Pleistocene Geology of Eastern South Dakota

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By RICHARD FOSTER FLINT

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PLEISTOCENE GEOLOGY OF EASTERN SOUTH DAKOTA

By Richard Foster Flint

ABSTRACT

The glaciated part of the State of South Dakota has an area of about 34,000 square miles that constitutes almost the entire eastern half of the State. It is underlain principally by flat-lying marine Cretaceous strata, capped very locally by residual remnants of Tertiary continental rocks. Lying partly in the Central Lowland province and partly in the Great Plains province, it is characterized topographically by two great plateau-like highlands, the Coteau des Prairies and the Coteau du Missouri, separated by the James River lowland, elongate from north to south. The extreme relief of the region is about 1,200 feet; in general the lowland is 300 to 700 feet lower than the surfaces of the coteaus. The region is drained mainly by the Missouri River and two of its tributaries, the James and the Big Sioux. The general direction of stream flow is toward the south.

The climate varies from subhumid to humid, and much of the region is almost treeless. The drainage apart from the main streams is poorly integrated, and considerable areas have interior drainage in consequence of the dry climate and of the blocking of ancient drainage lines by glacial drift.

East of the Missouri River glacial drift is very nearly continuous, averaging an estimated 40 feet in thickness but thickening at one place to 500 feet. West of the river the drift consists of little more than scattered erratic boulders lying on the bedrock.

The glacier ice entered the State from the northeast or north, and flowed generally southward and westward. The extreme outer limit of glaciation is marked, not by end moraine, but by the indistinct outer limit of scattered boulders and patches of till. The limit is lobate, with projections extending into major valleys.

Glacial erosion of the weak Cretaceous rocks is believed to have been great. Much of the width and part of the depth of the James River lowland are believed to be the result of this process.

Most of the drift consists of till, and most of it is made up of fragments of local rocks; only a small proportion was brought in from outside the State. The till is very rich in clay, reflecting the predominance of shale in the bedrock strata of the region. In most parts of the region, outwash deposits are scanty and thin. This fact results from the preponderance of clay and silt in the drift. The clay and much of the silt picked up by melt-water streams were carried onward out of the State, leaving only the very meager coarse fraction as bed-load deposits.

Many outwash bodies are of poor quality for use as concrete aggregate, owing in considerable degree to physical or chemical instability of the rock types that constitute the individual pebbles and cobbles.

Ice-contact stratified drift, chiefly in the form of kames and collapsed and pitted bodies, is conspicuous in certain localities, particularly where glacier margins stood across steep-sided valleys. Fine-grained sediments deposited in small temporary glacial lakes are present also in topographically favorable positions.

Stratigraphically the drift consists of layers of till separated by layers of loess or stratified drift, or fossil-bearing nonglacial sediment, or zones of weathering. The individual layers represent successive glacial stages and substages separated by features that record nonglacial conditions. Loess, particularly, is abundant and seems to have been deposited freely during each deglaciation of the region. Much of it was derived from the deflation of outwash silt along the Missouri, James, and Big Sioux Rivers, but some of the loess came from more local sources.

Both Wisconsin tills and pre-Wisconsin tills occur within the State. The Wisconsin tills are very much alike and can not be distinguished from each other on a basis of physical character. The pre-Wisconsin tills also resemble each other, but in many exposures they seem to be distinguishable physically from the Wisconsin tills. On a basis of stratigraphic relations, Illinoian till and at least one pre-Illinoian till—probably Kansan—have been identified.

In a few places a pre-Wisconsin till is overlain by oxidized loess correlated with the Loveland loess of Iowa and Nebraska. In other places pre-Wisconsin tills are overlain or underlain by sand and gravel, deposited by streams that flowed eastward from the Great Plains, Black Hills, and Rocky Mountains, and containing fossil mammal bones. On a basis of the fossils these are correlated with the Holdrege, Red Cloud, Grand Island, and Crete formations. These sediments have made it possible to correlate exposures of pre-Wisconsin till that could not otherwise have been correlated.

The Wisconsin stage in South Dakota consists of four glacial substages, correlated respectively with the Iowan, Tazewell, Cary, and Mankato substages recognized in Iowa. The Iowan and Tazewell substages are separated from each other by a residual concentration of wind-cut stones and by loess, but not by any features recording notable weathering. Similarly, although the Cary and Mankato substages are separated from each other by loess, little weathering, mass wasting, and stream erosion are recorded for the interval between them. In contrast, oxidation, soil development, and erosion occurred during the Tazewell-Cary interval. Accordingly it is believed that the Wisconsin stage in South Dakota can be properly viewed as consisting of two pairs of two glacial substages, the two pairs separated from each other by a significant break.

The areal extent of each of the pre-Wisconsin glaciations is not well known, owing mainly to subsequent erosion. The Illinoian glacier seems to have reached the position of the Missouri River from end to end of the State. The Kansan ice is believed

to have reached less far, and the Nebraskan ice still less far. During these early glaciations the topography of the region was substantially different from the present-day topography.

The most extensive of the Wisconsin drift sheets is the Iowan; it reaches south beyond the Missouri River into Nebraska, and west beyond the Missouri on a wide front extending into North Dakota. The post-Iowan drift sheets lap off successively upon each other in such a way that the Mankato drift is the least extensive of them. The topographic relations of the drift sheets to the two coteaus make it possible to estimate the thicknesses of at least the Mankato and Cary glaciers with less error than is generally possible in other regions. In this region these glaciers are estimated to have had thicknesses of 800 to 1,600 feet.

The Iowan drift sheet has no end moraines, the Tazewell has few, and the Cary has many. The Mankato drift is unique in that more than 80 percent of its area consists of end moraine. The progressive increase in development of end moraine is believed to be a result of increasing frequency of climatic fluctuation and decreasing thickness of the glacier.

During the melting of the Mankato glacier a large glacial lake, Lake Dakota, occupied much of the James River lowland for a time, leaving silt deposits over its floor and beach deposits at places along its shores as a record of its existence. Water flowing out from the lake cut the deep narrow trench occupied by the present-day James River. Still later the extensive glacial Lake Agassiz occupied, in part, the northeastern corner of South Dakota and overflowed southeastward through the Minnesota River, which forms a part of the eastern boundary of the State.

Although the chief valleys now drain toward the south, segments of former valleys, now partly destroyed by glacial erosion and deposition, indicate clearly that an earlier stream system drained toward the east. Much, though not all, of the former stream pattern has been reconstructed. It consists of eastward continuations of all the major streams now entering the Missouri River from the west. The belief, advanced as early as 1869, that an ice sheet flowing southwestward blocked these valleys and detoured the drainage so as to form the Missouri River is confirmed. One of the results of diversion was the shifting of the continental divide separating Arctic drainage from Gulf drainage from a position in South Dakota to a position hundreds of miles farther north.

The date of the drainage diversion is believed to be Illinoian. At the time of diversion the eastward-flowing streams were already well incised below the general surface of the Plains; evidence from fossil-bearing western alluvium indicates that much of this incision occurred during the Yarmouth interglacial age.

West of the Missouri River a pronounced preference for parallel, southeast-trending courses characterizes tributary streams. This pattern is independent of any known lithologic or structural features. It is suggested that the pattern has resulted from the headward growth of streams guided by longitudinal sand dunes and deflation basins on a high surface or surfaces no longer present in this region.

The Big Sioux River bisects the Coteau des Prairies longitudinally. It originated as an interlobate stream that flowed southward down a narrow ice-free belt of country between two major glacial lobes.

Pleistocene animal and plant life in South Dakota is represented by very meager collections. The forms that have been identified indicate subarctic floras similar to other floras in the same belt of latitude, and faunas consisting of large mammals and invertebrates that are quite similar to far better known assemblages collected in Nebraska.

SCOPE AND PURPOSE OF STUDY

The region herein described embraces roughly the eastern half of the State of South Dakota, including all of that part of the State overridden by glacier ice at one time or another in the Pleistocene epoch. The map, plate 1, shows the western and southern limit of glaciation as a line roughly parallel with the Missouri River, trending southward from Corson County to the vicinity of Pierre, and thence southeastward into Nebraska. The glaciated area embraces approximately 34,000 square miles, of a total area of 77,615 square miles constituting the State as a whole.

The present report is one of the results of the Missouri Basin studies made by the Geological Survey as a part of a general governmental program of improvement within the drainage basin of the Missouri River. The governmental program includes the construction of more than 100 dams across the Missouri River and its tributaries, the cutting of hundreds of miles of irrigation canals, and the building of a number of stations for generating hydroelectric power. The benefits expected to accrue from this overall project include the control of flood waters, the production of a large volume of electric power, the improvement of navigation on the lower Missouri River, and the irrigation of extensive tracts of land at present only marginally arable.

The dams now under construction are being built by the Corps of Engineers, U. S. Army, and the Bureau of Reclamation of the Department of the Interior. The Geological Survey's part in this program consists of studies of the areal geology of specially important parts of the Missouri River basin, followed by the publication of maps and reports through which the information gathered in the field is made available for use in the construction projects and for public use generally.

The Geological Survey takes the point of view that these areal studies should not be confined solely to fulfilling apparent immediate engineering needs, but should provide in great detail all the geologic information obtainable, of whatever kind. This policy probably will result in greatly increased usefulness of the maps and reports and through it information will be obtained, some of it of immediate practical use, the existence of which is unsuspected before the field study begins. Accordingly much of the geologic field mapping is being done in detail on air photographs, scale 1: 20,000, and the maps are published, as they are completed, in quadrangle units, some on a scale of 1: 62,500, each embracing 15 minutes of latitude and longitude, and others on a scale of 1:24,000, embracing 7.5 minutes in each direction.

Because a large part of the Missouri River basin and nearly all the territory immediately adjacent to the river itself is covered with glacial drift, much of the areal geologic field work undertaken in this program is concerned with the mapping of glacial features. When the Geological Survey's program was set up in 1946 it was thought desirable to provide for reconnaissance glacial studies in South Dakota, North Dakota, and Montana, in order to create a framework of regional information into which the detailed quadrangle mapping could be fitted.

The present report is the result of such a reconnaissance study, within the limits of South Dakota. Its purpose is to describe the glacial features of the State, to identify and briefly describe the layers of glacial drift and other materials exposed at the surface, to correlate these layers with those exposed in adjacent States, and to reconstruct the general outline of the history of South Dakota during the Pleistocene epoch.

FIELD WORK AND ACKNOWLEDGMENTS

This report is the result of four seasons' field study, carried on during the summers of 1946, 1947, 1948, and 1949. The 1946 season was devoted largely to reconnaissance along the southern part of the Missouri River within the State, and in the southeastern part of the State generally. During the three subsequent seasons systematic mapping was undertaken. Mapping was done largely by automobile road traverse with inspection of exposures in road and railroad cuts, supplemented by foot traverses in dissected areas such as the Missouri River trench and the valleys of other streams. The field data were plotted on planimetric county maps, scale half an inch to the mile, prepared by the South Dakota State Highway Commission. The data were later transferred to the base map of South Dakota, scale 1:500,000, published by the U. S. Geological Survey (see pl. 1 in this report).

County photo-index maps, consisting of air-photograph mosaics, were extensively used in the field, and much time between field seasons was spent in stereoscopic study of air photographs, scale 1:20,000, which proved to be of great aid in the identification and interpretation of glacial features, and in the location of exposures for later examination in the field. At one time or another air photographs covering the entire glaciated part of the State were inspected.

In August and September 1950, a rapid field check of critical exposures was made.

During the field work, conferences were held from time to time with personnel of the U. S. Geological Survey, Army Engineers, Bureau of Reclamation, and Department of Agriculture, and also with personnel of the State geological surveys of South Dakota, Iowa, Nebraska, and North Dakota, and with other scientists interested in local Pleistocene problems. Much benefit was derived from these conferences, especially as to the correlation of stratigraphic units in South Dakota with those in other States.

The writer was assisted in the field during 1946 by W. R. Hansen, during 1947 by D. R. Crandell, during 1948 by R. F. Brown, and during 1949 by Margaret C. H. Flint as a volunteer. During one or more of these years he benefited greatly from field conferences with W. E. Benson, C. R. Warren, H. E. Simpson, and D. R. Crandell, all of the Geological Survey and all chiefs of field parties engaged in detailed mapping of specific areas within the Dakotas.

The present report and the map accompanying it have been materially improved by the use of data furnished by many agencies, all of which gave willing and cordial cooperation. Acknowledgment of such aid is due principally to these organizations and individuals: South Dakota Geological Survey (E. P. Rothrock, C. L. Baker, Brewster Baldwin, and B. C. Petsch), Nebraska Geological Survey (E. C. Reed and G. E. Condra), Iowa Geological Survey (H. G. Hershey, R. V. Ruhe, A. C. Trowbridge), North Dakota Geological Survey (W. M. Laird), U. S. Department of Agriculture, Division of Soil Survey (James Thorp, Guy D. Smith, W. I. Watkins, C. A. Mogen), U. S. Army, Corps of Engineers, Fort Randall Project (John A. Trantina), U. S. Soil Conservation Service (Glenn Avery, O. J. Scherer, Vernon Moxon), Production and Marketing Administration, Photo Laboratory (Neil P. Berney), Omaha Drilling Company (Maurice E. Kirby), U. S. Bureau of Reclamation (V. A. Means), South Dakota Agricultural Experiment Station (F. C. Westin).

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Because an area of about 34,000 square miles was mapped during only four field seasons and because very little subsurface information could be obtained, it is apparent that not all the results of the study may be correct in detail. However, as the main purpose of the investigation was to correlate the glacial drifts of South Dakota with those in adjacent States, special attention was given to correlation, and close liaison was maintained with geologists working in contiguous regions. As a result, it is believed that, whereas future detailed mapping will modify the positions of boundaries shown on the accompanying map, and may even change the correlation of drift sheets with those in other regions, the correlations made are reliable within the limits of present knowledge of glacial stratigraphy.

Aside from the improvements that will accrue from detailed mapping, several refinements and new techniques can be effectively used in the further study of the Pleistocene of South Dakota. Interpretation of the logs obtained from systematic test-boring traverses in little-dissected areas, collection and analysis of fossil pollens from lake and swamp deposits, and refinement of lithologic-provenance analyses of the stones in the drift will radically improve our knowledge of the stratigraphy of the region. At present the known data are confined to the interpretation of relatively few, shallow exposures.

