cushing the discharge was temporarily ponded to form a small irregularly shaped lake (Fig. 24, stage B) marked by numerous islands of ice-rich moraine. As the level of the lake rose, the water apparently found its way over and through a maze of stagnant ice masses to enter the southward-discharging spillways then forming along the western edge of the Pierz lobe.

Deposition of Camp Ripley Terrace. Farther east, in the interlobate area recently vacated by the Pierz lobe north and east of Randall, the Brainerd meltwaters dropped their load of gravel and sand around and atop blocks of stagnant ice. A large outwash plain, the Camp Ripley terrace, was built up between the southern margin of the Brainerd lobe and the northern edge of the Pierz lobe (Fig. 24, stage B). The outwash surface sloped southward from about 1280 feet above sea level on the north to about 1200 feet on the south, with an average gradient of nearly 25 feet per mile.

Development of Lake Randall. As the stagnant ice masses melted away from beneath their outwash cover, much of the Camp Ripley terrace collapsed, leaving only remnants of the original depositional surface. Dammed on nearly all sides by moraine or ice, the ponded meltwaters gradually coalesced to form an irregularly shaped proglacial lake marked by islands of gravelly moraine and sandy outwash surfaces bounded by ice-contact slopes. Much of the area of the Camp Ripley outwash plain thus evolved into the site of Glacial Lake Randall (Fig. 25, stage C).

Unable to find an immediate outlet, the lake expanded in size until it extended westward around the nose of the receding Pierz lobe. At the northwestern tip of the ice, about 6 miles southwest of Randall, the water found or cut an escape across the ground moraine. This outlet is now occupied by Ted Brook Creek. A second outlet channel located a short distance east of the other apparently was utilized only briefly when the lake level was highest. After escaping through the pass(es), the water entered the youthful Irish Creek drainageway and followed a southward course around the western edge of the ice to Swanville (Fig. 25, stage C). From Swanville the discharge found its way into the Sauk-Mississippi system, possibly via the Grey Eagle drainageway.

After the lake had been partially drained, the Little Elk valley may have evolved from lake area proper into a drainageway outlet for the main body of water to the northeast. The evidence for this is obscure because, except for the linear forms of the drainageways and for the common depression of channel floors some tens of feet below the upland surface, there is no apparent difference in physiographic expression between drainageway floors and lake plains.

The bottom of Lake Randall generally lies between 1175 feet and 1200 feet above sea level, or physiographically below uncollapsed remnants of the Camp Ripley terrace. The difference in elevation between the lake plain and residual outwash surfaces ranges locally up to 75 feet, specifically in the vicinity of Round and Three Finger lakes. This suggests that part of the stagnant ice which was buried by Brainerd-lobe outwash in this area was at least 75 feet thick.

As indicated earlier, the lake appears to have been deepest in the vicinity of Randall, where at least 50 feet of fine-grained lake sediments were deposited. Although Lake Randall was supplied by meltwaters derived principally from Pierz and Brainerd ice, the occurrence of lacustrine red clay and calcareous yellowish-brown silt near Randall indicates that stagnant masses of Superior and Wadena ice still persisted in the area.

Brainerd-Lobe Recession. By this time the nose of the Brainerd lobe had withdrawn slightly from its terminus near Cushing to a position just west of the present Mississippi River. On the south the meltwaters discharged into expanding Lake Randall, dropped their load of sand delta-fashion, and built up the floor of the lake on the northeast to an elevation of about 1220 feet above sea level. The westward-dipping foreset beds exposed in the eastern part of Camp Ripley were deposited at this time.

North of the Lake Randall area the Brainerd-lobe outwash derived from the western edge of the ice found a course through the moraine north of Lake Alexander and Fish Trap Lake. The meltwaters streamed westward (Fig. 25, stage C), deposited the Scandia Valley outwash plain, and entered growing Lake Wadena, a finger of which now extended into the northwestern corner of the Randall region.

Pierz-Lobe Recession. As the Pierz lobe withdrew from the southeastern part of the Randall region, meltwaters from stagnant ice masses and from the western edge of the shrinking ice lobe, possibly augmented by overflow from Lake Randall, flooded the East Darling plain. Overloaded streams seem to have migrated almost freely across the area, distributing an irregular blanket of sand and gravel over the ground moraine and atop stagnant ice blocks. The ice-free swales were filled first, followed by sediment-burial of much of the till plain to an average depth of about 4–5 feet. The stronger positive features of the ground moraine, such as the Darling esker, conical hills of sand and gravel associated with the esker, and some probable drumlins (e.g., S½ Sec. 30, T. 130 N., R. 30 W.), were not submerged but projected as islands above the shallow floodwaters.

Dissection of the southern margin of the main Camp Ripley terrace remnant probably took place at this time also, by headward erosion of streams flowing from the terrace over stagnant ice onto the East Darling plain, where the streams dropped their load and locally produced a braided pattern (e.g., W½ Sec. 14, T. 130 N., R. 30 W.). This episode of erosion and deposition was soon followed by the birth of the Mississippi River at the close of the Cary subage, as the meltwaters found a through course around the western edge of the shrinking Pierz lobe.

CARY-MANKATO INTERSTADIAL

General. The history of the Randall region and adjacent areas during the Cary-Mankato interstadial is mainly one of accelerated deglaciation, highlighted by the establishment of the present course of the Mississippi River between Brainerd and St. Cloud. This segment of the river obviously could not have come into existence before the Pierz and Brainerd lobes had retreated beyond the eastern border of the Randall region proper.

The establishment of the river's course between Brainerd and St. Cloud was worked out by Cooper (1935, pp. 9–11). The following discussion is an elaboration of his interpretation, supplemented by greater detail and modified to the extent that it involves two eastward-retreating ice lobes rather than the single large Minneapolis lobe recognized by Cooper.

Draining of Lake Wadena. Withdrawal of the Brainerd lobe to the northeast opened Pillager gap to a flood of waters from west of the St. Croix moraine (Fig. 25, stage D), because it provided an outlet for Lake Wadena at an elevation lower than that of the pass south of Long Prairie. The direction of flow in the Long Prairie valley was thus reversed (from south to north), so that the western tributaries of the lower Long Prairie River now join the river at obtuse angles.

East of Pillager gap the discharge from Lake Wadena joined that derived from the receding Brainerd lobe, found a southward course east of the moraine, cut the prominent escarpment on the west side of the Mississippi River, and united with other southward-flowing waters skirting the western edge of the shrinking Pierz lobe (Fig. 25, stage D). North of Fort Ripley the meltwater may have been temporarily ponded, however, while cutting the Fort Ripley gap that separates the Nakasippi moraine from the main part of the St. Croix system west of the Mississippi River.

Draining of Lake Randall. At about this time the drainage around Randall was also being reversed, notably in the Little Elk valley. Glacial Lake Randall now drained eastward into the Mississippi River, rather than westward and southward via the Little Elk-Irish Creek drainageway system. The head of the lake appears to have drained directly into the master stream, as suggested by topographic evidence in the east-central part of Clough Township (Secs. 13, 14, 23, and 24, T. 131 N., R. 30 W.). Farther south the evidence is obscure but the outlet of the lake probably followed the present course of the Elk River east from Randall to the northwestern corner of the East Darling plain, where part of the moraine appears to have been cut away.

The small irregularly shaped lake southwest of Cushing appears to have been partially drained at this time also, via a narrow outlet into the northwestern tip of Lake Randall. This is suggested by a discontinuous low terrace along the upper Elk River in southwestern Cushing Township (Secs. 34 and 35, T. 131 N., R. 31 W.).

Abandonment of Swanville Spillways. The Swanville spillways in the western part of the Randall region and farther south in the Swanville quadrangle were gradually abandoned as meltwater drainageways, chiefly because of decreasing supply from stagnant ice. By the beginning of Mankato time some of the spillways may have been entirely abandoned, whereas in other valleys the streams slowly diminished in size to their present underfit condition (upper Swan River, Irish Creek, etc.). Masses of stagnant ice, previously submerged beneath the southward-flowing meltwaters, melted away from under their probable sand and gravel cover to leave undrained pits, the deepest of which are now occupied by ice-block lakes (Lake Beauty, Little Swan Lake, Long Lake, Big Swan Lake, Big Birch Lake, etc.). Deposition of peat in the channel bottoms may have begun during the Cary-Mankato interstadial, though most of the organic sediments are probably postglacial.

Although the field relations have not yet been studied, it appears likely that the course of the lower Swan River (east of Swanville) became established at this time. The headwaters of the lower Swan River captured the drainage of Irish Creek and the upper Swan River, resulting in a reversal of flow in some of the spillways near Swanville so that the drainage followed the lower Swan River eastward to the Mississippi. More definite dating of the events in this area is closely related to the cause for the deterioration of the spillway pattern south of Swanville.

Formation of the Green Prairie Terrace. The course of the glacial meltwaters between Brainerd and St. Cloud is represented by Cooper's Mississippi valley train. The valley train is recognized in and adjacent to the Randall region as the Green Prairie terrace, a southward-sloping braided outwash train with an average height of about 25 feet above the modern river gradient. Its continuation north of Fort Ripley gap is the abundantly pitted outwash plain described by Cooper (1935, pp. 18–20, 67–68), which must have been deposited in front of the Brainerd lobe as it withdrew northeastward to open Pillager gap.

Age of the Green Prairie Terrace. It was demonstrated earlier in this report that the outwash sand of the Green Prairie terrace can be no older than late Cary, an interpretation which agrees with that of Cooper (1935, pp. 18–20), who believed that deposition of the valley train was a late Cary and Mankato event. Cooper's evidence of residual Cary ice buried by Mankato outwash led him to conclude that the Cary-Mankato interstadial interval was relatively short. The interval was apparently long enough, however, to permit the Superior lobe to retreat sufficiently far to allow its late Cary drainage channels to be abandoned before readvancing during the Mankato subage (Wright, 1956). It may be that the Superior lobe had withdrawn into the Lake Superior basin considerably before the disappearance of the Pierz and Brainerd lobes from central Minnesota.

In any event, the accelerated rate of retreat of the Pierz and Brainerd lobes from the Randall region is taken to mark the end of the Cary subage in this area. The age of the Green Prairie terrace sediments is accordingly interpreted as Cary-Mankato interstadial, at least in part. If Cooper's conclusion is correct, the sand must also be partly Mankato in age. Radiocarbon dates for the Mississippi valley train and the Anoka sand plain between St. Cloud and Minneapolis are considered by Wright and Rubin (1956).

MANKATO AND VALDERS

General. Except for Cooper's study of the Mississippi River and for recent reconnaissance investigations in the Mille Lacs moraine, the Mankato and Valders history of central Minnesota has not been re-examined since the publication of Leverett's professional paper. In marked contrast to the complex sequence of events during the Cary subage, however, the Randall region was not re-covered by ice, and the course of the Mississippi River between Brainerd and St. Cloud remained open.

Des Moines-Lobe Advance. The Late Wisconsin (Mankato) Keewatin ice sheet of Leverett entered Minnesota from the northwest in the form of the Des Moines lobe. The eastern extent of this lobe in central Minnesota is not at all clear. Leverett (1932, pls. 1, 2, and 3) placed the outer limit of the "young gray drift" in Cass, Todd, and Stearns counties along the base of the St. Croix moraine, yet he tentatively assigned the calcareous drift of the Wadena drumlin field to the Iowan (Leverett, 1932, p. 63). His apparent confusion of this "peculiar district" west of the moraine in Todd and Wadena counties is readily understood when one considers that he did not recognize a Middle Wisconsin (Cary) ice advance from the northwest, now called the Wadena lobe.

North of Long Prairie the gray drift of central Todd County seems to be clearly attributable to the Wadena lobe; there is no evidence known to suggest a Mankato ice cover. South of Long Prairie (i.e., beyond the southern end of the Wadena drumlin field), however, the area may have been glaciated by the Des Moines lobe. The ice may in fact have overridden the St. Croix moraine, blocking and concealing segments of the late Cary drainageways south of the latitude of Swanville. The relationships in this area have not yet been studied, however.

According to Leverett, the Des Moines lobe gave birth to two major eastward protuberances, the St. Louis sublobe on the north and the Grantsburg sublobe on the south. The St. Louis sublobe spread across northern Minnesota to within 25 miles of the head of Lake Superior. Here its calcareous buff (gray where unoxidized) silty till overlies and is interbedded with red clayey till of the Valders Superior lobe (Leverett, 1932, p. 65; Wright, 1955, p. 410).