EARLIER STUDIES

Perhaps the earliest published mention of Pleistocene features in South Dakota is contained in a report by George Catlin (1840, p. 144–145), who made an ethnologic expedition into the Dakotas only 30 years after the explorations of Lewis and Clark. Catlin's vivid description of the Coteau des Prairies (p. 6) is followed by this inference:

> The direction of this ridge clearly establishes the course of the diluvial current in this region, and the erratic stones which are distributed along the base I attribute to an origin several hundred miles northwest from the Côteau. . . .
>
> The surface of the top and the sides of the Côteau is everywhere strewed over with granitic sand and pebbles, which . . . show clearly, that every part of the ridge has been subject to the action of these currents. . . .

Written before the theory of the glacial origin of the drift had reached America, these paragraphs apparently are based on the older concept of a vast flood or current of water. With this single exception, Catlin's inferences are in accord with modern beliefs.

The next significant observation of Pleistocene features, contained in the historic record, was made by an engineer, G. K. Warren, who made a reconnaissance shortly after the end of the Civil War, and prepared a report on certain rivers west of the Mississippi. In it he (Warren, 1869, p. 311) stated three major generalizations: that the Missouri River marks the southwestern limit of the glacial drift, that the direction of flow of the glacier ice near its border was toward the southwest, and that the Missouri River originated as a stream flowing along the margin of an ice sheet. If minor modifications are disregarded, all three generalizations have stood the test of time; subsequent investigations have confirmed them.

In 1883 the Geological Survey published a report by T. C. Chamberlin (1883, p. 388–395, pl. 35) on the drift border between the Atlantic Coast and the Missouri River. This report outlined the trend of the drift border in South Dakota and traced some of the more conspicuous end moraines in the eastern part of the State. The data given were based in part on the work of J. E. Todd, who had begun a study of the glacial features of South Dakota about 1883. This study continued for many years and led to the publication by the Geological Survey of 2 bulletins, 2 water-supply papers, and 7 geologic folios, as well as to publication of papers in various journals, the last appearing in 1914.

A comparison of three glacial maps of the State compiled by Todd is a key to the progress of study by him. The published maps are: Todd, 1896, pl. 1; 1899, pl. 1; and Hard, 1929, fig. 5. The last map, although not compiled by Todd himself, nevertheless, within the limits of South Dakota, was based largely on his work.

Todd's work was concerned mainly with topographic features and with drift exposed at the surface. Published information on the subsurface Pleistocene stratigraphy is mainly the work of Darton, a by-product of his study of the artesian water resources of the region. Darton's compilation (1896; 1897; 1905; 1909) of the logs of many deep wells drilled during the settlement of east-central South Dakota continues to be the best available source of subsurface information both on the bedrock and on the Pleistocene deposits. As a result of his field work, Darton compiled a generalized topographic map of the State. Although never published, this map is an important and useful source of information. It is the chief source from which the map, plate 2 in the present report, was compiled.

In 1912 Leverett made a rapid reconnaissance study of the drift in northeastern South Dakota, but the results were not published until 1932, when they were incorporated into a report on the Pleistocene of Minnesota (Leverett, 1932). Features in the extreme northeast corner of South Dakota, related to the glacial Lake Agassiz, were mapped and described by Upham (1895).

In 1929 Hard (fig. 5, p. 24) published a detailed report on a part of the James River lowland immediately north of the northern boundary of South Dakota. This report contains information pertinent to the adjacent area in South Dakota, as well as a map (the work of O. A. Ljungstedt) of the drift border and end moraines in South Dakota, compiled from all earlier sources.

The South Dakota Geological Survey has published many reports on the glacial geology of specific areas, mostly concerned with sand and gravel deposits and with municipal water supplies, as well as reconnaissance reports on three counties.

In 1945 Searight published a brief summary of some of the glacial features of northeastern South Dakota (Searight and Moxon, 1945). This publication amplified Leverett's reconnaissance and made progress in the differentiation of the drift sheets in that part of the State.

The publications mentioned constitute the principal contributions to Pleistocene research in South Dakota that were published at the time the present author began his study.

GEOGRAPHY

TOPOGRAPHY AND DRAINAGE

Eastern South Dakota is crossed each year by tens of thousands of tourists en route to the mountains farther west. To many of them the region seems monotonous and "flat." To be sure, the maximum relief is no more than a thousand feet, and throughout considerable areas the local relief is no more than a few tens of feet. Nevertheless the topography of eastern South Dakota possesses both variety and systematic arrangement. This is rarely apparent to anyone moving at fifty miles an hour in a train or an automobile or to one with an unpractised eye. But to the traveler who moves at a slower pace and notes the subtle details of a surface by no means "flat," the terrain reveals its character and history.

Although it does not show details, the topographic map (pl. 2) pictures the major topographic features of eastern South Dakota and the country immediately adjacent to it. Reference to the map will aid most readers in following the regional description given in the text.

In this region the most important physical boundary separates the Central Lowland from the Great Plains. Trending from north to south about midway between the James River and the Missouri, this boundary, unfortunately not everywhere distinct, is a belt of country that marks a transition from the relatively moist lowland to the subhumid plains.

This boundary, and others within the region, are considered systematically in the description that follows. As far as possible the description conforms with the subdivisions adopted by the U. S. Geological Survey and represented on a map, Physical Divisions of the United States (scale 1:7,000,000) prepared by Nevin M. Fenneman in cooperation with the Physiographic Committee of the U. S. Geological Survey, and published by the Survey, in 1930. However, this map was compiled before the areal relations and surface history of this region were as fully understood as they now are. Therefore, in the present discussion some new subdivisions are introduced and emphasis on the various boundaries is shifted somewhat, in accordance with up-to-date knowledge. The physical divisions of South Dakota as they are now understood are shown in figure 1. The boundaries west of the Missouri River are based in part on a map by Rothrock (1943, p. 8).

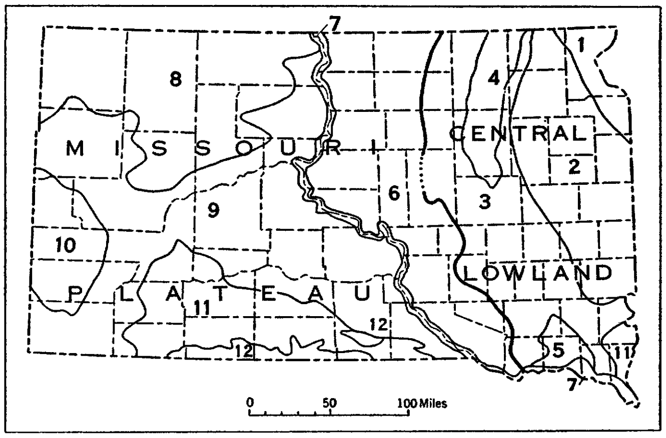

FIGURE 1.—Physical divisions of South Dakota. 1, Minnesota River—Red River lowland; 2, Coteau des Prairies; 3, James River lowland; 4, Lake Dakota plain; 5, James River highlands; 6, Coteau du Missouri; 7, Missouri River trench; 8, northern plateaus; 9, Pierre hills; 10, Black Hills; 11, southern plateaus; 12, Sand Hills.

MINNESOTA RIVER–RED RIVER LOWLAND

The extreme northeastern part of South Dakota, including parts of Roberts, Grant, and Deuel Counties, is included in the broad depression drained southeastward by the Minnesota River and northward by the Red River. This depression is referred to here as the Minnesota River—Red River lowland; most of it lies within Minnesota and North Dakota. At least 50 miles in width, the depression has the appearance of a broad, rather shallow river valley (pl. 2) 1,000 to 1,100 feet above sea level, and indeed it is believed to have been excavated by a large northward-flowing stream and subsequently enlarged by glacial erosion. It is now so thoroughly covered with glacial drift that bedrock is exposed only here and there in the sides of steep-walled valleys incised into the lowland.

In North Dakota and Minnesota the floor of the lowland is nearly flat; its most conspicuous features are low, narrow beach ridges and other strand lines made by glacial Lake Agassiz, whose southern part formerly covered this area.

Near the point at which South Dakota, North Dakota, and Minnesota meet, the lake floor narrows and funnels into a capacious, steep-sided trench, from less than a mile to more than 2 miles wide and about 100 feet deep. This trench was cut into the lowlands by the stream fed by overflow from Lake Agassiz; hence it is a former great spillway channel. Its southeastern part is drained today by the Minnesota River to the Mississippi; its northern part is drained by the Bois de Sioux River to the Red River. Hence the divide between drainage to the Gulf of Mexico and drainage to the Arctic Ocean lies across the northern part of the trench at the town of Browns Valley, Minn., midway between two elongate lakes, Lake Traverse and Big Stone Lake. So low is it that slight fluctuations in the levels of these lakes result in discharge at times toward the Gulf and at other times toward the Arctic. The surface of Big Stone Lake, 966 feet above sea level in 1915, is the lowest part of South Dakota.

West of the trench with its elongate lakes, the lowland, exclusive of incised tributary valleys, has an average local relief of less than 20 feet. The surface is that of ground moraine, merging into barely perceptible broad, swell-like, end-moraine ridges. Only one of these end moraines is conspicuous—that in T. 120 N., R. 47 W., Grant County. Here the ridge narrows to less than half a mile in width and its crest rises to a height of 100 feet above its base. Known in South Dakota as Mount Tom, this ridge trends southeastward into Lac qui Parle County, Minn., where it bears the name of Antelope Hills.

Within South Dakota the drainage of the lowland flows from the high Coteau des Prairies eastward to the trench, with minor modifications imposed by the end-moraine ridges and by the channels cut by outflowing water escaping from the glacial Lake Agassiz.

COTEAU DES PRAIRIES

SURFACE EXPRESSION

A massive highland standing between the Minnesota River—Red River lowland and the James River lowland, the Coteau des Prairies is easily the most conspicuous single topographic feature of eastern South Dakota. Its eastern slope is a striking escarpment which, in its northern part, reaches a height of 800 feet and has an average slope of about 200 feet per mile. Its western slope is less conspicuous because the top of the coteau slopes gently westward and because the lowland west of the coteau has a somewhat higher altitude than the lowland east of it. Both slopes are unusual in that they are nearly devoid of indentations made by streams. Their comparative smoothness and linear continuity are conspicuous, and are fairly well shown on the map, plate 2.

The French explorers and fur traders named this highland. In 1843 J. N. Nicollet described it, when seen from the low country to east or west, as "looming as it were a distant shore" (Upham, 1895, p. 37). Catlin (1840, p. 144–145) who saw the Coteau des Prairies in 1835, described it thus:

> This wonderful anomaly in nature, which is several hundred miles in length, and varying from fifty to an hundred in width, is undoubtedly the noblest mound of its kind in the world: it gradually and gracefully rises on each side, by swell after swell, without tree, or bush, or rocks, . . . and is everywhere covered with green grass, affording the traveller, from its highest elevations, the most unbounded and sublime views of—nothing at all,—save the blue and boundless ocean of prairies that lie beneath and all around him, vanishing into azure in the distance, without a speck or spot to break their softness.

The description is a good one. The Coteau des Prairies is a flatiron-shaped plateau some 200 miles long, pointing north and festooned with end moraines. The point, nose, or prow of the flatiron lies on the boundary line between Marshall County in South Dakota and Sargent County in North Dakota, and affords a magnificent view outward over the lowlands to the east, north, and west. With an axis trending a little east of south, the coteau broadens somewhat toward the south. Although its western margin in South Dakota becomes progressively lower and less distinct southward, the coteau is still fairly well defined in the southeastern corner of the State. Its eastern margin becomes less distinct as it passes across the southwest corner of Minnesota and enters northwestern Iowa. There it merges imperceptibly into the general upland surface of that region. On the south, likewise, the coteau merges into the general upland surface.

This gradual decrease in emphasis toward the south is partly the result of decreased relief. Along its northeastern margin, in Grant and Roberts Counties, the coteau reaches extreme altitudes exceeding 2,000 feet. In Brookings and Moody Counties, however, the highest points hardly exceed 1,800 feet. It is noteworthy that the western margin of the highland is generally 100 to 200 feet lower than the eastern. In other words, the surface of the coteau slopes westward. The slope is more conspicuous on a topographic map than on the ground, because the end moraines and stream valleys that diversify the surface produce an effect of irregularity that obscures the regional slope.

The topography of the Coteau des Prairies exhibits a rough linearity in directions nearly parallel with the scarplike margins of the highland. This results from the presence of several nearly parallel end moraines which lie along both margins, diverging slightly toward the south from a knotlike cluster at the point of the flatiron. The moraines were built along the lateral margins of two lobes of glacier ice held apart by the wedge-shaped highland between them.

Only one large stream, the Big Sioux River, drains the Coteau des Prairies. The Big Sioux has its origin in southwestern Roberts County, only 40 miles south of the point of the flatiron, and flows southward to the Missouri near Sioux City, Iowa, along a path that approximates the central axis of the coteau. As far south as Sioux Falls this unusual course seems to have been inherited from one of the glacial ages, when glacial melt water flowed southward, confined between the two glacier lobes that flanked the coteau. Most of the streams tributary to the Big Sioux enter the main stream from the east; very few enter it from the west, an element in the stream pattern that likewise is a result of the glacial history of the coteau.

The surface of the Coteau des Prairies is dotted with lakes, both perennial and intermittent; the largest are 5 to 10 miles in length. Unlike the minor streams, these lakes are more abundant west of the Big Sioux River than east of it. Many occupy parts of former valleys that have been blocked by glacial drift and have therefore ceased to be drainage ways.

GENERAL GEOLOGY

The Coteau des Prairies is a plateau—an erosion remnant, irregularly covered with glacial drift, that owes its partial isolation to the cutting of capacious stream valleys northeast, northwest, and southwest of it. It is only one part of a much more extensive plateau that continues northward through North Dakota into Manitoba and Saskatchewan. North of South Dakota, however, the plateau lacks a western escarpment sloping to a wide lowland. Instead it is broadly benchlike, having an escarpment only at its eastern margin: the Manitoba escarpment (Upham, 1894, p. 235–246; 1895, p. 36–42, 102–105) overlooking the lowland drained by the Red River. A brief description of the plateau and escarpment is necessary to an understanding of the Coteau des Prairies, its continuation in South Dakota.

For more than 40 miles northward from the northern tip of the Coteau des Prairies there is no escarpment. Probably this wide gap, as will be shown, represents the valley of a large ancient river, now occupied only in part by smaller streams. North of the present Sheyenne River the escarpment reappears. Its altitude there is 1,400 to 1,500 feet, 500 to 600 feet higher than the floor of the Red River valley to the east. Its rate of slope varies between 50 and 100 feet per mile. Broken only by minor streams, the escarpment continues northward to the international boundary, where it is locally known as the Pembina Hills or Pembina Mountains. In southern Manitoba the escarpment is interrupted by a 60-mile gap, now occupied in part by the eastward-flowing Assiniboine River, which has cut a trench several hundred feet deep into the plateau west of the escarpment. The escarpment south of the gap is locally known as the Tiger Hills and Brandon Hills; north of the gap it carries the local name of the Riding Mountain. It is steep, and its crest stands 500 to 1,000 feet above the Red River. The broad gap, like that in southern North Dakota, is believed to mark the preglacial path of a large eastward-flowing stream.

Trending northwest, the escarpment lies west of Lake Winnipegosis, where it carries the local name of Duck Mountain, and continues northward past the Saskatchewan River.

The escarpment and plateau are so thoroughly covered with drift, and so few subsurface data are reported from borings through the drift, that the character of the underlying material can be indicated only in general terms. It is known, however, that the plateau is a bedrock feature and the main form has not been obscured by the irregular blanket of drift that mantles it. The segment of the escarpment and plateau that lies in western Manitoba consists of Mesozoic strata ranging from sandstone of the Lower Cretaceous (Swan River group, of Canadian geologists), which is exposed in places at the base of the escarpment, upward through the Ashville, Favel, Vermilion River, and Riding Mountain formations of Canadian usage, the latter formation having a total thickness of more than 1,100 feet. This sequence (Wickenden, 1945, p. 5–50) has been regarded as approximating the Graneros shale (Ashville), Greenhorn limestone and Carlile shale (Favel), Niobrara formation (Vermilion River), and Pierre shale (Riding Mountain).

At Deloraine, Manitoba, on the plateau about 70 miles west of the escarpment, a drill struck bedrock beneath about 90 feet of drift (Tyrrell, 1892, p. 215E). This thickness of drift constitutes only a small proportion of the height of the escarpment. Other evidence that bedrock lies close to the surface is present in the Tiger Hills (Johnston, 1934, p. 4).

In North Dakota a similar relationship has been inferred. The plateau west of the escarpment has been described as a much-dissected bedrock area of considerable relief, irregularly covered after dissection, with drift averaging 150 to 300 feet in thickness (Leonard, 1930, p. 16; Barry and Melsted, 1908, p. 142–145, 151). The bedrock crops out in valleys at the base of the escarpment. Over much of the plateau the drift is now regarded as thinner than was formerly believed; in northeastern Cavalier County (Barry and Melsted, 1908, p. 144), near Lakota (Nelson County), and south of Devils Lake in Benson County, the bedrock is at or close to the surface (W. M. Laird, North Dakota State Geologist, written communication).

The wide variation in thickness of the drift is illustrated by the fact that at Michigan City, in Nelson County, 12 miles west of the escarpment, 25 test holes showed an average depth to bedrock of only 30 feet, whereas at Hope, in Steele County, 6 miles west of the escarpment, the drift is 150 to 200 feet thick (P. E. Dennis, written communication).

The escarpment and plateau owe their existence to lithology and structure, at least in part. In Manitoba the bedrock strata are believed to dip southwest (Wickenden, 1945, p. 52) at a rate of 6 to 10 feet per mile (R. T. D. Wickenden, written communication). Similar relations are inferred in North Dakota (W. M. Laird, written communication; Barry and Melsted, 1908, p. 162). In South Dakota a westward dip of a few feet per mile, inferred by Darton (1909, p. 87, 90, 123) from the records of deep wells in the Coteau des Prairies, is perhaps also reflected by the southwesterly slope of the upper surface of the coteau and by bedrock exposures in the Missouri River trench between Vermillion, S. Dak., and Sioux City, Iowa (Todd, 1908, figs. 5, 6; Petsch, 1946, profile in pocket).

The inference that the escarpment and plateau have a lithologic and structural origin gains some support from evidence that they are capped by beds, within the Pierre shale, that are slightly more resistant to erosion than the main body of the shale. In Manitoba the uppermost part of the Riding Mountain formation of Canadian geologists, possibly equivalent to the Pierre shale, is a siliceous shale harder than the beds underlying it (Wickenden, 1945, p. 47–49). It is not unlikely that this hard shale forms the bedrock surface under much of the plateau. The existence of a resistant cap in North Dakota has been implied (Barry and Melsted, 1908, p. 178) although no proof of it has been offered. In parts of the Coteau des Prairies in South Dakota the relatively resistant chalky Mobridge member of the Pierre shale may constitute the cap rock beneath the drift (Searight and Moxon, 1945, p. 6).

Only the acquisition of more stratigraphic data than are now available can form an adequate basis for a decision as to whether or not the plateau owes its existence partly or wholly to the presence of one or more resistant beds acting as cap rock.

The Coteau des Prairies, like its northern continuation, is underlain by Cretaceous strata, although it is very thoroughly mantled with drift. Dark-colored shale, probably the Carlile, crops out in the west wall of the Minnesota River trench in Roberts County, S. Dak., nearly opposite the town of Browns Valley, Minn., at an altitude of about 1,000 feet (Rothrock, 1934, p. 20–21). Shale, believed to be Pierre shale, crops out in several small valleys at the base of the western slope in Marshall and Day Counties, at about 1,400 feet (Rothrock, 1935, p. 9). At Iroquois, Kingsbury County, near the west base of the coteau, the same bedrock occurs in a well at about 1,350 feet (Todd, 1904b, p. 2). On the top of the coteau, in Marshall County, flat-topped buttes north of Roy Lake and near the northern tip of the plateau suggest that bedrock is close to the surface at 1,900 to 2,000 feet, though inspection of the shallow exposures in them revealed only drift. These data suggest, although they do not prove, that the bedrock surface within the mass of the coteau has a relief of 500 to 600 feet.

Information from well records suggests considerable variation in the depth of the bedrock surface beneath the drift. A boring at Bristol, Day County, altitude about 1,770 feet, penetrated a complex section of 370 feet of drift before striking bedrock (M. E. Kirby, written communication). A boring at Webster, 11 miles east of Bristol, altitude about 1,840 feet, passed through 380 feet of drift overlying bedrock (Rothrock, 1943, p. 19). A boring near Bryant, Hamlin County, penetrated three layers of till and ended at a depth of 320 feet without reaching bedrock (Searight and Moxon, 1945, p. 17). Although these three borings reveal great thicknesses of drift, a well at DeSmet, Kingsbury County, on top of the coteau at altitude 1,740 feet, reached bedrock (shale) at a depth of only 104 feet (Todd, 1904b, p. 2).

The foregoing inadequate, scattered information suggests that the surface of the bedrock beneath the drift has a greater relief than the surface of the drift itself. However, opinions have differed as to the relative importance of drift and bedrock in determining the topographic prominence of the coteau. Upham (1884, p. 601; 1895, p. 38) stated that

> The altitude of the Coteau des Prairies is due to the Upper Cretaceous formations, here spared and left by preglacial erosion as a broad and high ridge, upon which the drift deposits lie, rather than to extraordinary thickness of the drift beyond that which it commonly has on the lowlands at each side.

A different opinion was stated by Leverett (1932, p. 11):

> The prominent Coteau des Prairies, in the southwestern part of Minnesota, was for some time interpreted by geologists as owing its great prominence chiefly to Cretaceous strata, which were thought to fill in the gaps between the high areas of Sioux quartzite noted above. But studies by Meinzer along the Coteau and later studies by the present writer have shown that the filling between the quartzite areas consists largely of glacial material, borings having been put down to depths of 400 to 500 feet without encountering rock. The quartzite areas thus seem to stand above the general level of the bordering Cretaceous formations, much as the Baraboo quartzite of southern Wisconsin stands above the surrounding Paleozoic formations. The highest altitude reached by the Cretaceous of southwestern Minnesota may not exceed 1,300 feet. The Coteau surface has an altitude of 1,700 to 1,900 feet or more along the highest part of its crest in Minnesota. The morainic ridges of Wisconsin age, which to some extent follow the crest of the Coteau, stand only about 50 feet above the district outside. It thus appears that the great

bulk of the glacial material on the Coteau was laid down in earlier stages of glaciation.

This point of view was adopted by Rothrock (1943, p. 19–20). However, the subsurface data adduced by Meinzer (Hall, Meinzer, and Fuller, 1911, p. 233–236, 36–37) and referred to in the quotation from Leverett are scattered, and are confined to the extreme eastern part of the coteau. Meinzer's inference is more cautious than that of Leverett, although it is based on the same data. It consists essentially of a modification of Upham's view. "It still seems altogether probable," he wrote (Hall, Meinzer, and Fuller, 1911, p. 233), "that the elevation of the coteau is to large extent caused by older formations * * *." He visualized the late-preglacial coteau as a high, dissected bedrock area which, when overlapped by the margins of successive glaciers, was built up by glacial deposition between and upon the preexisting bedrock hills. The hills acted as a barrier against and within which the ice, flowing slowly near its margins, lodged its basal load of drift.

Admitting that the matter cannot be fully explained until many more subsurface data have been assembled, the present writer believes Meinzer's view is essentially correct. The successive glaciers packed the small draws and larger valleys full of drift and thereby smoothed the formerly ragged margins of the coteau. It seems unlikely that the smooth slopes of the coteau are to any considerable extent the result of glacial erosion, at least during the Wisconsin glacial age, because at most places along the lateral margins of the glacier lobes that were separated by the coteau, the direction of glacier flow had a component toward the coteau slopes that was stronger than the component parallel with them.

The very slight dissection of the coteau slopes that is evident today is occurring chiefly in the drift itself; only locally has it denuded the bedrock of its cover of glacial deposits. The present-day dissection is the beginning of a process that in time could reestablish the ragged outline and deep indentations that probably existed before glaciation.

SUBDIVISIONS

The standard map of the physical divisions of the United States [1] shows a hairpin-shaped boundary traversing the Coteau des Prairies and separating the western lake section, a "young glaciated plain," from the Dissected Till Plains. In South Dakota these two sections correspond essentially with the areas in which the Cary and Mankato drifts and the Iowan and Tazewell drifts, respectively, are at the surface, as shown on the geologic map, plate 1. This boundary is a valid one, though on the ground it is far less conspicuous than the boundary that separates the Coteau des Prairies from the lowlands at its base. Accordingly the coteau can be thought of as subdivided into the two sections represented in a generalized manner on the standard map.

JAMES RIVER LOWLAND

GENERAL FEATURES

The broad lowland that lies between the Coteau des Prairies and the Coteau du Missouri is here referred to as the James River lowland. It is an arcuate lowland 200 miles long and 50 to 60 miles wide, trending from north to south, and concave toward the east. Throughout South Dakota it is drained southward by the James River, which occupies the central axis of the tract.

Only near its southern end does the lowland possess conspicuous irregularity. In Turner, Yankton, and Bon Homme Counties it is interrupted by a group of ridges described in the following section as the James River highlands. West of these highlands the lowland opens narrowly southward into the Misouri River trench. East of them it opens more widely into the trench through a tract drained by the Vermillion River; it also has a broad eastward protuberance into the valley of the Big Sioux River. The James River itself occupies a narrow valley cut through the highlands. This peculiar pattern of topography and drainage is a result of glacial alterations of preexisting valleys.

The lowland is conspicuously lower than the coteaus that flank it. Its site is believed to have been determined by two ancient major streams that incised broad valleys below the surface now represented by the highest hills of bedrock in the coteaus. Later the valleys were widened and united by glacial erosion and were altered in detail by glacial deposition.

From end to end the general surface of the lowland lies at altitudes of 1,300 to 1,400 feet. Into this surface the James River has cut a steep-walled, rather narrow trench 30 to 100 feet in depth. Apart from the trenches of the James and its tributaries and the glacial Lake Dakota plain, the surface is smoothly rolling, with very broad, low subparallel ridges, trending eastward and lying convex toward the south, and with local relief rarely exceeding 20 to 30 feet and in places no more than 10 feet. The small streams that drain toward the James occupy broad, shallow depressions between the ridges. In detail the ridges and interridge areas are indented by thousands of barely perceptible closed depressions. The ridges are end moraines, built during the shrinkage of a glacier lobe that conformed to the general contour of the lowland.

In three districts this general topographic pattern is interrupted by relatively high isolated hills. They

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[1] Physical divisions of the United States. Scale 1 : 700,000. Prepared by Nevin M. Fenneman in co-operation with the Physiographic Committee of the U. S. Geological Survey (1930).

are higher and steeper than the systematic end-moraine ridges, and their long axes are at variance with the trends of the ridges. All these hills are believed to have cores of bedrock.

One of the isolated hills is in Davison County. It is a knobby ridge 3 miles long, half a mile wide, and 80 feet high; its center lies 5 miles south of the center of the city of Mitchell. Its trend is northwest, in contrast with the northeast trend of the minor end moraines in the vicinity. Although the knobs that form the crest of the ridge consist of drift, bedrock (a sandstone, apparently the Codell member of the Carlile shale), crops out in the middle part of the eastern end of the mass. From this outcrop and from the discordant trend of the ridge, it is inferred that the main body of the hill consists of bedrock. Probably the knolled drift that mantles it was deposited during the latest deglaciation, when the ridge formed a slight reentrant in the margin of the glacier and thereby localized sharply the accumulation of glacial deposits.

The second isolated group of hills consists of the Redfield Hills, lying south and east of Redfield in Spink County, and Bald Mountain, 6 miles southwest of Redfield. The Redfield Hills consist of a very irregular knobby ridge 8 miles long, 1 to 2 miles wide, and with an extreme height of 80 feet. The trend of the ridge is southwest, whereas the near-by minor end moraines trend south to southeast. Bedrock (the relatively resistant, chalky Mobridge member of the Pierre shale) is exposed in at least three places. It is probable that bedrock constitutes the main mass of the Redfield Hills, beneath an irregular covering of drift.

Bald Mountain is a hill 2 miles long, half a mile to 1 mile wide, and 140 feet high at its highest point. Its surface is marked by many conspicuous knolls. Its long axis trends northward, approximately parallel with the local end moraines. The latter, however, are broad, relatively smooth, and no more than 30 feet high. The surface of Bald Mountain appears to consist entirely of drift, but the similarity of the hill to the Redfield Hills in both trend and surface expression suggests that, like the latter, it has a massive core of bedrock.

The third high hill also lies in Spink County, 20 miles east of Redfield, and extends southward from the town of Doland. It is known locally as Doland Ridge. Low at its northern end, it increases southward to an extreme height of 60 feet and an extreme width of 1½ miles. The ridge is less knobby and irregular than the hills described previously. Drift covers its surface, but dark-gray shale is exposed well down in its southeast and northwest flanks and in a valley just north of Doland. From the altitude and prominence of the ridge, from its southward trend in contrast with the southwest trend of the nearby end moraines, and from the fact that a well at Doland reached bedrock at only 42 feet below the surface, it is inferred that Doland Ridge has a core of bedrock. The core is probably capped by the relatively resistant, chalky Mobridge member of the Pierre shale.