The Grantsburg sublobe overrode the St. Croix moraine between St. Cloud and the Minneapolis-St. Paul region, and protruded northeastward across the Mississippi and St. Croix rivers to the vicinity of Grantsburg, Wisconsin. Its moraines and the distribution, lithology, and stratigraphy of its calcareous gray drift are treated in papers of the early Minnesota and Wisconsin geologists (Winchell, 1877; Winchell and Upham, 1888; Berkey, 1897; Upham, 1900; R. T. Chamberlin, 1905) and in later accounts by Sardeson (1916; in Leverett, 1932, pp. 78–90). The drainage relations and other details concerning the Grantsburg sublobe, Glacial Lake Grantsburg, and the Anoka sand plain were carefully worked out by Cooper (1935).

Neither the St. Louis sublobe nor the Grantsburg sublobe is known to have come within 30 miles of the Randall region, which was located within the balloon-shaped area of central Minnesota that remained free of active ice during the Mankato. It is unnecessary, therefore, to elaborate further on these sublobes.

Superior-Lobe Advance. The Valders Superior lobe pushed westward from the head of Lake Superior to the vicinity of Crosby, 15 miles northeast of Brainerd, where it terminated in a segment of the Mille Lacs moraine (Wright, 1955, p. 409; fig. 1). The red clayey till deposited by this ice has been traced southward around the western side of Mille Lacs Lake but it has not been found west of the moraine at this latitude. Further investigation of Superior-lobe deposits in this area is now being conducted by the author.

Valley-Train Deposition. As noted above, Cooper believed that the Mississippi valley train between Brainerd and St. Cloud is partly Late Wisconsin (Mankato) in age. The sequence of events relative to valley-train deposition during the Mankato is described as follows (Cooper, 1935, p. 18):

"The Pillager gap . . . owed its origin to the drainage of proglacial Lake Wadena during the early shrinkage of the Patrician ice. Waters from the Keewatin ice, advancing from the northwest, may actually have flowed into this lake before its extinction. At any rate, they invaded its former bed soon after, and found a ready-made passage at the gap, joining, just beyond it, the waters from the still persisting Patrician ice within the moraine. The combined drainage from the point of junction followed the present course of the Mississippi southward.

"While the Keewatin ice was at its maximum extension its front lay close to the gap. This condition was transient, and the margin soon receded. It made a lengthy halt, however, where the massive subterminal morainic belt [Altamont-Gary moraine] now stands, and during this period the drainage from an extensive ice front flowed across the region just vacated by the ice, which in turn had occupied, at least in part, the site of Lake Wadena. The front thus drained extended approximately from Park Rapids southward to Alexandria, a distance of about eighty miles. Evenly graded outwash aprons tributary to it show clearly that the waters converged toward the Pillager gap."

Cooper's account of the glacial movements west of Pillager gap is based largely on Leverett's interpretation of this area, which can not be properly evaluated at the present time; its validity depends upon detailed study of a large area north and west of the Randall region. Recent reconnaissance investigations do not lend support to Leverett's mapping of the eastern limit of the Late Wisconsin Keewatin ice sheet; the calcareous drift just west of the St. Croix moraine and adjacent to the Long Prairie River in north-central Todd County appears to have been deposited by the Cary Wadena lobe and not by the Mankato Des Moines lobe. Furthermore, the Altamont-Gary moraine may in fact represent the terminus of the Wadena lobe, as suggested by Wright (1954), rather than a lengthy recessional stand of the Des Moines lobe.

However, even if the Brainerd-St. Cloud segment of the valley train (including the Green Prairie terrace) did not receive contributions from the Des Moines lobe via Pillager gap, it may well have been supplied by outwash derived from the margins of the St. Louis sublobe and the Valders Superior lobe about 20 miles upstream from Brainerd (see Wright, 1955, fig. 1). Conclusions regarding this possibility are not warranted here, however, because investigation of these ice lobes lies beyond the scope of the present study.

POST-VALDERS

Withdrawal from the upper Mississippi drainage basin of the St. Louis sublobe and also of the Superior lobe at the close of the Valders subage resulted soon thereafter in the establishment of the Mississippi River from its source in Lake Itasca to the edge of the Keewatin drift northeast of Brainerd. This segment of the river has been described by Cooper (1935, pp. 66–67). The glacial meltwaters probably dropped much of their load in Glacial Lake Aitkin (Upham *in* Winchell *et al.*, 1899, pp. 46–47; Leverett, 1932, pp. 65–66), which was ponded behind the terminal moraine of the St. Louis sublobe.

Downstream from Brainerd the increased ratio of discharge to load resulted in downcutting, and the Mississippi River began to entrench itself into the outwash sand of the Green Prairie terrace. Approximately 20–25 feet of vertical erosion has occurred since the cutting episode was initiated. The rate of incision was probably rapid at first, when the discharge was greatest, but undoubtedly decreased when the meltwaters abated and especially after the river encountered bedrock at Little Falls.

As the Mississippi River entrenched itself below the Green Prairie terrace, an integrated drainage system began to develop in the Randall region. Downcutting by the Mississippi lowered base level for the tributary Elk River, which allowed the lower Elk to incise its course into the terrace sand at its mouth and into the East Darling plain farther upstream. At the figured locality 2 miles north of Little Falls (Fig. 13), or about 1½ miles upstream from the mouth of the Elk, the incision amounts to at least 13 feet, and several miles farther upstream, at the figured locality 2½ miles east of Randall (Fig. 17), the depth of downcutting is at least 11 feet.

The low cut-and-fill terrace along the lower Elk River indicates that downcutting was interrupted by an episode of deposition. Total thickness of the sand and muck fill is unknown but it probably does not exceed 7 or 8 feet, as suggested by the exposed thickness of the fill 2 miles north of

Little Falls (greater than 5 feet) and 2½ miles east of Randall (about 4 feet). Deposition appears to have been controlled from downstream and may have resulted from a rise in local base level, but failure to trace the terrace to the Mississippi River makes correlation difficult. Subsequent downcutting has reached a depth of about 4–6 feet and is apparently continuing at the present time.

Upstream from Randall the Elk and Little Elk rivers are marked by tiny consequent meanders and have barely begun to incise their courses. Elsewhere in the Randall region valley development is likewise in its infancy. As stated earlier, the area is poorly drained, much of the drainage is intermittent, and even the few permanent streams possess no true valleys of their own but occupy instead the floors of glacial lakes and meltwater drainageways. The ravines or gullies in the headwater regions of the Elk and Little Elk rivers appear to have been cut through local divides as the streams eroded headward from one small lake area or ice-block basin to the next.

9. LABORATORY ANALYSES

COLLECTION OF SAMPLES

Samples of the gray, red, and brown drifts were collected from road and railroad cuts, drainage ditches, gravel pits, and cut banks of streams. The sampling sites are shown in Figure 26 and are listed in Appendix B. Figure 26 follows the scheme used by Shepps (1953, fig. 1) to designate the type of sample. Each locality is shown as a circle divided into quadrants, with one or more of the quadrants darkened: a solid NW quadrant indicates a sample of gray till; NE quadrant, brown till; SE quadrant, red till; and SW quadrant, stratified drift.

All but two of the samples are from central Minnesota; these two (T63–52 and T64–52) are samples of Cary gray and red till, respectively, from the Wayzata Boulevard exposure west of Minneapolis described by Wright (1953, pp. 467–68). Samples 53–192A and 53–192C were collected by Professor Wright, the remainder by the writer. All samples were obtained from horizons 4 or 5 of the profile of weathering (Leighton and MacClintock, 1930). An area at least 18 inches square was scraped clean to a depth of several inches beneath the face of the exposure, and a spot sample of 1500 to 2000 grams was taken.

MECHANICAL ANALYSIS

General. Studies of size distribution have proved useful in differentiating and correlating tills in Illinois (Krumbein, 1933), Wisconsin (Murray, 1953), Ohio (Shepps, 1953), and southern Ontario (Dreimanis and Reavely, 1953), and it was considered that particle size might be a helpful parameter in the identification of Minnesota drifts. Forty samples were analyzed mechanically, including 33 of till and 7 of stratified drift. The 33 till samples included 12 samples of gray till, 5 of red till, and 16 of brown till. Thirteen of the samples were run in duplicate.

Procedure for Till Samples. After each field sample had been thoroughly air dried, the larger aggregates were broken down as the sample was gently crushed with a wooden rolling pin on a bread board covered with brown kraft paper. Particles coarser than 4 mm. were picked out by hand so far as possible and the remainder removed by screening the sample through a 5-mesh Tyler sieve. The sample was then split to approximately 55 grams with a commercial-model Jones sample splitter. It was determined empirically that, for most of the samples, a test sample of 50–60 grams would yield about 15–20 grams of material finer than .062 mm.; this latter amount was found to be more satisfactory for pipette analysis than the 20–30 grams

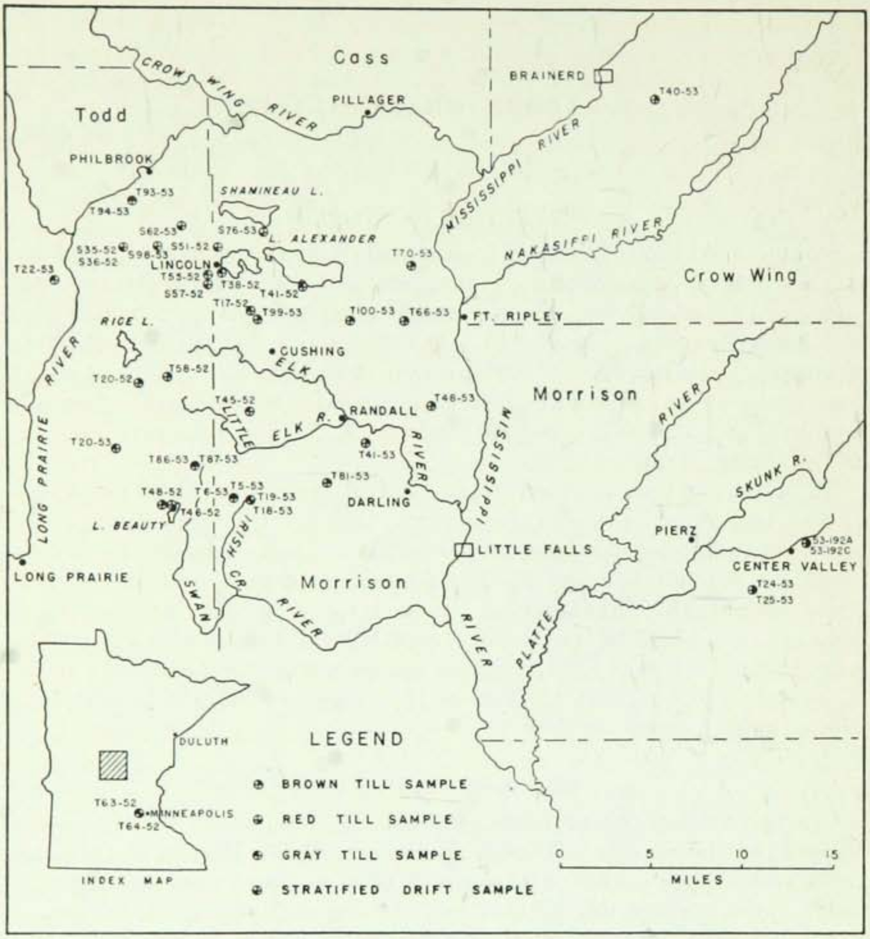

FIGURE 26. — Index map showing locations of analyzed samples.

recommended by Krumbein (1932, p. 144), particularly in the case of the highly calcareous samples.

The test sample was weighed to the nearest .001 gram and transferred to a 400- or 600-ml. beaker. As 100 ml. of sodium oxalate ($Na_2C_2O_4$) solution was added slowly, the mixture was stirred with a rubber-tipped glass rod. Concentration of the dispersing agent varied with the sample: the standard N/100 sodium oxalate solution was very satisfactory for the noncalcareous or slightly calcareous brown- and red-till samples; for the highly calcareous gray-till samples, however, this solution proved too highly concentrated, and an N/200 solution was found to be much more effective.

After soaking for at least 24 hours, the sample was split into coarse and fine fractions by wet sieving the material through a 250-mesh (.062 mm.) Tyler screen set in a large glass funnel over a metal dispersing cup. The sediment that remained on the sieve was washed with sodium oxalate solution, dried on the hotplate, weighed, and dry sieved into the six Wentworth grades between 4 mm. and 1/16 mm. In order to standardize the sieving procedure the screens were placed in a Ro-Tap electrical shaker for 15 minutes. The separates were weighed to the nearest milligram and examined under the binocular microscope for aggregate particles and adherence of clay to sand grains. If the separation of silt and clay from the coarser material was incomplete, the samples were either rerun or the sand grains were washed again and resieved.