In all three districts—Mitchell, Redfield, and Doland—the isolated hills described are believed to be remnants of major prediversion divides, still prominent despite repeated glacial alteration.

The James River, known to the French fur traders as the Jacques and commonly referred to by the local inhabitants as the Jim, has been called "the longest unnavigable river in the United States." It follows a conspicuously meandering course along the flat floor of its trench, and has an average gradient, within South Dakota, of only 5 inches per mile. In drought years short stretches of it have been known to go dry temporarily. Its tributaries are few and are intermittent throughout the greater parts of their lengths. Most of them are perennial only in their downstream parts. This habit results from the subhumid character of the region, which receives a mean annual precipitation of only 18 to 20 inches. In fact, of the lowland as a whole, more than 10,000 square miles in area, probably more than 80 percent has interior surface drainage (Visher, 1917, p. 36). Most of the immediate surface runoff finds its way into nearby shallow depressions, where it forms temporary lakes that dwindle away and disappear by evaporation. As the impervious, clay-rich drift in which the basins occur inhibits downward percolation, little water disappears from the lakes in this manner.

LAKE DAKOTA PLAIN

The Lake Dakota plain is a part of the James River lowland topographically distinct from the dominantly morainic main part of the lowland because it is the floor of an abandoned lake. It occupies the axis of the lowland from south of Redfield northward into North Dakota. It is about 90 miles long in South Dakota and extends 15 to 20 miles farther in North Dakota. Throughout most of its length it is 25 to 30 miles wide, but it becomes narrow at both ends.

The plain is remarkably flat, having a local relief that in many places is no more than 10 feet. Its general altitude varies from a little more than 1,300 feet near the State line to a little less than 1,300 feet near its southern end. The flatness results from the deposition of sediment in glacial Lake Dakota, a former water body that occupied part of the James River lowland during the last deglaciation of the region. Fine-grained lake-floor deposits filled in the irregularities in the existing morainic surface, thus reducing the relief. The entire area of the Lake Dakota plain is underlain by lake-floor silt, sand, and clay. Only near their southern limit do these sediments fail to mask the gently rolling morainic surface that underlies them.

The plain is dissected by the James River and its tributaries. The steep-sided trench cut by the James is about 30 feet deep near the State line, and increases to about 100 feet near the southern end of the plain. The tributary streams, having steeper gradients than the James, occupy conspicuous trenches only near their mouths. Elsewhere they are incised only very slightly below the general surface.

The pattern of the streams tributary to the James River is different from that of the streams south of the Lake Dakota plain. It was stated that throughout much of the James River lowland the streams have an arcuate pattern related to the broad, swell-like end moraines. In the Lake Dakota plain, in contrast, their general courses are straight rather than arcuate and have a strong component toward the south. Apparently these streams assumed their courses on the south-sloping surface of the abandoned lake floor. As the lake deposits mask the morainic topography beneath them, the end moraines do not control the stream pattern as they do farther south.

The northeastern part of the plain, notably in Brown and Marshall Counties, is diversified by patches of windblown sand having a faintly hummocky topography.

JAMES RIVER HIGHLANDS

The features referred to in this paper as the James River highlands consist of a group of three ridges of drift-covered bedrock that partially block the southern end of the James River lowland. They owe their positions and general outlines to a series of drainage changes. During one or more of the glacial ages, new stream valleys were cut and old ones were abandoned but not obliterated. The ridges are the most conspicuous of the cut-up intervalley areas that still remain. From east to west the highlands are Turkey Ridge, James Ridge, and Yankton Ridge. All owe their prominence chiefly to the fact that they are underlain by the relatively resistant chalk and limestone of the Niobrara formation.

Turkey Ridge, the largest, is more than 40 miles long by 10 miles wide, and stands more than 300 feet higher than the surrounding country. Trending southeast, it forms the divide between the nearly parallel James and Vermillion Rivers. The northeast flank of the highland has a gentler and less conspicuous slope than the southwest flank. This is because the northeast flank slopes down to an ancient valley (now occupied by the Vermillion River) that has been modified only by glaciation, whereas the southwest flank slopes down to a trench whose sides have been undercut more recently by the James and Missouri Rivers. Indeed, between Volin and Vermillion the flank of Turkey Ridge is a steep bluff that has been undercut by the Missouri since the latest glaciation of the district.

Turkey Ridge has a curious drainage pattern. The principal stream, Turkey Creek, bisects the main part of the highland longitudinally, flowing for nearly 20 miles through a narrow canyon as much as 200 feet deep. The stream has an interlobate origin. That is, it began to flow down the surface of the ridge at a time when the lowlands on the two sides of the ridge were occupied by lobes of glacier ice that stood higher than the top of the ridge itself. The stream's course was therefore guided by retaining walls of ice until it intrenched itself into the glacial drift and bedrock.

Turkey Ridge consists of chalk of the Niobrara formation overlain in places by Pierre shale. In the canyon of Turkey Creek the Smoky Hill chalk member of the Niobrara formation is exposed beneath the Sharon Springs member of the Pierre shale. Both chalk and shale crop out also in places along the steep west flank of the ridge. Elsewhere, however, exposures are rare because the bedrock is mantled with 30 to 200 feet of glacial drift. The surface expression of the drift consists of a succession of end moraines draped, as it were, across the top and along the sides of the highland.

James Ridge, the smallest of the James River highlands, is west of the James River a few miles above its mouth. It is 9 miles long, 1½ miles wide, and 100 to 260 feet high. Its long axis trends southeast, parallel with the axis of Turkey Ridge. At its southern end shale crops out, and near its northeastern end shale is exposed overlying chalk; apparently these strata constitute the bulk of Turkey Ridge. Glacial drift with a conspicuously morainic topography covers the ridge and is banked massively against its northern and eastern sides, so that at first view the highland conveys the impression of a conspicuous end moraine. Individual end moraines are present, but they are secondary to the bedrock ridge and their positions were determined by it. Well logs show that the drift on and around the ridge is very thick.

The third highland, Yankton Ridge, forms the northern side of the Missouri River trench from Yankton westward for 16 miles, reaching an extreme height of nearly 500 feet above the river. Its southern side is steep, whereas its northern slope is gentle. In this asymmetry it resembles Turkey Ridge and for a similar reason, as Yankton Ridge slopes on its north side to an ancient stream valley, abandoned and partly filled with glacial drift. Also like its neighbors, Yankton Ridge has a massive core of chalk (Niobrara) overlain by Pierre shale. The two formations are well exposed at an abandoned cement plant 4 miles west of Yankton. The bedrock is veneered with drift except along the Missouri River bluffs, where the chalk is almost continuously exposed. The drift is relatively thin.

In addition to the three ridges described, a fourth and smaller ridge, about 6 miles long, elongate eastward, and about 100 feet lower than James Ridge, occupies the southern part of T. 95 N., R. 57 W. The town of Lesterville stands on its summit. Although proof is lacking that this ridge consists of bedrock, it is believed to be a bedrock ridge because of two facts. One is that end moraine is "draped" around it in such a way as to suggest an obstacle to glacier flow similar to the obstacles formed by James, Yankton, and Turkey Ridges. The other fact is that immediately west of Lesterville this ridge is cut by a valley, incompletely filled with drift, that possesses steep side slopes and a winding ground-plan pattern similar to those of predrift valleys in other parts of the State where bedrock is known to lie at or very close to the surface.

COTEAU DU MISSOURI

The Coteau du Missouri is that part of the Missouri Plateau section of the Great Plains province which lies east of the Missouri River. Its name dates back to the days of the French fur traders. It is the western counterpart of the Coteau des Prairies. Each coteau is an extensive remnant of a former nearly flat bedrock surface that was incised by major streams in the days before the great drainage diversion. The two plateaus are underlain by much the same sequence of strata and are similar in several other respects. Although the Coteau du Missouri is separated from the main body of the Missouri Plateau only by the trench of the Missouri River, the character of its surface is sufficiently distinct to justify separate description.

Considered as a unit, therefore, the Coteau du Missouri in South Dakota is an unevenly dissected plateaulike highland occupying the curving belt of territory, 200 miles long, between the Missouri River and the James River lowland. It is nearly 75 miles wide near the North Dakota boundary, but narrows to a width of about 25 miles in Charles Mix County, at the southern edge of the State. The coteau ends at the southeast corner of that county, where the Missouri River cuts through the escarpment that forms the eastern boundary of the coteau.

Except in a few places the Coteau du Missouri is somewhat less high and has a limiting slope less steep than the Coteau des Prairies, but it continues northward through North Dakota higher and steeper than the part that lies in South Dakota. Although the Coteau du Missouri is considered to end at the Missouri River, the escarpment that forms its eastern margin trends southward with a broad sweep concave toward the east and continues across the Missouri River into Nebraska.

Beneath the glacial drift over much of the Coteau du Missouri the uppermost bedrock formation is the Pierre shale. Deep-well logs show that the bedrock strata dip gently toward the west, with a variable inclination of the order of only a few feet per mile. Comparable strata with a comparable dip underlie the Coteau du Missouri in southern North Dakota also (Hard, 1929, p. 49). However, the Pierre shale is not everywhere the youngest bedrock unit present. Both the escarpment and the plateau west of it vary in height and steepness, and despite the thick and nearly ubiquitous mantle of glacial drift, there is reason to believe that the highest and steepest areas owe their prominence to caps of resistant rock of post-Pierre age.

Unlike the Coteau des Prairies, the Coteau du Missouri lacks a well-defined western escarpment. Its western limit is the trench of the Missouri River, which has cut deeply into the Missouri Plateau and has started innumerable closely spaced tributaries working headward into the high lands east and west of the trench. The western margin of the coteau, therefore, is a belt of intricately dissected country that overlooks the Missouri River trench.

The fact that resistant strata cap the higher parts of the Coteau du Missouri is evident in eastern McPherson County, at the North Dakota State line. There the surface reaches an altitude of more than 2,100 feet, 800 feet above the Lake Dakota plain at its base. In that district the plateau is capped, beneath the drift, by Fox Hills sandstone overlying Pierre shale. The Orient Hills, in southern Faulk County and northwestern Hand County, about 10 miles long and 200 feet high, form a steep escarpment facing east and are undoubtedly underlain by resistant rock. The drift that covers them is so thick, however, that bedrock exposures have not been found in this mass. Southwest of Miller, in Hand County, the plateau increases in altitude to form a great mesa, the Ree Hills, more than 2,200 feet in altitude. The cap rock here, beneath the drift, is a sandstone (Ogallala?). In Jerauld County the escarpment forms a very deep promontory, the Wessington Hills, 1,800 feet in altitude and underlain by a siliceous sandstone referred to the Ogallala formation. The Ree Hills and Wessington Hills together form the highest parts of an extensive upland that extends from Miller at the north to near Chamberlain at the south. The upland appears to be the surface expression either of a very broad, very shallow syncline, or of an apparent structure caused by differences in altitude of the depositional surface of the cap rock.

In this upland as well as in the upland capped by Fox Hills sandstone in McPherson County, the bedrock is mantled with a complex accumulation of glacial drift.

Farther southwest, away from the escarpment, the coteau has other high areas underlain by resistant rocks. A group of high hills near the southeast corner of Charles Mix County, and the prominent buttes, 300 to 400 feet high, known as the Bijou Hills, close to the Charles Mix County—Brule County line, have a thin capping of quartzitic sandstone of Ogallala(?) age. Beneath these local cap rocks the main body of the Coteau du Missouri consists of Pierre shale, which is found in deep wells and is exposed at a number of places in the escarpment.

Less conspicuous than the high areas just mentioned, the low areas are none the less significant, for at least some and perhaps all mark the positions of capacious former stream valleys now buried beneath glacial drift. The low areas are broad, shallow sags, with well-defined lateral limits, that traverse the Coteau du Missouri, in an easterly or northeasterly direction, from the Missouri River trench to or through the escarpment that overlooks the James River lowland (pl. 2).

The most obvious of these sags traverses Hughes, Hyde, and Hand Counties, north of the Ree Hills. It was termed by Todd (1885, p. 392, 393) the Great Ree Valley. At its highest point the axis of this depression is only about 1,750 feet above sea level. Because of its low altitude this sag has been chosen as the route of a projected canal to carry irrigation water from the Missouri trench across the Coteau du Missouri to the James River lowland.

Another sag, broad but less conspicuous than the one mentioned above, traverses the Coteau du Missouri through southwestern Edmunds and Potter and northeastern Faulk Counties. It is difficult to trace because it is interrupted in places by massive end moraines. Partly because of the presence of these moraines, the altitude of the axis of the sag exceeds 1,900 feet at its highest point.

Farther south, three narrower sags traverse the Coteau du Missouri. One is in the northern parts of Brule and Aurora Counties, a second leads eastward across northern Douglas County, and a third, trending northeast, crosses eastern Charles Mix County and southeastern Douglas County.

With the exception of the Great Ree Valley, these topographic low areas merge smoothly into the upland across which they lie; their lateral margins are poorly defined because both low areas and upland have been glaciated and smeared with drift one or more times since the lows were abandoned by the streams that originally cut them. The sags are most conspicuous in their effect on the escarpment of the Coteau du Missouri that faces the James River lowland. In the sectors where three of the sags debouch into the lowland there is, properly speaking, no escarpment at all. Where the escarpment should be, only a long gentle slope leads down toward the lowland. Each slope is apparently the floor of a large abandoned stream valley, modified by glacial erosion and covered with a variable thickness of drift. The two sags traversing Douglas and Charles Mix Counties have no such gaps and slopes because they are blocked by massive end moraines. At these places the position of the bedrock floor beneath the drift can only be conjectured.

The drainage of the Coteau du Missouri is generally symmetrical. The eastern slope drains toward James River, mostly through short, nearly parallel streams. The western part drains toward the Missouri with a more irregular stream pattern. In the northern part of the coteau, in Hyde, Faulk, Edmunds, and McPherson Counties, there is a large area between the heads of these two sets of streams in which the drainage is interior. Here the runoff drains into the many local depressions in the glacial drift.

Here and there throughout the entire Coteau du Missouri, there is interior drainage, but it is far less widespread in the southeastern part than in the northern, for two reasons. The first is that in the southeast the coteau is narrower, a fact that has allowed tributaries of the James and Missouri to work headward into the central area with relative rapidity. The second is that a moister climate in the southeastern part results in greater runoff and hence more vigorous erosion by small seasonal streams, than in the northern region.

Even in the northern part of the Coteau du Missouri, however, some integration of depressions in the drift has taken place. This is evident from the common presence of two or more depressions linked together like a string of beads by narrow streamways.