The fine material caught in the pan during dry sieving was added to the suspension in the dispersing cup and the contents of the cup stirred with a Hamilton Beach electric drink mixer for 15 minutes. The suspension was then transferred to a liter graduate and the volume increased to 1000 ml. by the addition of sodium oxalate solution (N/100 or N/200). After the mixture was thoroughly agitated with a stirring rod and allowed to stand for 24 hours, a few drops of the suspension were placed on a glass slide and examined under the microscope for evidence of flocculation, as recommended by Krumbein (1932, p. 145; also Krumbein and Pettijohn, 1938, p. 73). Periodic checks of the suspension indicated that the dispersion technique was generally adequate to prevent visible flocculation for about 12 days in the case of calcareous samples and for more than 3 weeks in the case of noncalcareous samples.

The fine-grained material was analyzed by the pipette method described by Krumbein (1932; also Krumbein and Pettijohn, 1938, pp. 166–68). Pipette samples of 25 c.c. each were withdrawn at the designated time intervals, discharged into tared 50-ml. beakers, brought to dryness on the hotplate, cooled in the desiccator, and weighed to the nearest .0001 gram. Altogether, eight aliquots were taken from each sample except one (T45–52),* so the analysis yielded four silt sizes and five clay sizes on the Wentworth scale. Duplicate analyses were run on 13 of the 33 till samples. The good agreement of the results indicated that a single analysis is adequate.

Results of Till-Sample Analyses. The weight percentage of each size fraction (a total of 15 for each sample except T45–52) was calculated from the weight of the original test sample. The results are given in Table 4. They are also shown in Figure 27, in which the total percentages of granules and sand, silt, and clay are plotted as points on a triangular diagram.

It may be noted that sample T45–52, collected from the north Parker exposure 5 miles west of Randall, is extremely atypical of the gray-till samples in terms of its low percentage of sand (19.0 per cent) and very

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* Sample T45–52 flocculated after only six aliquots had been withdrawn. Other gray-till samples also flocculated when N/100, N/50, and N/25 solutions of sodium oxalate were used, but did not show evidence of visible flocculation when run with N/200 sodium oxalate solution.

TABLE 4. MECHANICAL ANALYSES OF TILL SAMPLES

(Percentage by weight in each grade size. Grade sizes in millimeters.)

Sample	3.96–1.98	1.98–.991	.991–.495	.495–.246	.246–.124	.124–.062	.062–.0312	.0312–.0156	.0156–.0078	.0078–.0039	.0039–.00195	.00195–.00098	.00098–.00049	.00049–.00024	Below .00024
Gray till															
T17–52	2.7	6.1	12.0	23.5	19.0	8.7	10.5	4.1	3.2	2.6	2.2	2.2	1.5	0.9	0.7
T38–52	2.6	6.7	13.6	24.0	18.7	8.4	10.6	3.9	2.8	2.0	1.9	1.5	1.7	0.7	1.0
T41–52	3.3	5.6	11.2	22.4	18.2	8.8	12.5	3.3	3.2	2.4	2.5	2.2	2.1	1.0	1.2
T45–52	1.7	1.8	2.6	4.6	5.0	5.0	9.5	10.2	7.1	7.8	7.3	6.9	30.5*		
T55–52	3.1	5.7	11.3	20.6	16.0	7.5	11.0	5.3	5.2	3.8	3.1	2.7	2.3	1.1	1.4
T63–52	2.3	4.5	6.3	11.4	13.1	9.9	15.7	6.7	6.6	5.7	5.2	4.1	3.9	2.2	2.5
T6–53	2.8	3.5	5.7	10.8	12.2	9.9	19.2	7.7	5.9	4.8	3.9	3.5	3.5	2.9	3.7
T19–53	2.5	4.9	8.2	15.3	13.1	8.1	15.8	8.7	6.2	4.7	4.1	3.3	2.7	2.2	0.3
T20–53	4.0	6.2	10.2	17.9	15.4	8.5	13.6	6.0	4.8	4.0	3.2	2.7	1.8	1.1	0.6
T22–53	3.6	8.2	12.6	20.3	16.0	8.0	11.9	4.8	3.8	3.5	2.7	1.9	1.4	0.8	0.6
T86–53	4.7	7.1	13.3	24.7	18.0	7.4	9.1	3.7	3.1	2.8	2.4	1.8	1.1	0.6	0.3
T94–53	2.7	5.6	11.4	21.2	16.7	7.9	12.1	6.1	4.7	3.3	2.8	2.1	1.7	0.9	0.7
Red till															
T46–52 †	1.7	3.1	7.1	17.5	16.6	9.5	12.9	6.2	4.0	3.6	2.1	2.6	2.6	2.9	7.7
T64–52 †	4.6	6.2	11.3	22.2	18.3	9.4	11.2	4.5	3.4	2.6	2.1	1.3	1.1	0.7	1.2
T18–53 †	3.5	5.3	9.9	25.4	21.3	7.9	10.2	3.8	3.0	2.7	2.4	1.9	1.2	1.1	0.2
T25–53 †	2.8	3.4	4.4	9.8	14.6	12.4	20.5	6.2	5.6	5.6	4.8	3.6	2.8	1.2	2.3
53–192C	3.9	5.3	10.1	23.5	20.4	9.8	11.1	3.7	3.1	2.6	2.1	1.7	1.4	0.9	0.2
Brown till															
T20–52 †	3.8	7.2	13.3	24.5	18.1	9.4	8.1	2.3	2.2	1.7	1.8	1.8	1.6	1.4	2.6
T48–52 †	4.5	7.6	12.8	21.2	16.1	9.2	8.3	3.5	3.4	2.9	2.5	2.1	2.0	1.4	2.1
T58–52 †	3.8	6.0	11.3	21.3	17.2	9.2	8.5	3.9	3.1	2.3	2.1	2.4	1.8	2.1	5.0
T5–53 †	4.3	7.2	11.3	21.3	18.0	9.7	11.1	3.9	2.8	2.1	1.8	1.7	1.5	0.9	2.2
T24–53 †	3.9	6.5	9.1	16.6	15.5	9.4	14.7	6.3	5.8	4.9	2.9	1.9	1.2	0.4	0.7
T40–53 †	4.4	6.8	12.6	23.0	17.7	8.6	9.3	3.3	2.9	2.6	2.2	2.0	1.6	1.0	2.2
T41–53	4.4	6.3	11.2	21.0	16.8	7.9	9.9	4.4	4.0	3.0	2.9	2.6	1.9	1.1	2.6
T48–53	3.6	9.1	14.1	23.8	16.8	7.4	8.8	3.2	3.1	2.6	2.3	1.7	1.1	0.6	1.6
T66–53	3.5	6.4	11.9	23.0	17.6	8.2	10.4	3.8	3.4	3.3	2.9	2.2	1.6	0.9	0.9
T70–53	3.4	6.3	13.2	27.2	19.1	7.5	8.2	2.9	3.0	2.1	2.1	1.7	1.4	1.0	1.0
T81–53 †	3.9	6.5	12.1	22.9	18.0	8.8	10.2	4.1	3.1	2.5	2.1	1.6	1.1	0.8	2.4
T87–53	3.9	6.4	10.8	20.3	17.4	9.3	12.3	4.8	4.1	3.2	2.5	1.9	1.2	0.7	0.9
T93–53	2.7	5.3	11.6	22.5	17.4	7.5	9.9	5.1	3.8	2.3	2.1	1.8	2.3	2.1	3.7
T99–53 †	2.7	6.7	13.2	25.0	18.5	7.6	8.0	3.3	2.0	1.9	1.9	1.5	1.7	1.3	4.7
T100–53 †	2.4	6.1	12.6	24.2	18.6	7.7	8.7	3.5	2.7	1.9	1.8	1.7	1.7	1.7	4.8
53–192A	5.4	6.0	10.2	19.0	17.6	10.1	12.5	4.4	3.9	3.0	2.6	2.1	1.5	0.8	0.8

* Weight percentage finer than .00098 mm.

† Percentages are averages of runs on duplicate subsamples.

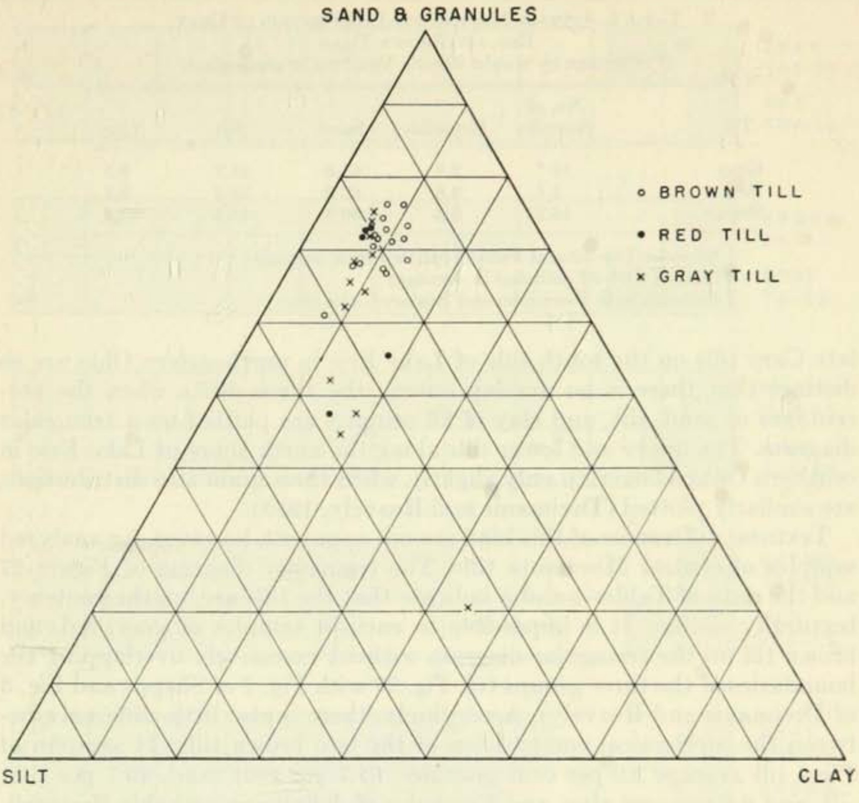

FIGURE 27. — Mechanical composition of gray, red, and brown tills.

high clay content (44.7 per cent). For this reason the sample was not included in computing the data of Table 5, which shows the average mechanical composition of the three till types. Sample T63–52, collected at the Wayzata Boulevard exposure 7 miles west of Minneapolis, is also omitted from the mean composition of the gray till because it was deposited by a Cary advance of the Des Moines lobe (Grantsburg sublobe) (Wright, 1953, p. 470), and not by the Wadena lobe. The average mechanical composition of the gray till, therefore, represents only samples of fairly typical Wadena drift. Sample T64–52, also obtained at the Wayzata Boulevard locality, is included in the average mechanical composition of the red till, however, because it was deposited by the same advance of the Superior lobe that left red sandy till in central Minnesota (Wright, 1953, pp. 469–70).

As noted above, recent investigations have shown significant differences in the mechanical composition of tills. Murray (1953) found a distinct difference in grain size between the Cary and Valders tills of northeastern Wisconsin. Shepps (1953) has shown that the Tazewell, early Cary, and

TABLE 5. AVERAGE MECHANICAL COMPOSITION OF GRAY, RED, AND BROWN TILLS
(Percentage by weight in each Wentworth grade class)

Till	No. of Samples	Granules	Sand	Silt	Clay
Gray	10 *	3.2	61.6	25.7	9.5
Red	5 †	3.8	67.0	19.8	9.3
Brown	16 ‡	3.3	60.9	25.3	10.4

* Samples T45–52 and T63–52 omitted from average.
† Sample T64–52 included in average.
‡ Includes both Pierz-lobe and Brainerd-lobe tills.

late Cary tills on the south side of Lake Erie in northeastern Ohio are so distinct that there is no overlap among the three drifts when the percentages of sand, silt, and clay of 76 samples are plotted on a triangular diagram. The upper and lower tills along the north shore of Lake Erie in southern Ontario overlap only slightly when their grain-size distributions are similarly plotted (Dreimanis and Reavely, 1953).

Textural differences of this kind are not apparent, however, for analyzed samples of central Minnesota tills. The triangular diagram of Figure 27 and the data of Tables 4 and 5 indicate that the tills are, on the contrary, texturally similar. It is impossible to encircle samples of gray, red, and brown till on the triangular diagram without excessively overlapping the boundaries of the three groups (cf. Fig. 27 with Fig. 2 of Shepps and Fig. 3 of Dreimanis and Reavely). Accordingly, there is also little difference between the mechanical composition of the two brown tills; 11 samples of Pierz till average 3.9 per cent granules, 65.7 per cent sand, 20.7 per cent silt, and 9.6 per cent clay, and 5 samples of definite or probable Brainerd-lobe till average 3.5 per cent granules, 69.9 per cent sand, 17.9 per cent silt, and 8.7 per cent clay. These small differences are much less than textural variations among the samples within each group and can not be considered significant.

In addition to showing the textural similarity of the various Cary tills, the triangular diagram brings out another factor that may be significant — the greater homogeneity of the brown till than of either the gray or red drifts. Only one (T24–53) of the 16 samples of brown till shows much departure from the general grouping, as opposed to the wider scatter of the other two drifts.

Although the gray, red, and brown tills can not be differentiated on an average textural basis, there is commonly, though not everywhere, a distinct textural difference between two tills in stratigraphic contact (Fig. 28). It appears that although till A at locality 1 may be texturally similar to till B at locality 2, tills A and B tend to be texturally dissimilar where they occur in contact at locality 3. This difference is believed sufficiently significant to be used as an aid in drift differentiation, a conclusion which

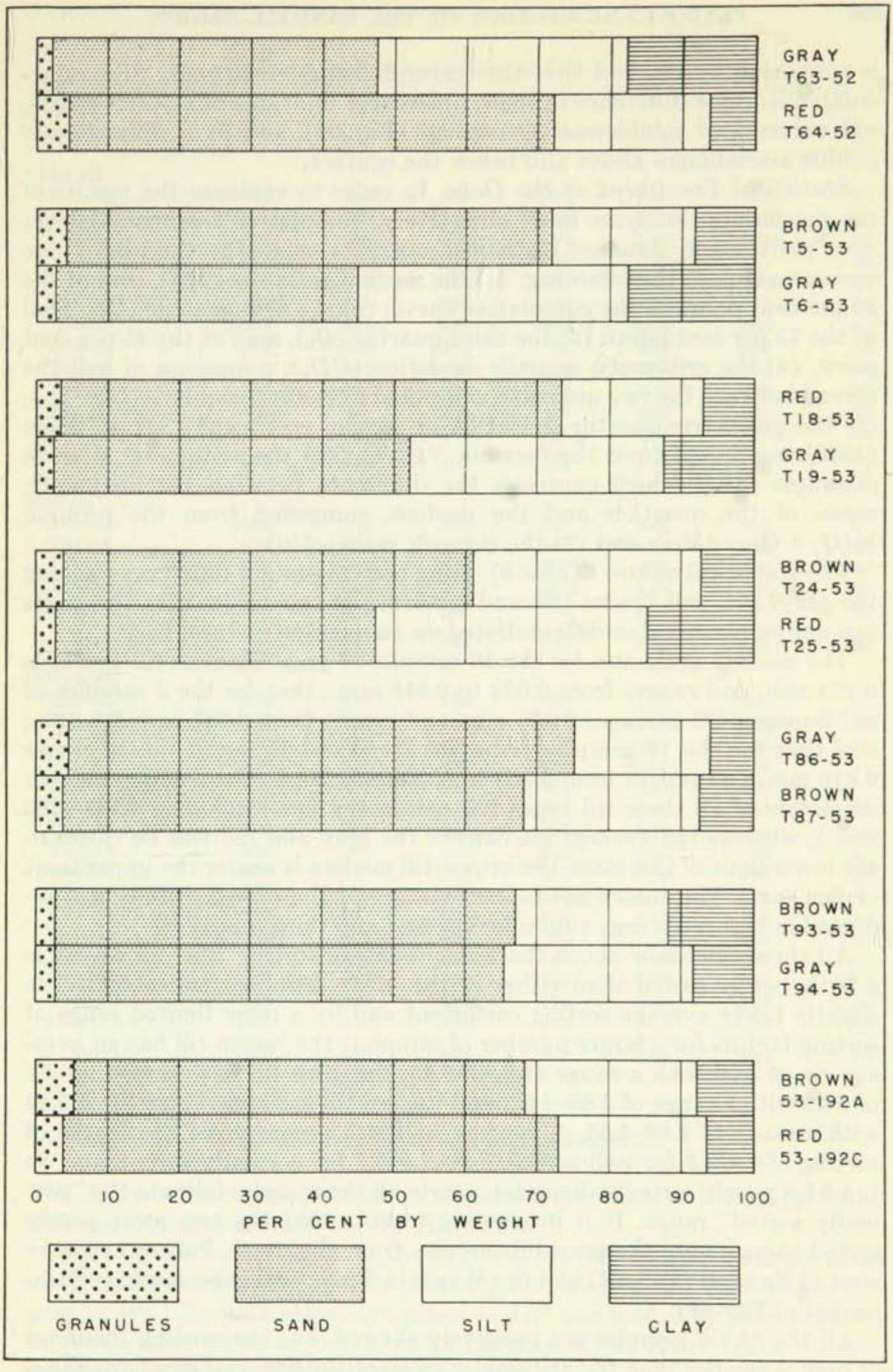

FIGURE 28. — Comparisons of mechanical composition of till samples collected from the same exposure.

is supported by the fact that the textural change is virtually always accompanied by a difference in color, differences in degree of calcareousness, pH values, and soluble-matter content (Fig. 30), and by a difference in pebble assemblages above and below the contact.

Statistical Treatment of the Data. In order to evaluate the results of the mechanical analyses more objectively, cumulative frequency curves were plotted and standard statistical measures applied to the tills. These measures include the following: (1) the median grain size (Md), read at the 50 per cent point on the cumulative curve; (2) the first quartile (Q_1), read at the 75 per cent point; (3) the third quartile (Q_3), read at the 25 per cent point; (4) the arithmetic quartile deviation (QD_a), a measure of half the spread between the two quartiles, computed from the formula $\frac{1}{2}(Q_3 - Q_1)$; (5) the geometric quartile deviation or sorting coefficient (So) of Trask (1932), computed from the formula $\sqrt{Q_3/Q_1}$; (6) the arithmetic quartile skewness (Sk_a), which expresses the difference between the arithmetic mean of the quartiles and the median, computed from the formula $\frac{1}{2}(Q_1 + Q_3 - 2Md)$; and (7) the clay-silt ratio (cl/si).

The statistical values (Table 6) bring out only minor differences among the gray, red, and brown tills and confirm the conclusion that the drifts can not be identified or differentiated on an average textural basis.

The median grain size for the 10 samples of gray Wadena till averages 0.174 mm. and ranges from 0.052 to 0.245 mm.; that for the 5 samples of red Superior till averages 0.160 mm. and ranges from 0.057 to 0.220 mm.; and that for the 16 samples of brown Pierz and Brainerd tills averages 0.210 mm. and ranges from 0.135 to 0.256 mm. Thus, the average median diameters of all three till types fall within the fine sand class (.125–.250 mm.); whereas the average medians of the gray and red tills lie closer to the lower limit of this class, the brown-till median is nearer the upper limit of fine sand. The somewhat coarser texture of the brown drift is also reflected in higher average values for the first and third quartiles.

All three tills show about the same degree of sorting. The brown till is a little better sorted than either of the other drifts, as indicated by its slightly lower average sorting coefficient and by a more limited range of sorting factors for a larger number of samples: the brown till has an average So of 3.08 with a range of 2.41–3.45; the gray till has an average So of 3.43 with a range of 2.82–4.52; and the red till has an average So of 3.34 with a range of 2.66–4.55. According to Trask's measure of the degree of sorting ($So < 2.5$ for well-sorted, $So = 2.5$–4.5 for normally sorted, and $So > 4.5$ for poorly sorted sediments), nearly all the samples fall into the "normally sorted" range. It is interesting to note that the two most poorly sorted samples are the gray-till samples from the north Parker exposure west of Randall (T45–52) and the Wayzata Boulevard exposure near Minneapolis (T63–52).

All the 33 till samples are positively skewed, i.e., the median diameter of each is smaller than the arithmetic mean of the first and third quartiles.

TABLE 6. STATISTICAL VALUES OF TILL SAMPLES

Sample	*Md* (mm.)	Q_1 (mm.)	Q_3 (mm.)	QD_a	*So*	Sk_a*	*cl/si*
Gray till							
T17–52	.220	.051	.425	.187	2.89	.018	.37
T38–52	.230	.058	.470	.206	2.85	.034	.35
T41–52	.195	.046	.420	.187	3.02	.038	.42
T45–52	.006	.0006†	.045	.022	9.05	.017	1.29
T55–52	.178	.031	.410	.190	3.64	.043	.42
T63–52	.056	.009	.245	.118	5.22	.071	.52
T6–53	.052	.011	.225	.107	4.52	.066	.47
T19–53	.080	.018	.320	.151	4.22	.089	.36
T20–53	.150	.032	.410	.189	3.58	.071	.33
T22–53	.205	.043	.490	.224	3.38	.062	.31
T86–53	.245	.063	.500	.219	2.82	.037	.33
T94–53	.180	.036	.400	.182	3.33	.038	.31
Average ‡	.174	.039	.407	.184	3.43	.050	.37
Red till							
T46–52	.102	.014	.290	.138	4.55	.050	.67
T64–52	.210	.051	.440	.195	2.94	.036	.29
T18–53	.220	.055	.390	.168	2.66	.003	.35
T25–53	.057	.014	.200	.093	3.78	.050	.39
53–192C	.210	.053	.400	.174	2.75	.017	.31
Average	.160	.037	.344	.154	3.34	.031	.40
Brown till							
T20–52	.240	.074	.485	.206	2.56	.040	.64
T48–52	.218	.046	.495	.225	3.28	.053	.56
T58–52	.190	.037	.430	.197	3.41	.044	.75
T5–53	.206	.050	.460	.205	3.03	.049	.41
T24–53	.135	.032	.380	.174	3.45	.071	.22
T40–53	.228	.054	.475	.211	2.97	.037	.50
T41–53	.195	.037	.440	.202	3.45	.044	.52
T48–53	.256	.062	.530	.234	2.92	.040	.41
T66–53	.210	.047	.445	.199	3.08	.036	.41
T70–53	.252	.080	.465	.193	2.41	.021	.44
T81–53	.215	.051	.450	.200	2.97	.036	.40
T87–53	.186	.042	.425	.192	3.18	.048	.30
T93–53	.193	.036	.410	.187	3.38	.030	.57
T99–53	.234	.054	.465	.206	2.93	.026	.73
T100–53	.216	.047	.430	.192	3.03	.023	.70
53–192A	.180	.043	.430	.194	3.16	.057	.33
Average	.210	.050	.451	.201	3.08	.041	.49

* All skewness values are positive.

† By extrapolation.

‡ Samples T45–52 and T63–52 omitted from average computations.

The degree of skewness is small in all samples, and there is no significant difference in skewness among the three tills.

The clay-silt ratios indicate that the brown till, with an average ratio of 0.49, has a relatively greater proportion of clay to silt than either the gray or red tills, with respective ratios of 0.37 and 0.40. The proportion is, however, more variable in the brown till than in the other drifts, as indicated by a wider range of ratios.

TABLE 7. MECHANICAL ANALYSES OF STRATIFIED-DRIFT SAMPLES
(Percentage by weight in each grade size. Grade sizes in millimeters.)

Sample	Above 4	4–2	2–1	1–½	½–¼	¼–⅛	⅛-1/16	Below 1/16
S35–52	1.6	4.6	5.9	19.2	44.7	18.7	3.8	1.1
S36–52	13.6	11.2	18.1	27.9	23.8	3.8	0.7	0.6
S51–52		0.8	4.0	13.8	20.6	31.6	24.4	4.6
S57–52			Tr.	0.1	21.4	56.9	12.3	9.3
S62–53				Tr.	1.4	39.7	39.2	19.5
S76–53		0.1	0.3	5.0	38.9	45.1	7.3	3.1
S98–53			Tr.	0.1	3.7	61.2	31.4	3.5

Analyses of Stratified Drift. Several samples of stratified drift from the northern part of the Randall region were also analyzed. After the air-dried field samples had been split with the Jones sample splitter, each test sample was dry sieved with the aid of the Ro-Tap shaker into eight possible grade sizes. The results are shown in Table 7.