Despite its seemingly simple pattern, the drainage on the Coteau du Missouri has had a complex history, and some streams now flow in directions opposite to those of streams that formerly occupied the same areal positions.

With the exception of four small areas in Charles Mix County, all the Coteau du Missouri has been glaciated. Much of the more dissected area, especially in the belt close to the Missouri River, lacks a cover of drift, which was thin when deposited and which has since been removed by erosion. The broad upland between the eastern and western slopes of the coteau is largely covered with ground moraine. This mantle of drift has swell-and-swale topography with many shallow depressions, slopes so gentle that in some places they are almost imperceptible, and a local relief of less than 20 feet. Here and there the ground moraine is interrupted by sharply marked belts of end moraine having a relief of 100 feet or more, and with very steep, boulder-covered slopes separating knolls from basins. Many of the depressions in the surface of both ground moraine and end moraine contain intermittent lakes and marshes. Some of these are connected by ill-defined channels that carry lake overflows only during wet seasons.

Nearly flat expanses of sand and gravel washed out from the glacier ice during its melting occupy parts of valleys as well as areas beyond the outer margins of major end moraines.

In parts of the Ree Hills and Wessington Hills, where weak Pierre shale forms steep slopes beneath caps of resistant younger strata, the shale has slumped extensively, large masses of it having slid downslope through considerable distances. In such localities the topography is knobby and irregularly benched in detail. A good accessible example is found in sec. 13, T. 107 N., R. 65 W., immediately south of Wessington Springs.

MISSOURI RIVER TRENCH

The Coteau du Missouri is separated from the main part of the Missouri Plateau by the trench cut and occupied by the Missouri River. Trench is a more descriptive term for this feature than valley, because the cut made by the river into the plateau is deep, generally narrow, and notably steep. It is a very conspicuous relief feature and constitutes a major barrier to east-west travel. As an example, the Missouri River in South Dakota is spanned at only 6 points by a total of 9 bridges. In addition there was but 1 ferry operating during the years 1946–1950.

From North Dakota to the vicinity of Pierre, the trench has an irregularly southward trend. From Pierre to the mouth of the Niobrara River it trends southeast, and from the Niobrara to the Iowa State line it trends nearly east. Throughout South Dakota, therefore, its trend is arcuate, convex toward the southwest. As the general slope of the land is easterly, it is evident that the Missouri River flows partly along the regional slope and partly oblique to it, in a very anomalous relationship.

The floor of the trench, including flood plain and low terraces, averages little more than a mile in width. At places where the river occupies segments of major valleys that antedate the present drainage system, the width increases. Thus, for a few miles south of the North Dakota boundary, the trench is 4 miles wide, between the mouth of the Niobrara and the mouth of the James it is 2 to 3 miles wide, and between the mouth of the James and the mouth of the Big Sioux it is 6 to nearly 10 miles wide.

The side slopes of the Missouri River trench are steep, dissected bluffs ranging in height from 300 to more than 600 feet above the river. Throughout much of the trench the bluffs are about 400 feet high. North of Mobridge they reach 600 feet and between Chamberlain and Wheeler they reach nearly 700 feet. Downstream from Yankton the trench is little more than 300 feet deep.

Between Bon Homme County and the North Dakota State line the Pierre shale is extensively exposed in the bluffs. In places these strata, which are comparatively nonresistant to erosion, have been intricately dissected to form badlands. In others (particularly where the shale contains bentonite) slumping has occurred on a large scale, carrying the upper strata in great masses, some exceeding half a mile in individual length, downslope to the very margin of the flood plain. In many places glacial drift is present in abundance, covering the bedrock slopes. The trench contains a considerable number of terrace remnants at various altitudes.

From Yankton upstream to the North Dakota State line the trench is fringed on each side by a zone of closely spaced, steep-sided ravines that extend several miles back into the plateau. When viewed from the air these zones give the plateau the appearance of being frayed or ravelled at its edges. The zones of ravines are referred to by local inhabitants as "the breaks." The ravines are an expression of the youth of the greater part of the Missouri River trench, whose short, steep, and numerous tributaries have not yet had time to evolve into a simpler system composed of a smaller number of longer and gentler valleys. Downstream from Yankton, where the Missouri River occupies an old broad valley, the breaks, as might be expected, are far less conspicuous.

The Missouri River trench constitutes a dividing line between two kinds of topography. The Coteau du Missouri east and north of the trench reveals the effect of glaciation conspicuously, though on the plateau west and south of it glacial evidence is less conspicuous or is absent altogether. The most obvious difference is that the surface of the Coteau du Missouri, beyond the breaks, is smoother, less dissected, and more nearly flat than the plateau to the west.

The gradient of the Missouri River through South Dakota averages about 1 foot per mile. Erosion and deposition by the river are believed to be approximately in equilibrium (Whipple, 1942). The form of the channel changes from place to place. In the segments of the trench that are comparatively wide, namely, near the North Dakota State line and between the mouth of the James and that of the Big Sioux, the channel has a meandering habit, with a meander belt 2 to 4 miles in diameter. Elsewhere the trench is too narrow to contain meanders of this width. Instead, the channel swings from side to side of the trench, undercutting the bluffs at various points and building crescent-shaped point bars of alluvium at the inner sides of the bends. In places bars are built within the channel itself, creating "split channels". The maps (pls. 1 and 2) show 2 features of the Missouri River that superficially resemble incised meanders. One, Big Bend, lies midway between Pierre and Chamberlain. The other, Little Bend, is at the mouth of the Cheyenne River. Both are isolated features rather than being units in a systematic sequence. It is not likely, therefore, that either of these loops is a meander that has become incised into the surface. Probably the sides of the loops mark the approximate positions of small valleys utilized by the water that established the present route of the Missouri River under glacial conditions. The centrifugal erosive force exerted by the new stream at the sharp bends has smoothed them into the semblance of meanders.

Although the main channel of the Missouri River stands out distinctly in the pattern of the trench floor, bars, both large and small, have created numerous short subsidiary channels. In the spring when the river is in flood, many of these bars are not apparent, but as the summer progresses increasing numbers of them appear as islands. The bars and subsidiary channels, however, are not so numerous as to give the flood plain the braided pattern that characterizes the North Platte, South Platte, and other rivers farther south.

The Missouri River carries suspended in its water a bulky load of sand, silt, and clay, derived from the Pierre shale and other materials exposed upstream and along tributaries. The water is therefore brownish yellow with mud. Even early travellers reported that the Missouri was turbid. Hence, although it is likely that cultivation of the soil in the tributary region has added to the sediment carried by the river, rapid erosion was in progress before the advent of agriculture. Such erosion may have been enhanced by progressive climatic desiccation.

Although both are stream-cut valleys, the Missouri River trench and the James River lowland differ markedly from each other in most respects. The James River lowland is many times wider, somewhat deeper, and smoother in detail, lacking entirely the breaks that characterize the borders of the Missouri trench. The difference is partly one of age, for the lowland is much older than the trench. It is also partly one of glaciation, for the lowland has been repeatedly enlarged and smoothed by glacial erosion along its length and repeatedly coated with a covering of glacial drift. The trench, on the other hand, bears fewer indications of glacial modification even in those places where the glacial effects have not been removed by later rapid erosion.

The peculiarities of the Missouri River in South Dakota—its anomalous relationship to the regional slope, its relatively steep gradient, its narrow trench with youthful side slopes, the distribution of its meanders, and the varying height of its bluffs—are the result of the peculiar manner and recent date of its origin. It is a river forced into existence by glacial blockade, which sealed off the eastern continuations of several large eastward-flowing streams and obliged their waters to seek escape southeastward along a patchwork route improvised from a number of preexisting valleys.

MISSOURI PLATEAU WEST OF MISSOURI RIVER

The Missouri Plateau is the main plateau region from which the Coteau du Missouri has been isolated by the river trench. It is very extensive, for it reaches northward into North Dakota, westward around both sides of the Black Hills into Montana and Wyoming, and southward a short distance into Nebraska. Along the Nebraska-South Dakota State line the Missouri Plateau is overlooked by a rugged north-facing escarpment which marks the northern edge of the comparatively flat High Plains region.

Within South Dakota the Missouri Plateau embraces three regions of distinctive aspect. The most southerly of these is a series of plateaus and broad benches underlain by Cenozoic strata. This region slopes upward from 2,000 feet near the Missouri River trench to more than 3,000 feet near the Black Hills. It is drained by the Keya Paha River and by southern tributaries of the White River. Near the southern edge of the State it is bordered by the Sand Hills region, most of which lies in Nebraska to the south.

The most northerly region is a series of plateaus, benches, and isolated buttes underlain by the Fox Hills sandstone and younger Cretaceous strata. The dissected, steplike surface of this region, too, rises from about 2,000 feet near the Missouri to well over 3,000 feet in the extreme northwestern part of the State. It is drained eastward, chiefly by the Grand and Moreau Rivers.

The third region lies between the two just described. To most local inhabitants it is known as "the west river country." More specifically it has been called the Pierre hills (Rothrock 1943, p. 47), because it is underlain almost entirely by the Pierre shale. It is known also as the "gumbo region" because of the ubiquitous dark plastic clay into which most of the Pierre strata break down as a result of weathering. These strata do not form benches and plateaus as do the younger strata to the north and south. Instead, they are reduced by weathering, mass wasting, and stream cutting to a network of smooth hills and ridges with convex tops. The seemingly endless procession of grassy hills and, in the larger valleys, the extensive exposures of somber brownish and grayish shales combine to give the region a monotonous and rather dismal aspect. The region, no doubt because of the erodibility of the surface rocks, has lower altitudes at comparative longitudes than do the adjacent plateau lands on the north and south. It is drained eastward through the Cheyenne, Bad, and White Rivers.

In a few places the Pierre hills region is surmounted by isolated buttes standing as much as 400 feet above the general surface and visible from distances of many miles. Examples are the Iona Hills in Tripp, Gregory, and Brule Counties, and Medicine Butte in Lyman County. These buttes are capped by Tertiary strata such as form the plateaus farther south. The caps show that such strata extended over much if not all of the Pierre hills region, and that they have been removed, largely by undermining of the weak underlying shales.

In all three regions the major rivers flow eastward, occupying trenches 200 to more than 300 feet deep and meandering along the trench floors, their channels fringed with cottonwood trees. Each river has a well-graded, well-integrated system of tributaries. The pattern of the larger tributaries is normal, but over wide areas the minor tributaries have a pronounced southeast-trending parallelism, well shown on plate 1. This parallelism, present in all three regions as well as in a few areas east of the Missouri River, is most clearly evident in the central or Pierre hills region, probably because the weak rocks in that region are easily eroded and readily assume a pattern impressed on them by minor streams without offering lithologic or structural obstacles of their own. The southeast-trending drainage lines are believed to be chiefly inherited from Pleistocene eolian deposits that formerly covered much of the Plateau.

Glaciation, clearly evident east of the Missouri River trench, has affected only a narrow and discontinuous belt of country west of the river. The glaciated belt reaches a maximum width of 40 miles in Corson County at the north, and narrows to a mere fringe in Lyman County. Evidence of glaciation in Gregory County has not been observed. In contrast with the Coteau du Missouri, the country west of the Missouri River has been affected very little by glacial action even within this narrow belt. The evidence consists chiefly of ice-abraded boulders, foreign to the Dakotas, which lie scattered in patches over the dissected surface.

STREAMS

The positions and directions of flow of nearly all the streams, large and small, in eastern South Dakota have been either wholly determined or strongly influenced by glaciation.

Each of the four major rivers of the region—the Missouri, James, Big Sioux, and Minnesota (including Lake Traverse and Big Stone Lake)—bears the impress of strong glacial influence. Most of the present course of the Missouri River was formed by the diversion of streams, which originally flowed eastward, into a single course directed southeastward. Most of the James River follows the broad depression formed by two old, nearly collinear valleys, one extending northward from the vicinity of Redfield, the other southeastward. The Big Sioux is an interlobate stream, created originally by melt water flowing southward down the long narrow depression between the Des Moines glacial lobe on the east and the James lobe on the west. The valley formed by the Minnesota River, Big Stone Lake, and Lake Traverse occupies the position of a former major northward-flowing stream.

The lesser streams are divisible into four principal groups, based on their origin. These groups are listed below, together with conspicuous streams in each group. The list is representative but is not complete. Valleys in the first two groups lie in the areas where bedrock relief was too great to be completely masked by glacial deposits.

Valleys antedating one or more glaciations, and now reoccupied by streams flowing in the same direction as formerly.
- Spring Creek downstream to Herreid, Campbell County
- Crow Creek, Jerauld and Buffalo Counties
- West Fork Vermillion River, Turner County

Valleys antedating one or more glaciations, and now occupied by streams flowing in the opposite direction.
- Swan Creek, Walworth County
- Little Cheyenne Creek, Potter County
- Medicine Creek between Blunt and Canning, Hughes County
- Smith Creek, Buffalo and Brule Counties

Valleys cut by proglacial streams formed along the outer margins of end moraines. These valleys have no apparent relation to any former valleys.
- Okobojo Creek in the northern half of Sully County
- Medicine Creek in Hyde County
- Platte Creek in Aurora County
- Emanuel Creek in Hutchinson County and northern Bon Homme County
- Clay Creek in Turner County and northern Yankton County
- East Fork Vermillion River in Lake and McCook Counties
- Firesteel Creek in Jerauld County
- Whetstone Creek in Roberts County

Minor streams in intermoraine swales, generally lacking outwash deposits and probably mostly postglacial.

Scores of such streams exist in the James River lowland between minor ridges in the Mankato end moraines.

Most of them appear only on large-scale maps; examples shown on plate 1 are the headwaters of Dry Creek and of South Fork of Twelvemile Creek, both in northwestern Hutchinson County.

LAKES

In eastern South Dakota lakes, or at least depressions capable of holding water, are numerous. There is a complete gradation from minor depressions in the glacial drift, containing water only temporarily in exceptionally wet seasons, to basins that have contained lakes continuously, at least since the earliest settlement of the region. Hence any map of the "lakes" of this region would necessarily be based on some arbitrary determination of what constitutes a lake.

Most of the natural lake basins in eastern South Dakota are of glacial origin. Such basins occur in till or stratified drift or a combination of them. The deepest is believed to be the basin of Pickerel Lake in Day County, reported to have a depth of 60 feet. Many lakes, including large ones, are so shallow that reeds, rushes, and other aquatic plants project above their water surfaces even in their central parts.

A fact that appears curious at first sight is the virtual concentration of major lake basins on the two coteaus, with the James River lowland represented only by the basins of Lake Byron, Sand, and Cottonwood Lakes, and a few lesser lakes. This fact finds an explanation in the origin of the basins, explained on page 67.

The levels of all the lakes in the region fluctuate, both seasonally and over periods of years (see, for example, Caddes, 1947). Data on the areas of individual lakes are not significant in detail because the combination of shallow basins and fluctuations of water level results in considerable expansions and shrinkages. The largest, Lake Poinsett in Deuel and Brookings Counties, has a maximum area of about 12 square miles, and Lake Thompson in Kingsbury County is nearly as large.

The proportion of saline lakes and dry lake basins to lakes essentially fresh is much greater in the western part of the region than in the eastern. This is a direct result of less precipitation and more evaporation in the western than in the eastern part.

Throughout the region the lakes tend to be connected by more or less distinct channels so as to form irregular, discontinuous chains. This arrangement is strikingly evident in the air photographs that cover the entire eastern part of the State. It is not clearly evident on the map, plate 1, which shows only the largest lakes. Even on plate 1, however, the chain formed by Brant Lake and Lakes Herman and Madison in Lake County, and the Grass Lake chain in Codington County are apparent. Most of the connecting channels carry water only at times of extremely high lake levels. A typical lake system of this kind occurs in eastern Day County. Pickerel Lake has an overflow channel leading southwest to Waubay Lake, which in turn has an overflow eastward to Blue Dog Lake. Enemy Swim Lake has an independent high-level outlet leading southward also to Blue Dog Lake, which in turn is similarly connected southward with Bitter Lake. The latter is apparently the "sink" for this entire system. It is somewhat saline, and although it possesses a high-level outlet, draining eastward into the Big Sioux River, this outlet seems to be rarely used.

Most of the lake basins are somewhat related to ancient valleys that have been only partly obliterated by glacial deposition. The majority of the basins are not kettles, as that term is generally understood among geologists.

Both the contemporary strand lines and the abandoned strand lines (p. 130) of the lakes are characterized generally by surface concentrations of boulders and large cobbles at and slightly below the bases of wave-cut cliffs. The boulders are similar to those cropping out in the cliffs, and clearly are a residuum accumulated through erosion by waves. Similar concentrates are seen commonly at the shores of lakes occupying basins in till in other regions.

Less common are horizontal ridges of similar coarse residuum, mixed with stones of smaller size, fringing existing and abandoned lacustrine strand lines. Such ridges occur in places on the Coteau du Missouri. A particularly good example lies in secs. 22, 23, and 27, T. 114 N., R. 72 W. This ridge fringes three sides of a lake basin at a height of 17 feet above the water surface of June 1948. It is 3 feet high, 15 to 20 feet wide from base to base and consists mainly of boulders with diameters as large as 30 inches. As the boulders are too large to have been moved by wave action in a lake that could not have had a maximum diameter of more than 2 miles, the ridge is probably the work of ice, moving possibly by expansion during the freezing of lake water, but more likely as floating masses driven by winds during the spring breakup of the ice.

CLIMATE

Because of its midcontinental position and its location near the paths of many cyclonic storms, South Dakota has a markedly continental climate with extreme summer heat, extreme winter cold, and rapid fluctuation of temperature. Temperatures of 100° F or more are not uncommon during summer months, but as they are ordinarily accompanied by low humidity, they are less oppressive than are such temperatures in the States farther east. Temperatures fall below zero frequently from November to March, and at times these low temperatures are accompanied by strong winds. The extreme annual range recorded in the eastern half of the State is from +120° F (at Gannvalley, Buffalo County) to −58° (at McIntosh, Corson County). In winter the ground freezes to depths of 3 to 6 feet.

The distribution of precipitation in South Dakota is shown in figure 2. In the eastern half of the State precipitation diminishes quite regularly from 26 inches annually in the southeast corner, to about 18 inches in the central region. This range includes the transition from humid to subhumid climate, a transition clearly reflected in the vegetation and soils. About three-quarters of the annual precipitation falls during the period from April to September and about half during May, June, and July. Occasional storms may precipitate 3 or 4 inches of rain, or even more, within a 24-hour period.

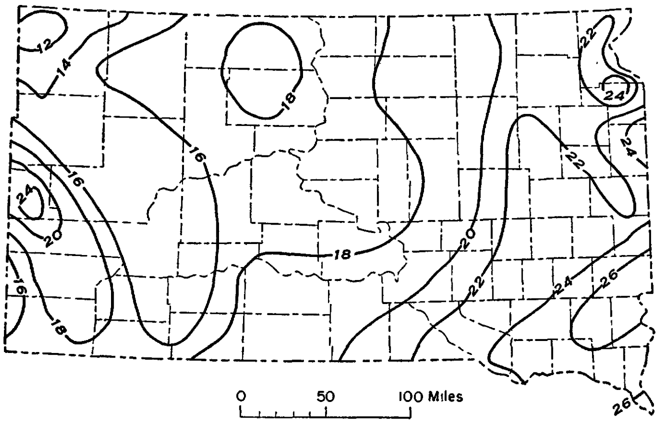


FIGURE 2.—Map showing distribution of average annual precipitation in South Dakota. Figures represent inches of precipitation expressed as water. (U. S. Department of Agriculture, Yearbook 1941, p. 117.)

Despite a rather high frequency of cyclonic storms, the precipitation totals are small. Low winter temperatures are the result chiefly of frequent outbursts of polar air that flow generally southeastward across South Dakota. During the winter polar air covers the region so much of the time that tropical air from the Gulf of Mexico is rarely felt at the surface. Instead this warm moist air rides over the heavier polar air masses and, through condensation, precipitates snow.

During the summer months warm, moist air from the Gulf of Mexico invades the region from the southeast and produces most of South Dakota's rainfall when it overruns cold air masses. The decrease in precipitation from southeast to northwest, shown in figure 2, perhaps reflects the general northwest direction of flow of the tropical air. Violent summer storms of the convectional thundershower type bring additional rainfall to the region.

These general conditions of circulation are reflected also by the surface winds, prevailingly northwest during the cold season and southeast during the warm season. Velocities are ordinarily low, but occasional high velocities occur during blizzards.

Because of the generally low humidity, cloudy days are few. In South Dakota as a whole the average number of clear days per year is 173, with 104 days partly cloudy. This leaves only 88 cloudy days per year.

SOILS

Most of the soils of South Dakota are zonal soils, that is, soils that occur throughout large areas, or geographic zones, having broad distinctive geographic characteristics. The zonal soils are subdivided into groups, each reflecting the nature of the climate and the ecologic complex under which it is formed. The soil groups found in eastern South Dakota reflect the subhumid climate and the accompanying predominant tall-grass cover that prevails in that region in contrast with the prairies and woodlands of moister regions.

Figure 3 shows the distribution of zonal soil groups in South Dakota and States adjacent to it. Eastern South Dakota lies in a broad north-south belt of Chernozem soils. Chernozem (a Russian word meaning black earth) is the black soil of subhumid regions, developed under a dense stand of predominantly tall grasses. In the regions where Chernozem occurs, rainfall is adequate to remove calcium carbonate, by leaching, only from upper to lower horizons of the soil. Hence this compound is dissolved slowly and is reprecipitated, commonly either as a soft whitish deposit or as small nodular masses, 18 inches to 5 feet below the surface. At the same depth, or deeper, gypsum may accumulate in the same manner. The grasses that cover the surface absorb calcium in large amounts, and return this element to the soil as they decay. The calcium is then absorbed by colloidal compounds, imparting a stable granular structure to the soil. This type of soil is favorable to the bacteria that produce dark-colored humus, and thus the Chernozem acquires its black hue. Many Chernozem soils develop quickly, some maturing within perhaps no more than a few hundred years.

East of the Chernozem soil zone in the latitude of South Dakota lies a zone of acid Prairie soils, which, like the Chernozem soils, develop under a cover of tall

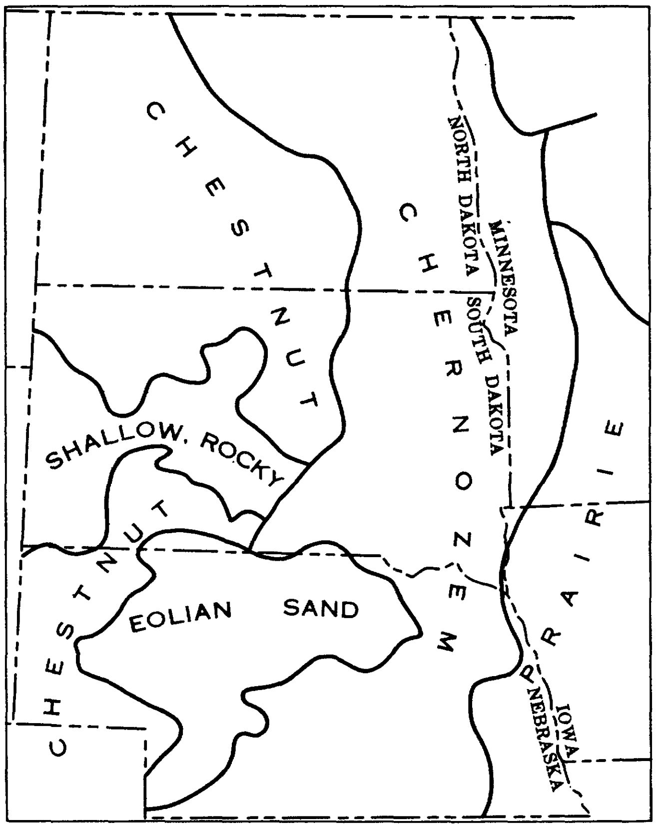


FIGURE 3.—Map showing distribution of soil groups in South Dakota and parts of adjacent States. Alluvial, Solonetz, and Solonchak soils and Wiesenböden are not shown. (U. S. Department of Agriculture, water. (U. S. Department of Agriculture, Yearbook 1941, p. 117.)

grasses. They, too, are black, but as they form in a climate moister than that prevailing to the west, leaching of calcium carbonate is effective, and this material, in time, is removed entirely. Therefore the horizon of secondary calcium carbonate that characterizes the Chernozem soils is not present in Prairie soils. In this region the boundary that separates Prairie soils from Chernozem soils is not far from the line representing a mean annual precipitation of 26 inches. This boundary barely touches southeastern South Dakota.

West of the Chernozem soil zone in South Dakota is an interrupted zone of Chestnut soils. These soils are characteristic of predominantly short-grass country having less rainfall than the Chernozem zone. In South Dakota the boundary between the Chernozem soil and the Chestnut soil very nearly coincides with the line representing a mean annual precipitation of 18 inches. The scanty rainfall in the zone of Chestnut soils will not support such a heavy stand of grass nor such a large microbial population as those characteristic of the Chernozem zone. Hence the Chestnut soils have less organic matter than the Chernozems, and, as their name implies, are dark brown rather than black. Because of scanty moisture, only the more soluble salts are leached from these soils, and the calcium carbonate leached from the upper part of the soil profile is usually reprecipitated within 1 to 2 feet of the surface, where it forms conspicuous whitish layers.

The means by which calcium carbonate accumulates in soils is not thoroughly understood. Secondary accumulation of carbonate apparently is the result of the low rainfall and high evaporation characteristic of subhumid and semiarid climates. Where parent materials are calcareous, a clear general correlation exists between annual precipitation and the conspicuousness of calcium carbonate in soil exposures. Within the region mapped, this material is thickest and most conspicuous in the northwest, where precipitation is least, and becomes increasingly patchy and discontinuous southeastward through the Chernozem soil zone. Near the eastern limit of that zone carbonate of lime is still present, though it is very scanty and is not visible in every exposure.

Associated with the zonal Chernozem, Prairie, and Chestnut soils in South Dakota are widespread additional soil groups that are not zonal. These are shallow rocky soils (lithosols), eolian-sand soils, alluvial soils, Solonetz and Solonchak soils, and Wiesenböden.

The shallow rocky soils are confined principally to the area of outcrop of Pierre shale in the nonglaciated country west of the Missouri River. These soils owe their thinness and poor development principally to the impermeability of the shale and to rapid erosion resulting from extensive dissection and steep slopes that prevail where this formation crops out. Much of the soil in this region is scarcely more than slightly altered bedrock. Where the Fox Hills sandstone and other formations more permeable than the Pierre shale crop out within the same climatic belt, dissection is generally less intense and slopes are less steep; in consequence, Chestnut soils form.

Eolian sands underlie a vast area in northern Nebraska and extend in places into South Dakota. The soils in this area are little more than the parent sand leached of its calcium carbonate and other soluble constituents, and slightly darkened in upper layers by humus.

The alluvial soils are essentially fresh alluvium along the streams that have been darkened slightly by accumulation of humus.

Dotted throughout the Chernozem- and Chestnut-soil zones are complexes of soils of groups known as Solonetz and Solonchak. Solonetz soils occur ordinarily in poorly drained or nondrained areas such as depressions in the surface of glacial drift, where parent materials contain easily soluble salts, especially the salts of sodium. Because of poor drainage and a consequent complicated series of chemical reactions involving the leaching of salts and deflocculation of colloidal clay particles, the soil becomes jellylike, strongly alkaline, and nearly impermeable. As it dries it develops a prismatic columnar structure. It supports a very sparse plant cover. Soils that still retain their soluble salts remain fairly permeable to water but are generally too salty for economic plants. These are the Solonchak soils.

The shallow rocky soils and the eolian-sand soils are shown on figure 3. Solonetz and Solonchak soils are not shown on this map because most individual areas are small and are dotted over parts of the Chernozem-soil and Chestnut-soil areas.

Many soils of the poorly drained flats and morainic depressions are not sufficiently salty to affect the natural vegetation or the direction of soil development. Most of these areas are covered by rank herbaceous vegetation, the roots of which decay to form black humus in the upper soil horizons. Lower horizons have blue-gray or mottled colors that reflect the effects of high water table and irregularly alternating oxidizing and reducing conditions. These dark-colored poorly drained associates of Chernozem and Chestnut soils are known as Wiesenböden (meadow soils). Some are calcareous throughout and nearly all in South Dakota are at least neutral in reaction.

The detailed classification of soils, important for a wide range of agricultural purposes, is made easier by the existence of a map and description of the geologic materials from which the soils have developed. Conversely the identification and mapping of glacial drift deposits is aided by field conference and discussion with soil scientists familiar with the soils. The chart on page 21 represents a correlation of soil types (soil series) with the glacial drift sheets and other Pleistocene deposits in eastern South Dakota.

Soil types are dependent on a number of factors, among which are parent material, topography and drainage, climate, organisms, and time. It has long been recognized that soils vary from place to place as controlling factors vary. However, the concept that soils vary from time to time is of fairly recent origin. In this respect an important control is climate, which, during the Pleistocene epoch, has fluctuated notably. The evidence of repeated glaciation in South Dakota implies such fluctuations, which must have been accompanied by appropriate changes in vegetation and in other organisms living in the soil.