SIZE-FRACTION OBSERVATIONS

Sand Fractions. Sand fractions of the red and brown tills were noted to be distinctly darker than those of the gray-drift samples. Examination of the very fine sand (1/8–1/16 mm.) fraction of the red and brown tills under the binocular microscope disclosed that the sands are composed largely of angular to subrounded quartz grains coated with red to brown iron oxide stains. Calcite and limestone fragments were not observed and the application of several drops of 1:1 hydrochloric acid failed to produce visible effervescence.

Microscopic examination of the very fine sand fraction of gray-till samples showed the grains to be virtually free of iron oxide stain. The separation of sand from silt and clay was generally less clean than in the case of the eastern drifts, so that some of the grains were marked by the adherence of minute aggregates of white clay. The fractions were found to be highly calcareous when tested with dilute acid.

Fine sand (¼–⅛ mm.) fractions of several samples of the gray, red, and brown tills were also examined under the binocular microscope. These observations proved similar to those of the very fine sand fraction, except that the iron oxide and white clay coatings (especially the latter) were not so heavy.

Fine Fractions. The colors of the silt-clay suspensions prepared for pipette analysis were noted to correspond closely with the colors of moist till samples observed in the field. Furthermore, the hue of each suspension remained almost unchanged throughout the analysis, i.e., the color was nearly the same regardless of whether total silt and clay or only fine clay was in suspension. Both the microscopic examinations and these color-size observations suggested that the drifts owe their color to finely divided pigments disseminated throughout the tills. It was decided, therefore, to examine the silt and clay fractions more closely in an attempt to determine the nature of the pigments. Some of the observations are discussed below; other tests and interpretations are treated under the heading of clay mineralogy.

After the last pipette samples had been withdrawn and the suspensions checked for flocculation, several of the suspensions were left to stand undisturbed for an extended period of time. Two suspensions (from duplicate pipette runs) of red-till sample T18–53 were allowed to settle for 27 days before they were discarded. At the bottom of each graduate two distinct layers were deposited: a basal layer 6–7 mm. thick, assumed to be mainly silt, which was brown in color; and an upper layer 5–6 mm. thick, assumed to be mainly clay, which was dark pink or red and similar in color to the original suspension. The contact between these layers was exceptionally sharp. The upper part of the brown layer was lighter in color than the underlying material; this was probably due to a lower concentration of heavy mineral grains than at the bottom of the graduate. Near the base of the red layer, but clearly above the sharp brown-red contact, was an undulating surface above which the clay appeared to be much less compact than that below; this line was interpreted to mark the boundary between free-falling particles and floccules.

Two suspensions (also duplicate pipette runs) of a brown-till sample (T99–53) were left to settle for a period of 30 days. Two layers, each about 4 mm. thick, were deposited from each suspension: a lower gray "silt" layer and an upper layer of brown "clay." The lower layer was again darkest at its base, presumably because of a higher concentration of heavy mineral grains of coarse silt size.

Two suspensions each of two additional brown-till samples (T40–53 and T100–53) were permitted to stand undisturbed for 42 days. In each cylinder layers similar to those of sample T99–53 were observed to form: a basal deposit of gray "silt" sharply overlain by a layer of brown "clay" similar in color to that of the suspension itself. (It was interesting to note that the relative thicknesses of the brown layers approximated the relative percentages of clay in the samples as previously determined by pipette analysis.)

The upper 400 ml. were withdrawn from two of the suspensions (T40–53A and T100–53A) and poured into glass funnels lined with filter paper. Virtually no residue from T40–53A remained on the filter, and only a small quantity of residue from T100–53A was left on the paper. In both cases the filtrates were identical in color with the unfiltered suspensions (T40–53B and T100–53B).

The upper 300 ml. of a third suspension (T40–53B) were transferred to a beaker, to which was added dilute (1:1) hydrochloric acid and a small piece of pure tin. As the mixture was heated, the brown color of the suspension disappeared, with reduction and solution of the ferric oxide.

The above observations indicate that the pigments of the red and brown tills are concentrated in the clay-size fraction and persist well down into the colloid range. The sharp color boundaries in the sedimentation cylinders suggest that there may be some size limit below which the pigment is abundant and above which it is apparently present only in minor amounts. Finely divided hematite is believed to be responsible for the color of the red till, whereas the pigment of the brown till is believed to be largely goethite. The gray till probably does not contain enough iron oxide (goethite) to obscure the light color imparted to it by finely crushed limestone.

SOLUBLE MATTER

General. The percentage of soluble constituents in the gray, red, and brown drifts was determined for the same 33 till samples that were analyzed texturally. Duplicate analyses were performed on each sample according to the procedure outlined below. An apparent relationship between the results of the soluble-matter and mechanical analyses was analyzed statistically.

Procedure. After the air-dried field sample had been disaggregated and freed of particles coarser than 4 mm. as described under size analysis, duplicate samples weighing between 10 and 17 grams each were split from the bulk sample by use of the Jones splitter. Each sample was weighed to the nearest .001 gm. and transferred to a 250-ml. beaker, to which 100 ml. of cold 1:1 hydrochloric acid were added. The mixture was brushed with a rubber-tipped glass rod and allowed to stand for 2–3 days, during which time it was occasionally stirred or gently swirled in the beaker. After this period the contents of the beaker were heated to about 100° C. for approximately 90 minutes, cooled to room temperature, and the effectiveness of the acid was checked. The mixture was then filtered and the residue thoroughly washed with distilled water so that most of the water-soluble chlorides were removed, as indicated by the $AgNO_3$ test. The residue was dried and weighed, and the loss in weight calculated as per cent soluble matter.

Results and Interpretation. The results of the analyses are reported in Table 8 and are shown graphically in Figures 29 and 30.

It may be observed that sample T45–52 (from the north Parker exposure) is again very atypical. The per cent soluble matter of T45–52 (and also of sample T63–52 from the west Minneapolis exposure) is accordingly omitted from the average (Table 8), so the mean soluble content of 13.7 per cent for the gray till represents only fairly typical Wadena-lobe till of central Minnesota. This figure is substantially and significantly higher than that for the brown-till samples of central Minnesota, whose soluble content averages only 7.0 per cent.

The high percentage of soluble matter in the gray till is due mainly to calcium carbonate, as evidenced by field determinations which show that typical Wadena till is highly calcareous, moderately alkaline (pH 8.0), and

TABLE 8. SOLUBLE MATTER IN GRAY, RED, AND BROWN TILLS
(Percentage by weight)

Sample	Subsample A	Subsample B	Average
Gray till			
T17–52	9.62	9.90	9.76
T38–52	9.40	9.00	9.20
T41–52	8.73	9.15	8.94
T45–52	39.87	38.91	39.39
T55–52	12.15	12.47	12.31
T63–52	22.97	22.12	22.54
T6–53	24.27	23.21	23.74
T19–53	18.77	19.18	18.97
T20–53	14.33	13.68	14.00
T22–53	15.14	15.54	15.34
T86–53	12.94	12.63	12.79
T94–53	11.28	11.72	11.50
Average *			13.66
Red till			
T46–52	8.30	7.98	8.14
T64–52	5.41	5.41	5.41
T18–53	10.61	9.96	10.29
T25–53	13.50	13.34	13.42
53–192C	6.44	6.42	6.43
Average			8.74
Brown till			
T20–52	6.59	6.27	6.43
T48–52	8.50	8.25	8.37
T58–52	7.17	7.24	7.21
T5–53	7.40	7.11	7.26
T24–53	7.11	7.31	7.21
T40–53(B)†	6.12	6.17	6.15
T41–53	7.07	6.98	7.03
T48–53(B?)	6.04	5.96	6.00
T66–53(B)	7.11	7.15	7.13
T70–53(B)	6.42	6.94	6.68
T81–53	6.00	5.92	5.96
T87–53	8.50	8.41	8.45
T93–53	7.23	6.91	7.07
T99–53	6.20	7.94	7.07
T100–53(B)	6.23	6.16	6.20
53–192A	7.04	6.88	6.96
Average			6.95

* Samples T45–52 and T63–52 omitted from average.
† (B) denotes definite or probable Brainerd-lobe sample.

contains abundant limestone pebbles. Other soluble constituents are undoubtedly present but are not believed to be abundant. Chlorides and sulphates, for example, which are generally abundant in well waters from gray drift (Allison, 1932, pp. 13–30; Thiel, 1944, pp. 42–53), should not be so common in the Wadena till as in the Mankato gray drift farther west because the Wadena lobe is believed not to have crossed the Cretaceous shales which contributed these radicals to the Mankato drift.

The soluble content of the brown till, on the other hand, can not be

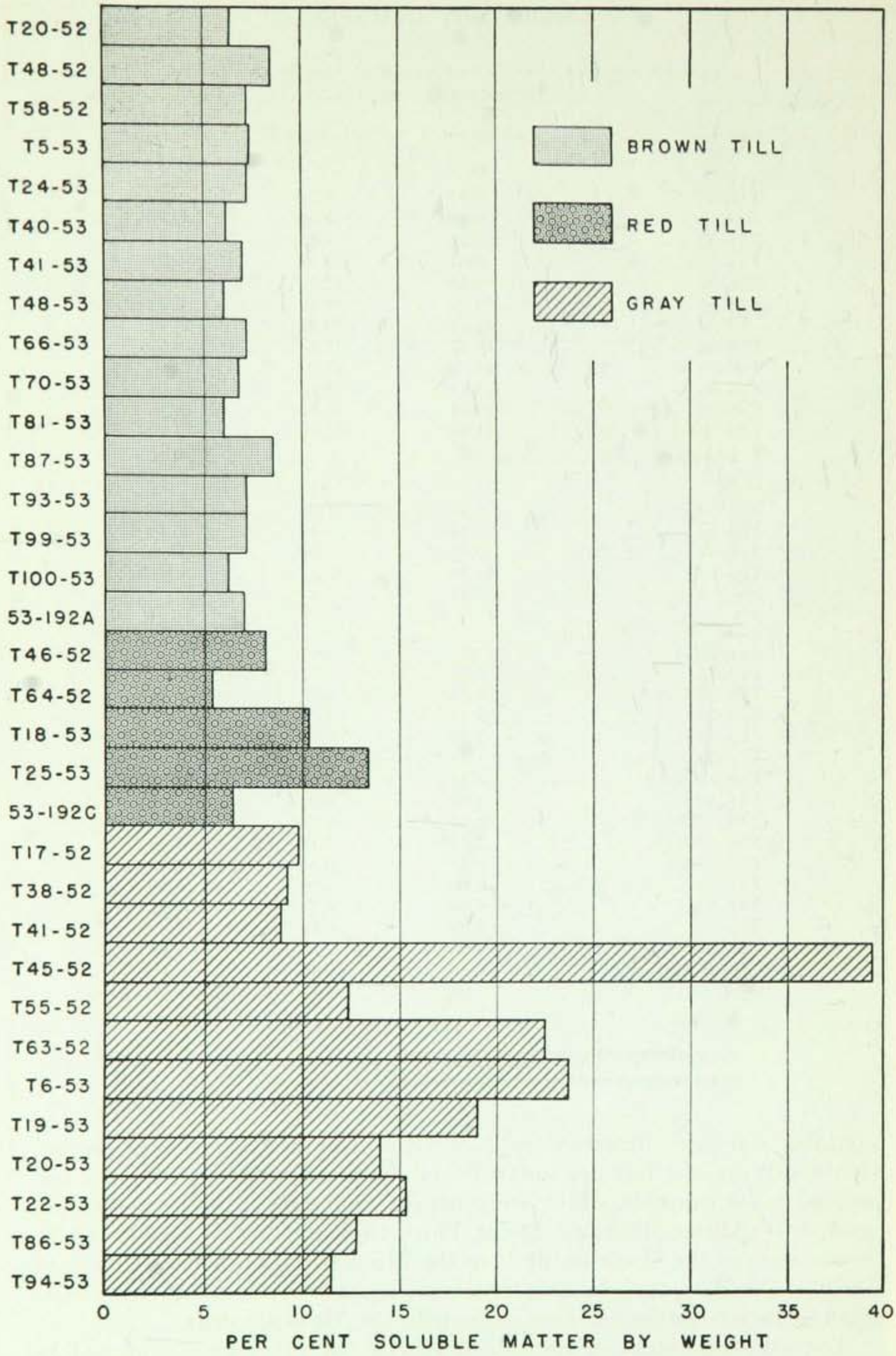

FIGURE 29. — Soluble matter in gray, red, and brown tills.