It is expectable, therefore, that these changes should be reflected in the soils formed on the several sheets of glacial drift and loess, although the time intervals between the successive glacial incursions do not seem to have been great enough to bring about strikingly obvious changes in the soils. Pedologists have not yet examined the soils of eastern South Dakota in detail sufficient for the general recognition of soil differences brought about by these climatic fluctuations. Hence the soil types currently recognized in this region are based largely on differences in present-day climate, topography, and drainage.

The soil types are shown in the following chart. The left-hand column represents parent materials as shown on the map, plate 1, supplemented by loess data from the text. The column next to it represents climate and vegetation, expressed in terms of the soil-group zones taken from figures 2 and 3. The remaining columns represent various types of topography.

A comparison of the table with the text descriptions of the several drift sheets is instructive. For example, the Iowan drift is characterized by a nearly continuous covering of loess, and has a topography that includes very few undrained depressions. In contrast, the Mankato drift has a loess cover only locally and is marked by thousands of small closed depressions.

Again, the lithologic composition of a drift sheet, varying from place to place, gives rise to a variety of soil series. In eastern Spink County, for instance, the Mankato till is rich in clay and is very tough and compact. The soil series formed on it is different from the loamy soil in the western part of the same county, where the Mankato till is rich in silt and is friable.

Conversely, a single soil series occurs on two or more drift sheets, in places where the latter are similar in lithology and texture. The Barnes series, formed on silty till, occurs on all four Wisconsin drift sheets.

Local topographic details strongly affect the soil series formed on them. Thus, in the region of Chernozem soils, on silt-rich Cary till, soils of the Buse series occur on steep convex slopes (rolling topography), Barnes soils occur on gentler convex slopes (undulating topography), Aastad soils on nearly flat surfaces, and Parnell and Tetonka soils in the shallow closed depressions. On the same till in the region of Chestnut soils, four distinctly different soils occur in the four topographic situations named above. These soils in the Chestnut zone are thinner, paler in hue, less rich in humus, but richer in secondary carbonates, than are the corresponding soils in the Chernozem zone.

Correlation of soils with Pleistocene deposits in eastern South Dakota

Symbols: *Tentative name; N, not set up; P, probably does not occur.

[Prepared by F. C. Westin and W. I. Watkins, South Dakota State College Experiment Station; Glenn Avery, U. S. Soil Conservation Service; and C. A. Mogen, Soil Survey Division, U. S. Department of Agriculture, from Pleistocene data furnished by R. F. Flint.]

Pleistocene deposits	Great soil-group zones	Topography						
		Rolling	Undulating	Slightly undulating		Level		Nondrained depressions
				Well drained	Saline alkali	Nonsaline, nonalkali	Saline alkali	
Dune sand	Chernozem			Mixed—Valentine and dune sand.		Loup		Gannett.
Beach ridges and offshore bars	Chernozem	P	N	N	P	*Foxhome	N	*Barnett.
	Chestnut	N	N	N	N	N	N	N.
Glacial-lake sediments	Chernozem	*Zell	Bearden	Bearden	*Harmony		Aberdeen; *Exline.	Tetonka.
	Chestnut	N	N	N	N	N	N	N.
Outwash and alluvium:								
Gravelly substratum	Chernozem	Sioux; Fordville.	Sioux; Fordville.	Sioux; Fordville.	N	Sioux; Fordville.	N	Benoit.
	Chestnut	*Alaska	*Alaska	*Alaska	N	*Alaska	N	N.
Sandy substratum	Chernozem	N	Ulen	Ulen	N	Ulen	*Letcher	Tanberg.
	Chestnut	N	N	N	N	N	N	N.
Silty and clayey substratum	Chernozem	P	P	*Castlewood	N	Lamoure	N	Rauville.
	Chestnut	P	P	Tripp	N	Havre	N	N.
Collapsed drift	Chernozem	Pierce	Pierce	Pierce	N	N	N	N.
	Chestnut	*Alaska	*Alaska	*Alaska	N	N	N	N.
Glacial drift, Mankato substage:								
Friable till	Chernozem	*Buse	Barnes	Aastad	N	*Flom	Cavour	Parnell; Tetonka.
	Chestnut	Zahl	Williams	N	N	N	Estevan	N.
Tough, compact till	Chernozem	N	*Turton	N	N	N	N	N.
	Chestnut	N	N	N	N	N	N	N.
Glacial drift, Cary substage:								
Thin loess on till	Chernozem	N	Kranzburg	Waubay				
	Chestnut	N	Eakin					
Thin loess on laminated silt and clay	Chernozem	N	*Sinai	Waubay	N	N	N	N.
	Chestnut	N	N	N	N	N	N	N.
Friable till	Chernozem	Buse	Barnes	Aastad	N	Flom	Cavour	Parnell; Tetonka.
	Chestnut	Zahl	Williams	N	N	N	Estevan	N.
Glacial drift, Tazewell and Iowan substages:								
Thick loess	Chernozem	Crofton	Moody	*Trent	N	N	N	P.
	Chestnut	N	*Agar	N	N	N	N	P.
Thin loess on till	Chernozem	N	*Kranzburg	Waubay	N	N	N	P.
	Chestnut	N	*Eakin	N	N	N	N	P.
Friable till	Chernozem	Buse	Barnes	Aastad	N	*Flom	Cavour	P.
	Chestnut	Zahl	Williams	N	N	N	Estevan	P.

BIOGEOGRAPHY

The glaciated eastern half of South Dakota can be divided into two biogeographic zones, an eastern zone corresponding fairly closely with the Central Lowland physical division, and a western zone corresponding with the Great Plains. The boundary that separates the two approximates the scarp that constitutes the eastern limit of the Coteau du Missouri (fig. 1).

The eastern zone is largely prairie, with groves of trees (many planted since the settlement of the region) on the flood plains of the larger streams and, in the southeastern part of the zone, on the upland itself. The eastern half of this zone is dotted with many lakes and marshes. Indigenous plants and animals, both terrestrial and aquatic, have marked affinities with the region lying east of South Dakota. The human population is less sparse here than farther west. Farming is the chief occupation, with corn the chief crop. Extensive cattle and hog feeding is carried on, particularly in the southeastern part of this zone.

The westbound traveller notices the transition from the eastern zone to the western within a few miles of crossing the boundary between them. The western zone is not prairie but steppe, with few trees other than those planted in rows for shelter on the uplands and the cottonwoods and box elders that fringe the principal streams. The native vegetation consists chiefly of grasses. The human population is sparse and is engaged in farming (with wheat the chief crop) and the grazing of stock.

Both biogeographic zones, especially the western zone, are to some degree marginal with respect to agriculture and grazing. In moist years the land is highly productive, but during dry years crops may fail and stock may suffer from hunger and thirst. The climate of South Dakota has fluctuated conspicuously since the beginning of settlement. In consequence, and because of the marginal character of the region, repeated shifts of population have resulted. The most recent changes began during the dry years of the middle 1930's, when thousands of ranches, farms, and homesteads were abandoned. This movement was followed, during the moister 1940's, by a partial return of the displaced population and by a great increase in agricultural production.

It is expected that the governmental plan for the development of the Missouri basin, now being put into effect, will when completed, minimize or do away altogether with the natural difficulties that have hitherto beset agriculture and grazing in South Dakota.

PRE-PLEISTOCENE ROCKS

STRATIGRAPHIC SEQUENCE AND LITHOLOGY

Most of the geology of eastern South Dakota that is visible at the surface is Pleistocene. Except in the trenches cut by the Missouri River and other large streams, exposures of pre-Pleistocene rocks are rare. Not much is known, therefore, about these rocks, and what little information is available is necessarily derived in part from the logs of deep wells, many of them drilled before 1900.

A brief description of the rocks exposed in eastern South Dakota is necessary to an understanding of the composition of the glacial drift, the variations in which, from one district to another, are in part the result of the distribution of the bedrock formations. This description is contained in the following chart, which gives the name, stratigraphic position, and thickness of each rock unit exposed in the region, together with a condensed description useful for identification.

Only the rocks known to be exposed at the surface are described. A number of formations, found in deep borings but not known to crop out in this region, are omitted as having exerted no apparent lithologic influence on the Pleistocene deposits. The distribution of bedrock units exposed at the surface or immediately underlying the drift, within the glaciated part of the State, is shown in the sketch map, figure 4.

Chart showing sequence and characteristics of the bedrock units occurring in eastern South Dakota

System	Group	Name of unit		Description	Thickness (feet)	Remarks and References
Tertiary.		Ogallala formation(?)		Sandstone, quartzite, marl, and shale. High-level remnants only; sandstone and quartzite facies cap buttes.	Unknown	See accompanying text.
		Hell Creek formation.		Shale, siltstone, and sandstone, tough, light-gray to brownish; interbedded with carbonaceous shale and thin beds of lignite. Contains bones of terrestrial vertebrates. Forms steep buttes and mesas.	[1] 200	
		Fox Hills sandstone.		Sandstone, medium-grained, poorly indurated, medium-gray, olive-gray, and greenish-gray hues, with subordinate gray siltstone and gray shale in lower part. Contains ferruginous and calcareous concretions. Weathers to orange sand. Irregular cementation results in lenticular weathered masses unrelated to stratification. Forms buttes and mesas with rounded profiles.	[1] 300	
Cretaceous.	Montana group.	Pierre shale.	Elk Butte member.	Shale, blue-black, noncalcareous; with subordinate siltstone.	100 to 250	Crandell (1950).
			Mobridge member.	Shale, dark blue-gray with bentonite beds, chalk, chalky shale, and sandy shale. Chalk beds are gray, weathering to yellowish and orange hues, and form cliffs.	[2] 100 to 300	
			Virgin Creek member.	Shale, dark-gray, noncalcareous, siliceous in northern part of region. Thin bentonite beds occur in lower part of member, and scattered large concretions in upper part. Weathers to orange and brownish hues. Forms cliffs where siliceous.	240	
			Verendrye member.	Shale, olive-gray, nonsiliceous, with abundant large, flattish, very dark purple concretions. Shale weathers to gumbo; concretions break down to small angular fragments.	180	
			De Grey member.	Shale, noncalcareous, gray, with layers of bentonite, and (in southern part of region) conspicuous concretions of manganese-iron oxides and iron carbonate.	[1] 160	
			Crow Creek member.	Shale and marl, calcareous, with a thin basal sandstone.	[1] 15	
			Gregory member.	Shale, medium-gray to yellowish-gray, with concretions and calcareous layers. Includes discontinuous marl beds at base.	[1] 125	
			Sharon Springs member.	Shale, thin-bedded, grayish-black, bituminous, weathering brownish black. Includes thin bentonite beds.	[1] 35	
	Colorado group.	Niobrara formation	Smoky Hill chalk member.	Chalk, massive and shaly chalk, bluish-gray to dark-gray, weathering to yellowish orange and white.	150 to 300	Moxon, Olson, and Searight (1939, p. 17).
			Fort Hays limestone member.	Chalk, massive and chalky shale; gray when fresh; weathering to white or yellowish orange.		
		Carlile shale	Codell sandstone member.	Sandstone, coarse, massive to crossbedded; pale-brown to brownish-gray.	[1] 100	
			Unnamed unit.	Shale, bluish-gray to greenish-gray; with calcareous and ferruginous concretions. Fossiliferous.	200	
		Greenhorn limestone.		Limestone, bluish-white, firm, thin-bedded, well-jointed, chalky, with layers of calcareous shale. Fossiliferous.	[1] 100	
		Graneros shale.		Shale, dark-gray, with sandy beds near base. Locally contains pyrite.	[1] 100	
		Dakota sandstone.		Sandstone, fine-grained, irregularly bedded; with siltstone, shale, and carbonaceous beds. Light olive gray when fresh; yellowish orange to light brown on weathered surfaces.	[1] 300	
Pre-Cambrian.		Sioux quartzite.		Quartzite, mostly fine textured, but including conglomerate, siltstone, and shale. Light brownish gray to grayish red purple; less commonly gray, white, and orange. In places cut by basic igneous intrusions.	[3] 3,000	
		Granite.		Granite, coarse-textured, dark-red, showing faint grain on weathered surfaces caused by subparallel orientation of minerals.		

[1] Maximum thickness.
[2] 100 feet in south; 300 in north.
[3] Minimum thickness.

EASE OF EROSION OF PIERRE SHALE

The Pierre shale as a whole is very easily eroded because of the large proportion of clay and the small proportion of quartz in this rock; poor consolidation; and the presence in it of many layers of bentonite, a rock rich in the clay mineral montmorillonite, a product of the chemical alteration of volcanic ash. When dry and where it is not weathered, the Pierre shale is firm and compact. When wet with rain or melting snow, however, the weathered mantle absorbs water readily and swells notably, and the shale becomes a plastic mass. In consequence the surface shale flows downslope, even on extremely gentle gradients. The floors of many small draws and larger valleys are thickly covered with shale debris—part alluvium, part earth-flow detritus—which has reconsolidated by drying while en route to the main rivers. As the flowed material dries, it cracks and spalls into small flaky particles suitable for removal by slope wash, streams, and wind.

Because of the behavior just outlined, the Pierre shale is destroyed, almost as rapidly as it is weathered, by both aqueous and eolian erosion. On nearly flat surfaces its destruction is retarded by the root network of the grasses, which form, under the climate that now exists, a continuous mat of sod in such situations. But on many slopes erosion is so rapid that it outstrips the rate of development of soil and thus inhibits the formation of a cover of soil and vegetation.

The very rapid rate of erosion of the Pierre shale partly explains the scarcity of glacial drift in the glaciated areas underlain by this formation west of the Missouri River. Also it seems to have been an important factor in the development of the anomalous pattern of minor drainage lines. Finally, it partly explains the great number of deflation basins that occur in flat areas underlain by the Pierre shale.

TERTIARY STRATA, CHIEFLY OGALLALA FORMATION

At several localities within and immediately west of the glaciated part of South Dakota erosion remnants of sandstone, quartzite, marl, and shale are believed, largely on a basis of their lithology, to represent the Ogallala formation of Pliocene and upper Miocene age. Silt and siltstone believed to be a fine-grained equivalent of at least a part of the Ogallala formation have been recognized in southeastern Nebraska by the Nebraska Geological Survey, and have been called the Seward formation (Condra, Reed, and Gordon, 1950, p. 15). The sandstone and quartzite remnants form conspicuous buttes and other highlands; the marl remnants exercise less obvious control of the topography.