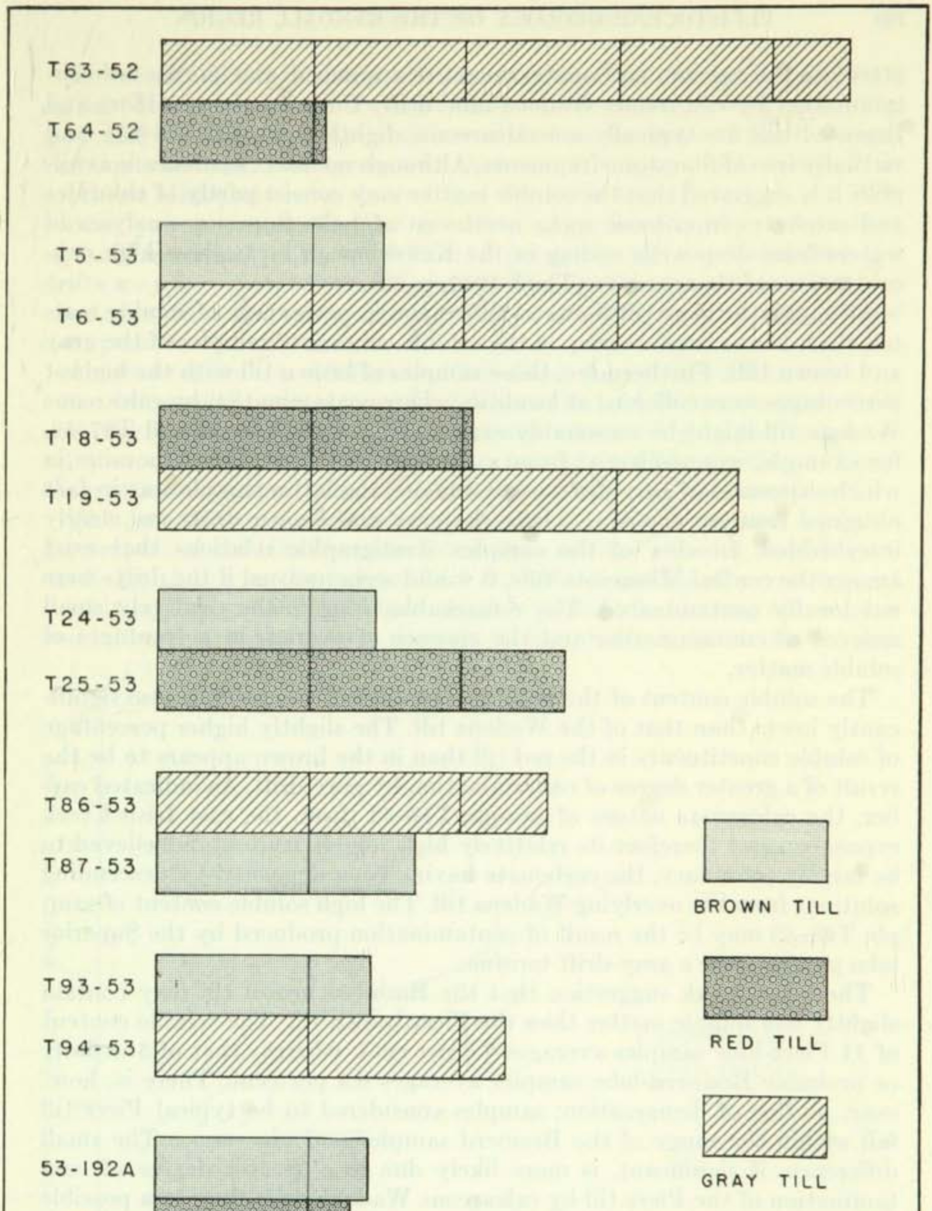

FIGURE 30. — Comparisons of soluble matter in till samples collected from the same exposure.

attributed to calcium carbonate, except to a minor degree in cases of contamination by calcareous Wadena-lobe drift. Uncontaminated Pierz and Brainerd tills are typically noncalcareous, slightly acid (pH 6.0–6.5), and virtually free of limestone fragments. Although no direct evidence is available, it is suggested that the soluble matter may consist partly of chlorides and sulphates from basic rocks northwest of Lake Superior; analyses of waters from deep wells ending in the Keweenawan lavas show high concentrations of these anions (Thiel, 1947, p. 43).

Although the gray till shows a wide range in percentage of soluble matter, there is no actual overlap in the soluble content of samples of the gray and brown tills. Furthermore, those samples of brown till with the highest percentages were collected at localities where contamination by calcareous Wadena till might be reasonably expected. Samples T48–52 and T87–53, for example, were collected from a segment of the St. Croix moraine in which exposures of gray drift are abundant; the latter sample was in fact obtained from an exposure where the gray and brown drifts are clearly interbedded. In view of the complex stratigraphic relations that exist among the central Minnesota tills, it would seem unusual if the drifts were not locally contaminated. The remarkable thing is the relatively small amount of contamination and the absence of overlap in percentages of soluble matter.

The soluble content of the red Superior till (8.7 per cent) is also significantly lower than that of the Wadena till. The slightly higher percentage of soluble constituents in the red till than in the brown appears to be the result of a greater degree of contamination by gray drift. As indicated earlier, the calcareous nature of sample T18–53 (from the east Irish Creek exposure), and therefore its relatively high soluble content, is believed to be largely secondary, the carbonate having been deposited by descending solutions from the overlying Wadena till. The high soluble content of sample T25–53 may be the result of contamination produced by the Superior lobe passing over a gray-drift terrane.

There is a weak suggestion that the Brainerd brown till may contain slightly less soluble matter than the Pierz brown till. The soluble content of 11 Pierz-lobe samples averages 7.2 per cent, whereas that of 5 definite or probable Brainerd-lobe samples averages 6.4 per cent. There is, however, no line of demarcation; samples considered to be typical Pierz till fall within the range of the Brainerd samples and vice versa. The small difference, if significant, is more likely due to a greater degree of contamination of the Pierz till by calcareous Wadena drift than to a possible difference in source area. South of Pillager gap the Brainerd lobe did not advance so far west as the Pierz lobe and thus it should not have incorporated so much of the underlying Wadena drift. In addition, the Brainerd lobe represents a slightly later advance than the Pierz lobe, whose drift is locally found interbedded with that of the Wadena lobe, whereas interbedding of Brainerd and Wadena tills is not definitely known.

The results of the soluble-matter analyses confirm the conclusion based on field determinations of degree of calcareousness and pH values that the gray and brown drifts may be differentiated on the basis of their calcium carbonate content. This agrees with the work of Kruger (1937) on tills from southern Minnesota, who showed that the carbonate content of the Wisconsin "young gray drift" (15.9 per cent) is significantly higher than that of the Wisconsin "young red drift" (1.7 per cent), and concluded that the drifts may be separated on this basis. The results also substantiate the conclusion that the light color of the Wadena drift is due mainly to the incorporation of limestone.

Relation of Soluble Matter to Grain Size. A general relationship was noted between the percentage of soluble matter and the percentage of silt and clay in the gray-till samples. A similar relationship in the brown-till samples was not so apparent. In order to ascertain the validity of these observations, standard graphic and statistical measures were employed.

The data were examined in terms of how the soluble content varies as the texture of the tills changes. Percentage of total silt and clay was accordingly chosen as the independent variable (x-axis) and percentage of soluble matter as the dependent variable (y-axis) in plotting the experimental results on the scatter diagram of Figure 31. A direct relationship

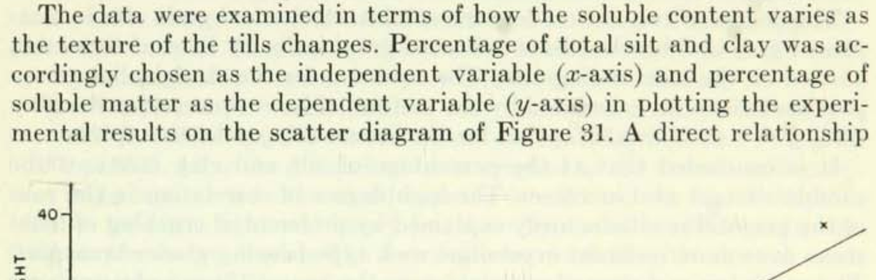

FIGURE 31. — Relation of soluble matter to silt and clay content in gray and brown tills. Equation of line of best fit calculated by method of least squares for the gray till is $y = -4.875 + 0.531x$; that for the brown till is $y = 4.801 + 0.074x$. Coefficient of correlation for the gray-till samples is +0.97; that for the brown-till samples is +0.39.

between the variables for the gray-till samples is apparent from this graph, which also serves to show that there is no actual overlap in the percentages of soluble matter for analyzed samples of the two tills.

Coefficients of correlation were calculated to determine the precise statistical relationships between the variables. It was found that a direct relationship exists in the case of the brown till as well as the gray, but to a much lesser degree. The correlation between percentages of soluble matter and fine-grained constituents of the 12 gray-till samples is nearly perfect (coefficient of correlation = +0.97), that of the 16 brown-till samples only fair (+0.39). It may be argued that data from sample T45–52, because of its atypical character, should not be included in calculating the coefficient of correlation for the gray till. However, the till at the north Parker exposure is atypically high in both silt-clay content and soluble matter, so the sample actually confirms the trend extremely well. When the sample is omitted the correlation is still nearly perfect (+0.93).

The degree of correlation between soluble matter and grain size in samples of gray and brown tills is indicated graphically by lines of regression plotted on the scatter diagrams. The equation for the straight line of approximate best fit, calculated by the method of least squares, for the gray till is $y = -4.875 + 0.531x$; that for the brown till, $y = 4.801 + 0.074x$.

It is concluded that as the percentage of silt and clay increases the soluble content also increases. The high degree of correlation in the case of the gray till is satisfactorily explained by preferential crushing of limestone over more resistant crystalline rock types during glacier transport. The much lower degree of correlation in the brown-till samples suggests that silt-clay content alone is much less of a controlling factor in soluble content than it is in the gray till, which in turn reflects the much lower percentage of easily crushed rock (i.e., limestone) in the brown till.

The limited data from the small number of red-till samples preclude the application of the above graphic and statistical measures to this drift.

HEAVY MINERAL SEPARATIONS

General. Separates of the 1/8–1/16 mm. grade class were selected for heavy mineral separation. Because it was thought advisable to remove the iron oxide coatings from the grains as an aid to mineral identification, the magnetic minerals (assumed to be mostly acid-soluble iron oxides) were removed from the samples before heavy-liquid separations were made. The determination of heavy minerals, therefore, involved two types of analysis: (1) magnetic mineral content, and (2) accessory mineral content exclusive of the magnetic fraction.

Procedure. After the 1/8–1/16 mm. size fractions had been reweighed to the nearest .001 gram, the magnetic minerals were removed from 27 sand separates by use of an Alnico magnet wrapped in cellophane. The magnet was passed through each sample several times until virtually all of the mgnetic grains had been segregated. This operation was repeated on the original separation and again on the second separation, so that the final (third) segregation was relatively free of nonmagnetic particles. The magnetic fraction was then weighed and the percentage of magnetic minerals calculated on the basis of the sand fraction before separation.

As a check on the reliability of this procedure, four samples were run in duplicate. The differences in magnetic mineral content between duplicate subsamples of three brown-till samples were found to be surprisingly low: 0.02 per cent, 0.04 per cent, and 0.07 per cent. The difference for the fourth sample, of red till, was somewhat higher — 0.22 per cent. It is believed that the procedure, if executed with care, is sufficiently accurate to permit quantitative comparisons of magnetic mineral content.

In order to remove the iron oxide stains from sand grains of the red and brown tills, the grains were boiled in dilute (1:1) hydrochloric acid, to which a small amount of $SnCl_2$ was added. Grains of the gray-till samples, though not coated with iron oxide, were treated similarly so that any common soluble heavy minerals would be altered or removed to an equal degree in all samples. Nineteen of the 27 sand fractions from which the magnetic particles had been removed were treated in this manner.

The samples were washed, dried, and quartered to approximately 2 grams each, according to the method outlined by Krumbein and Pettijohn (1938, p. 357). After the grains had been weighed to the nearest milligram, they were separated in the usual manner (see Krumbein and Pettijohn, 1938, p. 335) into light and heavy fractions by use of bromoform (sp. gr. 2.89) as the heavy liquid. The heavies were washed with alcohol, oven dried, weighed, and the percentage of heavy minerals was calculated on the basis of the magnetic-free sample. The heavy segregations were then split to about 400 grains each and the grains mounted in Canada balsam for future identification with the petrographic microscope.

Results and Interpretation. The results of the analyses (Table 9) indicate that the average magnetic mineral content of the brown-till samples (2.4 per cent) is more than twice that of the gray-till samples (1.1 per cent). The brown till is also richer in other heavy minerals (4.4 per cent vs. 3.6 per cent). These differences are attributable to differences in source areas of the drifts. It is to be expected that the Precambrian terrane of northeastern Minnesota, including the iron formations of the Vermilion, Mesabi, and Cuyuna districts, the Keewatin greenstone, and the basic Keweenawan volcanics, would contribute more heavy minerals to the Pierz and Brainerd drifts than would the Paleozoic carbonate belt of southern Manitoba and the Precambrian rocks of northwestern Minnesota to the Wadena till.

The lower percentage of heavy minerals in the red Superior till than in the brown till also appears to be significant. Although data on the red drift are limited, the analyses seem to confirm the conclusion that the Superior lobe had its origin in the Lake Superior basin and did not pass over so much iron formation as did the Pierz and Brainerd lobes. Other-

Table 9. Heavy Minerals in Gray, Red, and Brown Tills
(Percentage by weight in 1/8–1/16 mm. grade class)

Sample	Magnetic Minerals	Other Heavy Minerals
Gray till		
T17–52	1.4	4.0
T38–52	1.2	
T41–52	1.7	4.4
T45–52	0.3	
T55–52	1.5	3.2
T6–53	0.1	1.8
T19–53	1.0	3.2
T20–53	1.0	4.4
T22–53	0.9	3.3
T86–53	1.3	4.2
T94–53	1.4	
Average	1.1	3.6
Red till		
T46–52	1.1	1.7
T18–53	1.5	3.2
T25–53	1.8*	2.8
53–192C	2.2	
Average	1.7	2.6
Brown till		
T5–53	2.7*	6.1
T24–53	3.5	4.6
T40–53(B)†	2.1*	3.8*
T41–53	2.2	
T48–53(B?)	2.7	
T66–53(B)	2.3	4.3
T70–53(B)	2.2	3.6
T81–53	2.1*	4.3*
T87–53	2.8	3.9
T93–53	1.6	
T100–53(B)	2.3	4.6
Average	2.4	4.4

* Average of runs on duplicate subsamples.
† (B) denotes definite or probable Brainerd-lobe sample.

wise the red drift should be higher in magnetic minerals. It is believed significant that the percentages of magnetic minerals in the gray, red, and brown tills are consistent with the relative abundance of iron-formation pebbles in the tills (Table 3).

Samples of Pierz-lobe till are slightly higher in content of both magnetic minerals and other accessory minerals than definite or probable Brainerd-lobe till samples. The significance, if any, of these apparent differences is not known.

Analyses of a limited number of the 1/8–1/16 mm. size fractions from sand and gravel samples indicate that the percentages of magnetic minerals and other heavy minerals tend to be higher than in the till samples. Kruger, however, in his study of Minnesota drifts, found that "the well sorted phases of the drifts contain a lower percentage of heavy minerals than the tills" (Kruger, 1937, p. 350). The reason for these discrepant observations has not been determined.

CLAY MINERALOGY

General. Thirty clay fractions from 12 samples of gray, red, and brown till were tested by X-ray analysis to determine the mineralogic composition of the clay-size material. Four of these samples were also analyzed chemically for total iron content.

Procedure. The samples submitted for X-ray and chemical analyses were obtained from the suspensions prepared for pipette analysis. After the final pipette sample had been withdrawn, a few drops of the suspension were examined under the microscope for evidence of flocculation. If no apparent flocculation had taken place, the level of the suspension was brought back up to 1000 c.c. and the mixture reagitated. After the prescribed settling time had elapsed, the entire suspension above the appropriate depth was withdrawn and evaporated to dryness.

Four size fractions (<2 microns, <1 micron, <½ micron, and <¼ micron) were withdrawn from each of six suspensions. The <¼-micron diameter was obtained from five additional samples and the <½-micron size from a twelfth suspension.

In order that the X-ray photographs would not show undesirable sodium oxalate patterns, the dispersing agent was removed from each of the clay fractions according to the procedure worked out by Rosenzweig, Smith, and Weis (unpub.). Distilled water was added to the clay and the mixture heated to redissolve the sodium oxalate. The suspension was evaporated to 30 c.c. and centrifuged at moderate speed for 20 minutes, after which time the supernatant liquid was decanted. The sample was then washed with distilled water in order to dilute any residual solution and the centrifuge operation repeated. After a second washing, the suspension was transferred to a 50-c.c. beaker and evaporated to dryness.

The residue was ground to a powder in an agate mortar and the sample mounted for X-ray analysis in the powder-type camera. The photographs were taken by Deane Smith and Harry Taylor and the X-ray diffraction patterns interpreted by Prof. J. W. Gruner and Dr. Smith.

Four of the 30 clay fractions were submitted to Prof. S. S. Goldich for chemical determination of iron content by the University of Minnesota Rock Analysis Laboratory. The samples selected included one size fraction each of the gray and brown tills (<2 microns) and two fractions of red till (<2 microns and <½ micron).

Results and Interpretation. The results of the X-ray analyses are reported in Table 10. Quartz, feldspar, kaolinite, and montmorillonite are present in most of the samples. The quartz and feldspar lines are generally stronger and more consistent than the kaolinite and montmorillonite patterns. Some of the feldspar appears to be a species of plagioclase. Calcite

TABLE 10. MINERALS IN CLAY-SIZE FRACTIONS OF CARY TILLS
(J. W. Gruner, D. K. Smith, and H. L. Taylor, Analysts)

Sample	Size(μ)	Quartz	Feldspar	Calcite	Kaolinite	Montmorillonite	Mica
Gray till							
T17–52	<½	++	++	++			
T38–52	<2	++	++	++	?		
T38–52	<1	++	++	++	++	?	
T38–52	<½	++	++		++	++	
T38–52	<¼	++	++		?	++	
T22–53	<2	++	++	++		?	
T22–53	<1	++	++	++	++		
T22–53	<½	++	++			?	
T22–53	<¼	++		++	++	+	
Red till							
T18–53	<¼	++			++	?	
T25–53	<2	++	++			++	
T25–53	<1	++	++	?		?	
T25–53	<½	++	++			++	
T25–53	<¼	++	++		++	+	
53–192C	<2	++	++		++	+	
53–192C	<1	++	++		++	++	
53–192C	<½	++	++		+	++	
53–192C	<¼	++	++			++	
Brown till							
T5–53	<2	++	++		++	++	
T5–53	<1	++	++		++	++	?
T5–53	<½	+	+		+	++	
T5–53	<¼	++			++	+	
T24–53	<¼	++	++		++	+	
T40–53	<¼	++	++		++	?	
T70–53	<2	++	++		?		
T70–53	<1	++	++		++	?	+
T70–53	<½	++	++		++	++	
T70–53	<¼	++			++	?	
T81–53	<¼	++			++	?	
T99–53	<¼	?			?	++	

++ Definite and more abundant occurrences.
+ Definite but less abundant occurrences.
? Possible or questionable occurrences.

was identified only in samples of gray Wadena till, except for its questionable occurrence in one size fraction of a slightly calcareous sample of red Superior till. A little mica appears to be present in two of the samples.

No apparent relationship exists between grain size and mineralogic occurrence, unless it would be in the case of feldspar which was not identified in about half of the ¼-micron fractions. Likewise, there seems to be no correlation between till type and mineralogy, except for the significant occurrence of calcite in most of the Wadena-till clay fractions.

It was expected that X-ray analysis would disclose the presence of one or more iron minerals, at least in clay fractions of the red and brown tills, because the colors of these tills, which clearly persist down into the clay sizes, suggest the presence of iron oxides. Also, the source areas of the drifts virtually require the presence of iron. The red color of the Superior till is attributed to disseminated hematite derived from assimilated pebbles of the Upper Keweenawan red clastic rocks of eastern Minnesota. The Brainerd lobe followed the strike of the Deerwood iron formation (Cuyuna district) for many miles, and both the Pierz and Brainerd lobes probably crossed both the Vermilion and eastern Mesabi districts. Iron-formation pebbles and magnetic sand grains occur in both the red and brown drifts.

None of the X-ray photographs, however, indicates the presence of iron minerals in any of the tills. It was for this reason that four of the clay-size fractions were submitted to the Rock Analysis Laboratory for chemical determinations of total iron content. The results of these analyses (Table 11) show that the clay samples do contain a considerable quantity (average 10–11 per cent) of iron. It is possible, of course, that some or much of this iron may occur in the montmorillonite or that the clay fractions contain nontronite, but the colors of the clays still suggest the presence of iron oxides. It may be that the oxides are too finely divided to be detected by X-ray methods.

TABLE 11. CHEMICAL DETERMINATIONS OF TOTAL IRON CONTENT IN CLAY-SIZE FRACTIONS OF CARY TILLS
(C. O. Ingamells, Analyst)

Sample	Till	Size (μ)	Total Fe as Fe_2O_3 (%)
T22–53	Gray	<2	8.56
T25–53	Red	<2	10.27
T25–53	Red	$<\frac{1}{2}$	12.22
T5–53	Brown	<2	11.55

The lack of substantial differences in iron content among the clay fractions implies that the colors of the gray, red, and brown tills are related not so much to variations in total iron content as to differences in the distribution of the iron or, more likely, to differences in the form (degree of hydration) of the iron. Goldich (written communication) suggests that the color of the two red clay fractions of sample T25–53 is due to the presence of finely admixed hematite, whereas the brown clay of sample T5–53 probably derives its color from goethite (with some hematite?). He also suggests that the yellowish-brown clay of sample T22–53 contains goethite with little or no hematite.

That the color of the clays is related mainly to the form of the iron rather than to total iron content is also implied by the higher percentage of Fe_2O_3 in the brown-till fraction than in the red clay sample of the same size. If total iron were more important, then the red-till clay should probably contain the more iron. It is interesting to note that the comparative abundance of total iron in 2-micron clay fractions of the red and brown tills (Table 11) is consistent with the relative percentages of both iron-formation pebbles (Table 3) and magnetic sand grains (Table 9) in the two drifts.

The higher percentage of iron in the finer size of the two Superior-till fractions suggests that total iron may increase with decreasing grain size. This possibility is in accord with the color-size relationships noted in the sedimentation cylinders, which indicated that pigments of the tills are concentrated in clay-size material in preference to silt and that they persist well down into the colloid range.

The lower iron content of the gray-till sample is probably related to the western source of this drift, as opposed to the general eastern source of the darker tills. The Paleozoic limestone-Precambrian crystalline terrane of southern Manitoba and northwestern Minnesota should not be expected to have contributed so much iron to the Wadena drift as did the abundant basic rocks and iron formations of northeastern Minnesota to the various eastern drifts. It is again interesting to note the consistent relationship of iron in the clay fraction to other measures of iron content: the gray till contains the lowest percentage of total iron in the 2-micron clay size, and it is also lowest in both percentage of iron-formation fragments of pebble size and magnetic grains of fine sand size.

The yellowish-brown color of oxidized Wadena till undoubtedly reflects the presence of goethite suggested by Goldich. In contrast to the red and brown tills, however, in which hematite and goethite pigments appear to control the colors of the tills, the goethite in the Wadena drift only modifies the light color of the till, which is mainly controlled by an abundance of finely crushed limestone.

APPENDIX, REFERENCES, AND INDEX

APPENDIX

A. LOCATIONS OF PEBBLE SAMPLES

NOTE: PT samples collected from till. PG samples collected from stratified drift or ice-contact gravel. Figures in parentheses indicate corresponding till and stratified drift samples listed under B below.

Pebble Samples from Gray Drift

PT25-52 SW¼NW¼ Sec. 29, T. 130 N., R. 32 W., Todd County; north end of Mill Lake. Foot of St. Croix moraine.

PG37-52 SE cor. Sec. 19, T. 132 N., R. 32 W., Todd County; north end of Fawn Lake. Fawn Lake moraine. (S36-52)

PT39-52 SW¼NE¼NW¼ Sec. 31, T. 132 N., R. 31 W., Morrison County; ½ mile southeast of Lincoln post office. St. Croix moraine. (T38-52)

PT42-52 SE¼NE¼NW¼ Sec. 2, T. 131 N., R. 31 W., Morrison County; 0.3 mile south of Lake Alexander. St. Croix moraine. (T41-52)

PT56-52 SE¼NE¼ Sec. 36, T. 132 N., R. 32 W., Todd County; 0.6 mile southwest of Lincoln post office. St. Croix moraine. (T55-52)

PT6-53 S½SW¼SE¼ Sec. 31, T. 130 N., R. 31 W., Morrison County; 3.1 miles east of north end of Lake Beauty. Culdrum-Parker till plain, western slope of Irish Creek drainageway. (T6-53)

PT19-53 SW cor. SE¼ Sec. 32, T. 130 N., R. 31 W., Morrison County; 4 miles east of north end of Lake Beauty. Culdrum-Parker till plain, eastern slope of Irish Creek drainageway. (T19-53)

PT20-53 NW¼NE¼ Sec. 19, T. 130 N., R. 32 W., Todd County; 0.9 mile west of north end of Chain of Lakes. Foot of St. Croix moraine. (T20-53)

PG83-53 SE cor. SW¼ Sec. 35, T. 130 N., R. 32 W., Todd County; 0.4 mile east of north end of Lake Beauty.

PT94-53 Near center Sec. 8, T. 132 N., R. 32 W., Todd County; 2 miles southwest of Philbrook. Probable buried segment of Fawn Lake moraine. (T94-53)

Pebble Samples from Red Drift

PT60-52 NW cor. NE¼NE¼ Sec. 3, T. 129 N., R. 32 W., Todd County; ¼ mile west of north end of Lake Beauty. St. Croix moraine. (T46-52)

PT18-53 SW cor. SE¼ Sec. 32, T. 130 N., R. 31 W., Morrison County; 4 miles east of north end of Lake Beauty. Culdrum-Parker till plain, eastern slope of Irish Creek drainageway. (T18-53)

PT25-53 NW cor. Sec. 25, T. 40 N., R. 30 W., Morrison County; 3 miles southwest of Center Valley. Drumlin in Pierz drumlin field. (T25-53)

Pebble Samples from Brown Drift

PT54-52 NE cor. Sec. 36, T. 132 N., R. 32 W., Todd County; ¼ mile southwest of Lincoln post office. St. Croix moraine.

PT59-52 NW¼NE¼ Sec. 34, T. 131 N., R. 32 W., Todd County; southwest end of Loon Lake. St. Croix moraine. (T58-52)

PT62-52 NE¼NW¼ Sec. 3, T. 129 N., R. 32 W., Todd County; 0.6 mile west of north end of Lake Beauty. St. Croix moraine. (T48-52)

PT5-53 S½SW¼SE¼ Sec. 31, T. 130 N., R. 31 W., Morrison County; 3.1 miles east of north end of Lake Beauty. Culdrum-Parker till plain, western slope of Irish Creek drainageway. (T5-53)

PG23-53 SW cor. Sec. 34, T. 130 N., R. 32 W., Todd County; 1 mile west of north end of Lake Beauty. St. Croix moraine.

PT24-53 NW cor. Sec. 25, T. 40 N., R. 30 W., Morrison County; 3 miles southwest of Center Valley. Drumlin in Pierz drumlin field. (T24-53)

PG28-53 SE cor. SW¼ Sec. 18, T. 130 N., R. 32 W., Todd County; 1.1 miles west of north end of Chain of Lakes. Foot of St. Croix moraine.

PT45–53 SE¼SE¼ Sec. 27, T. 131 N., R. 31 W., Morrison County; 1½ miles southeast of Cushing. St. Croix moraine.

PT66–53 SW cor. Sec. 11, T. 131 N., R. 30 W., Morrison County; 4 miles southeast of east end of Lake Alexander. St. Croix moraine. (T66–53)

PG67–53 SW cor. Sec. 11, T. 131 N., R. 30 W., Morrison County; 4 miles southeast of east end of Lake Alexander. St. Croix moraine.

PT71–53 SW¼SW¼ Sec. 26, T. 132 N., R. 30 W., Morrison County; 3½ miles east of east end of Lake Alexander. St. Croix moraine.

PG72–53 SE¼SE¼ Sec. 29, T. 132 N., R. 30 W., Morrison County; 1 mile northeast of east end of Lake Alexander. St. Croix moraine.

PG74–53 SE cor. Sec. 14, T. 132 N., R. 31 W., Morrison County; 1.9 miles southeast of east end of Shamineau Lake. Shamineau Lake segment of St. Croix moraine.

PG77–53 SW cor. NW¼ Sec. 14, T. 132 N., R. 31 W., Morrison County; 0.8 mile east of east end of Shamineau Lake. Shamineau Lake segment of St. Croix moraine.

PT81–53 NE cor. NW¼NE¼ Sec. 36, T. 130 N., R. 31 W., Morrison County; 4 miles south-southwest of Randall. Culdrum-Parker till plain. (T81–53)

PT91–53 NE cor. NW¼ Sec. 14, T. 131 N., R. 32 W., Todd County; 3.6 miles southwest of Lincoln post office. St. Croix moraine.

PT93–53 Near center Sec. 8, T. 132 N., R. 32 W., Todd County; 2 miles southwest of Philbrook. Probable buried segment of Fawn Lake moraine. (T93–53)

B. LOCATIONS OF TILL AND STRATIFIED-DRIFT SAMPLES

Samples of Gray Till

T17–52 SW¼NE¼ Sec. 8, T. 131 N., R. 31 W., Morrison County; 2½ miles northwest of Cushing. St. Croix moraine.

T38–52 SW¼NE¼NW¼ Sec. 31, T. 132 N., R. 31 W., Morrison County; ½ mile southeast of Lincoln post office. St. Croix moraine.

T41–52 SE¼NE¼NW¼ Sec. 2, T. 131 N., R. 31 W., Morrison County; 0.3 mile south of Lake Alexander. St. Croix moraine.

T45–52 SW¼SE¼ Sec. 5, T. 130 N., R. 31 W., Morrison County; 5 miles west of Randall. St. Croix moraine.

T55–52 SE¼NE¼ Sec. 36, T. 132 N., R. 32 W., Todd County; 0.6 mile southwest of Lincoln post office. St. Croix moraine.

T63–52 SE¼NE¼ Sec. 1, T. 117 N., R. 22 W., Hennepin County; approximately 7 miles west of downtown Minneapolis. St. Croix moraine.

T6–53 S½SW¼SE¼ Sec. 31, T. 130 N., R. 31 W., Morrison County; 3.1 miles east of north end of Lake Beauty. Culdrum-Parker till plain, western slope of Irish Creek drainageway.

T19–53 SW cor. SE¼ Sec. 32, T. 130 N., R. 31 W., Morrison County; 4 miles east of north end of Lake Beauty. Culdrum-Parker till plain, eastern slope of Irish Creek drainageway.

T20–53 NW¼NE¼ Sec. 19, T. 130 N., R. 32 W., Todd County; 0.9 mile west of north end of Chain of Lakes. Foot of St. Croix moraine.

T22–53 SW¼ Sec. 34, T. 132 N., R. 33 W., Todd County; 1¼ miles west of Long Prairie River. Wadena drumlin field.

T86–53 NE cor. Sec. 26, T. 130 N., R. 32 W., Todd County; 2¼ miles northeast of north end of Lake Beauty. St. Croix moraine, western slope of easternmost branch of Swan River drainageway.

T94–53 Near center Sec. 8, T. 132 N., R. 32 W., Todd County; 2 miles southwest of Philbrook. Probable buried segment of Fawn Lake moraine.

Samples of Red Till

T46–52 NW cor. NE¼NE¼ Sec. 3, T. 129 N., R. 32 W., Todd County; ¼ mile west of north end of Lake Beauty. St. Croix moraine.

T64–52 SE¼NE¼ Sec. 1, T. 117 N., R. 22 W., Hennepin County; approximately 7 miles west of downtown Minneapolis. St. Croix moraine.

T18–53 SW cor. SE¼ Sec. 32, T. 130 N., R. 31 W., Morrison County; 4 miles east of north end of Lake Beauty. Culdrum-Parker till plain, eastern slope of Irish Creek drainageway.

T25–53 NW cor. Sec. 25, T. 40 N., R. 30 W., Morrison County; 3 miles southwest of Center Valley. Drumlin in Pierz drumlin field.

53–192C NW cor. Sec. 9, T. 40 N., R. 29 W., Morrison County; 1 mile northeast of Center Valley. Drumlin in Pierz drumlin field. Collected by H. E. Wright, Jr.

Samples of Brown Till

T20–52 NW cor. NE¼SE¼ Sec. 32, T. 131 N., R. 32 W., Todd County; 0.2 mile east of Thunder Lake. St. Croix moraine.

T48–52 NE¼NW¼ Sec. 3, T. 129 N., R. 32 W., Todd County; 0.6 mile west of north end of Lake Beauty. St. Croix moraine.

T58–52 NW¼NE¼ Sec. 34, T. 131 N., R. 32 W., Todd County; southwest end of Loon Lake. St. Croix moraine.

T5–53 S½SW¼SE¼ Sec. 31, T. 130 N., R. 31 W., Morrison County; 3.1 miles east of north end of Lake Beauty. Culdrum-Parker till plain, western slope of Irish Creek drainageway.

T24–53 NW cor. Sec. 25, T. 40 N., R. 30 W., Morrison County; 3 miles southwest of Center Valley. Drumlin in Pierz drumlin field.

T40–53 SE cor. NE¼ Sec. 32, T. 45 N., R. 30 W., Crow Wing County; 2½ miles southeast of downtown Brainerd. Drumlin in Brainerd drumlin field.

T41–53 NW cor. SE¼SE¼ Sec. 17, T. 130 N., R. 30 W., Morrison County; 2 miles southeast of Randall. St. Croix moraine.

T48–53 SE¼NE¼SW¼ Sec. 1, T. 130 N., R. 30 W., Morrison County; 2 miles north of west end of Fish Lake. St. Croix moraine.

T66–53 SW cor. Sec. 11, T. 131 N., R. 30 W., Morrison County; 4 miles southeast of east end of Lake Alexander. St. Croix moraine.

T70–53 NE¼NW¼ Sec. 35, T. 132 N., R. 30 W., Morrison County; 3½ miles east of east end of Lake Alexander. St. Croix moraine.

T81–53 NE cor. NW¼NE¼ Sec. 36, T. 130 N., R. 31 W., Morrison County; 4 miles south-southwest of Randall. Culdrum-Parker till plain.

T87–53 NE cor. Sec. 26, T. 130 N., R. 32 W., Todd County; 2¼ miles northeast of north end of Lake Beauty. St. Croix moraine, western slope of easternmost branch of Swan River drainageway.

T93–53 Near center Sec. 8, T. 132 N., R. 32 W., Todd County; 2 miles southwest of Philbrook. Probable buried segment of Fawn Lake moraine.

T99–53 NE cor. Sec. 17, T. 131 N., R. 31 W., Morrison County; 2 miles northwest of Cushing. St. Croix moraine.

T100–53 SW cor. Sec. 8, T. 131 N., R. 30 W., Morrison County; 2½ miles south of east end of Lake Alexander. St. Croix moraine.

53–192A NW cor. Sec. 9, T. 40 N., R. 29 W., Morrison County; 1 mile northeast of Center Valley. Drumlin in Pierz drumlin field. Collected by H. E. Wright, Jr.

Samples of Stratified Drift

S35–52 SE cor. Sec. 19, T. 132 N., R. 32 W., Todd County; north end of Fawn Lake. Fawn Lake moraine.

S36–52 SE cor. Sec. 19, T. 132 N., R. 32 W., Todd County; north end of Fawn Lake. Fawn Lake moraine.

S51–52 NW cor. Sec. 30, T. 132 N., R. 31 W., Morrison County; 0.8 mile north-northwest of Lincoln post office. Scandia Valley outwash plain.

S57–52 SE¼SE¼ Sec. 36, T. 132 N., R. 32 W., Todd County; 1 mile south-southwest of Lincoln post office. Intramorainic outwash plain in St. Croix moraine.

S62–53 SE¼SW¼ Sec. 14, T. 132 N., R. 32 W., Todd County; 2.7 miles northwest of Lincoln post office. Outwash plain at western end of Shamineau Lake segment of St. Croix moraine.

S76–53 SW cor. SE¼ Sec. 16, T. 132 N., R. 31 W., Morrison County; 1.1 miles north of northwestern tip of Lake Alexander. Scandia Valley outwash plain.

S98–53 SW¼SW¼ Sec. 22, T. 132 N., R. 32 W., Todd County; 2 miles east of north end of Fawn Lake. Fawn Lake outwash plain.

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