The outcrop areas, mostly small, are shown on the map, figure 4. Small buttes capping the northern tip of the Coteau des Prairies at an altitude of about 2,000 feet in Marshall County may consist of Fox Hills sandstone, though a complete covering of glacial drift makes knowledge of their composition uncertain. It is possible, also, that this sandstone underlies the drift in parts of Walworth, Edmunds, and Faulk Counties. The outcrops east of the Missouri River, with the predominant rock type exposed, are Bijou Hills, Brule County (quartzite), hills in southeast part of Charles Mix County (sandstone and quartzite), Wessington Hills, Jerauld County (quartzite), and Ree Hills, Hand County (marl and shale). Yellowish-gray to very pale orange sand containing volcanic ash shards, exposed in the high mass north of Lowry, Walworth County, probably also is referable to the Ogallala formation. High, flat-topped buttes here suggest a resistant cap rock like that in the Ree Hills farther south. Owing to the mantle of drift, however, no exposures of cap rock have been observed.

Outcrops west of the river are: western Gregory County generally (marl, shale, and quartzite), Iona Hills, Brule and Gregory Counties (quartzite), Medicine Butte, Lyman County (marl and quartzite).

These rocks occur at altitudes between 1,650 feet and 2,200 feet, and clearly are no more than small remnants of a formerly extensive cover. The sandstone is a medium- to fine-grained thin-bedded light olive-gray, pale-olive, and greenish-yellow rock and has a cut-and-fill type of crossbedding. The quartzite is a highly silicified facies of the sandstone; it fractures through the individual grains. According to Frye and Swineford (1946), closely similar rock of Ogallala age occurring in Kansas possesses a cement consisting of opal and chalcedony. Cementation is irregular, producing a lenticularity that is in part unrelated to the stratification.

The marl and shale are soft, are finely laminated with papery stratification, and are yellowish gray to white, and locally greenish yellow. No more than 11 feet of this sediment has been observed in a single exposure, but its thickness is undoubtedly greater. Some layers contain small, partly carbonized fossil fishes, at least one of which has been dated as possibly middle Pliocene or younger (Dunkle, D. H., U. S. National Museum, written communication).

Because of their close association with each other and because of their distinctive lithology, the sandstone, quartzite, marl, and silt in the widely scattered areas named above are believed to correlate with the sediments similar to them in southwestern South Dakota and northern Nebraska that are generally regarded as correlative with the Ogallala formation.

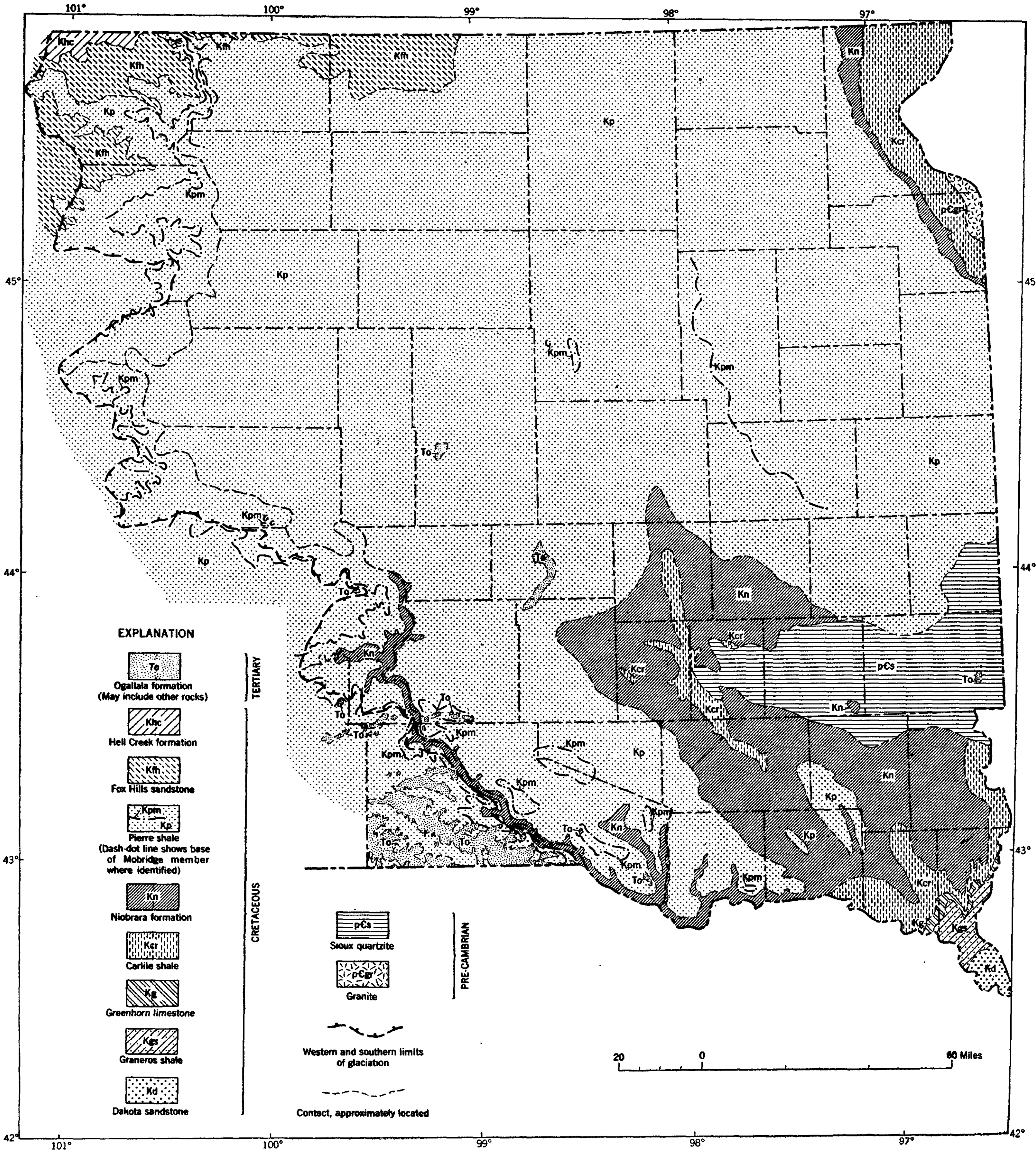


FIGURE 4.—Sketch map showing inferred distribution of bedrock units beneath the drift in the glaciated region of South Dakota. Compiled from various sources; distribution of Tertiary strata southwest of Missouri River in part from unpublished map by E. C. Reed.

The east-west linear distribution of the remnants of Ogallala strata that form the cap rocks of the Iona Hills and Bijou Hills suggests the possibility that these remnants constitute part of the filling of an eastward-trending, pre-Ogallala valley. This suggestion implies that differential erosion in post-Ogallala time has reversed the topography by lowering the surrounding country by several hundred feet while preserving parts of the floor of the old valley beneath the resistant Ogallala cover. No conclusive evidence for or against this suggestion has yet been found.

In the vicinity of Corson, Minnehaha County, sediments of unknown age, that may be Ogallala, are exposed overlying the Sioux quartzite. These sediments consist of light-gray clay and siliceous material, in places resembling weathered chert. They were mapped as Niobrara formation by Darton (1909, pl. 1) and were described briefly by Baldwin (1949, p. 14–16), who referred to the siliceous material as volcanic ash.

STRUCTURE

The rocks of eastern South Dakota are essentially flat lying. They are warped into broad gentle arches and basins, but the dips of the strata in such structures are so small as rarely to be visible to the eye. They are measured in terms of a few feet or a few tens of feet to the mile.

In broad terms the structure of eastern South Dakota is homoclinal, with a regional dip toward the northwest (fig. 5). This dip constitutes the east limb of a shallow syncline plunging north, with an axis trending through Todd, Washabaugh, Jackson, Haakon, Meade, and Perkins Counties. This structure has been called the Lemmon syncline, and also the Dakota structural basin (Rothrock, 1947, p. 21). It is not smooth; rather it is interrupted by local low folds that trend in various directions. The most conspicuous of these is the Sioux uplift, trending nearly westward through Minnehaha, McCook, Hanson, and Davison Counties. This uplift coincides with the axis of the ridge of Sioux quartzite (Darton, 1909, p. 33). Another conspicuous structure is the Medicine Butte anticline, a low dome trending northward through eastern Lyman County (Petsch, 1942). Still other gentle structures are exposed at various places along the Missouri River, and have been identified where exposures made mapping possible (Petsch, 1946, geologic profile; Rothrock, 1947).

All these structures involve the Cretaceous rocks, and appear (on incomplete evidence) to antedate the deposition of the Ogallala formation.

It is doubtful that structure has played any significantly direct part in determining the extent of glaciation or the distribution of glacial deposits. Indirectly, of course, structure has been important in creating an areal outcrop pattern that has resulted in noteworthy differences in the lithologic content of the drift between one district and another and in topographic differences that have affected the direction of flow of glacier ice.

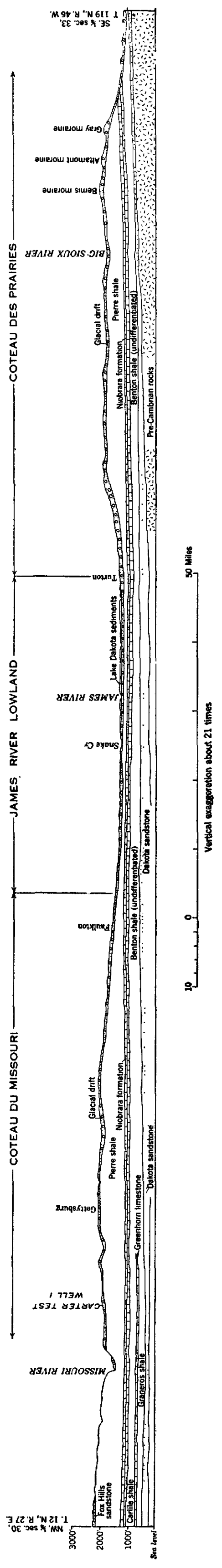


FIGURE 5.—East-west profile and geologic section across eastern South Dakota, modified after Darton (1909, pl. 6, sec. 1) with addition of log of Carter well (South Dakota Geol. Survey Rept. Inv. 58, p. 19, 1947) and controlled at western end by logs of Cherry Creek and Irish Creek wells, not shown (South Dakota Geol. Survey Rept. Inv. 4, p. 102–104, 1946).

PLEISTOCENE GEOLOGY

GLACIATION

In South Dakota, the area east and north of the Missouri River is almost completely covered by glacial drift (pl. 1). West of the river the drift consists principally of scattered boulders. Several features show that glacier ice entered the State from the northeast or north, and flowed generally south and west: the trend of the outer limit of glaciation, which is everywhere at right angles to the direction of former flow; striations on exposures of hard bedrock; and the lithology of the drift, which includes rock types derived from the north and northeast but only locally material derived from other directions.

The effects of glacial erosion in South Dakota are largely concealed beneath the thick mantle of drift; hence little information on this subject has been obtained. Wherever the pre-Cambrian granite and the Sioux quartzite are well exposed beneath drift or without any cover, their upper surfaces are smoothed, striated, or polished, proving glacial erosion but affording no quantitative information. The fact that the drift includes large amounts of material derived directly from the Pierre shale, Niobrara formation, and other local bedrock units supports the inference that extensive glacial erosion of these rocks has occurred. Probably much of this erosion took place in what is now the James River lowland, for there the ice was thickest and therefore flowed most rapidly, and there the topographic and geologic relations suggest that glacial alteration of preglacial land forms was greater than in other parts of the State.

GLACIAL DEPOSITS

The glacial drift, spread as a blanket over the eroded preglacial surface, radically altered the topography of eastern South Dakota by partly filling major valleys, entirely obliterating many small valleys, forcing the cutting of new valleys, and forming massive end moraines. The topographic map (pl. 2), even though greatly generalized, clearly shows the difference between the glaciated country and the territory beyond the limit of glaciation.

As a rule the surface of the drift has less relief than the surface of the bedrock beneath it. The principal exceptions are in the belts of massive end moraines, which impart exceptional relief to the drift. In general, therefore, the effect of glaciation has been to reduce the local relief. This is particularly true in the coteaus. It is less evident in the James River lowland.

The thickness of the drift (fig. 5) ranges from a mere trace to a presently known extreme of 480 feet, found in a well boring at Webster. Only rarely is a thickness greater than 25 feet seen in a single exposure; the significant thickness data therefore are derived principally from the logs of borings. These logs show that, in the Minnesota lowland the average thickness of the drift is about 50 feet. In the James River lowland the thickness generally ranges from 50 feet to 100 feet, although locally it exceeds 300 feet. Over the coteaus the thickness is extremely variable, owing to the irregularity of the bedrock surface in their areas. West of the Missouri River the drift consists only of scattered boulders. A rough estimate of the average thickness of the drift in South Dakota east of the Missouri River is 40 feet.

Physically the drift is divisible into four groups: till, outwash, glacial-lake deposits, and ice-contact stratified drift. Of these, till is by far the most abundant. Most of it is rich in clay, and nearly all is believed to have been deposited by lodgment upon the ground from the under part of the flowing ice.

Outwash consists of crossbedded gravel, sand, and silt deposited by melt water as it flowed away from the ice. In South Dakota it occurs commonly as thin veneers that cap benches cut into till and bedrock along the courses of southward-flowing stream systems. Although abundant in the till, clay is a rare constituent of the outwash. Its scarcity is believed to be the result of the ability of the turbulent proglacial streams to keep the tiny clay particles in suspension, thus preventing their deposition and resulting in their being carried entirely out of the region.

Glacial-lake deposits, consisting chiefly of parallel-bedded silt, sand, and clay, occupy depressions of various sizes that were temporarily blocked by the glaciers and so were filled with ponded water. Most of the lakes were small, but two very large lakes—Lake Agassiz and Lake Dakota—occupied considerable areas in South Dakota.

Ice-contact stratified drift shows by its surface form and disturbed internal structure that it was accumulated upon or against melting glacier ice. Commonly it occurs as mounds or knolls, and as irregular masses pitted with closed depressions of various diameters.

The till, which constitutes the great bulk of the drift, consist of an intimate mixture of rock fragments of all diameters from clay particles up to large boulders. Clay, silt, and sand sizes constitute most of the till; larger pieces, although conspicuous because of their their size, constitute only a small fraction of the mass. Most of the bedrock of eastern South Dakota is weak, and breaks down into small particles. The predominantly fine texture of the till probably reflects the derivation of the till in large part from the local bedrock. Such a relationship is commonly observed in glaciated regions.

Stratigraphically the drift in South Dakota, like that in the Central Lowland generally, consists of several distinct layers of till separated by layers of loess or stratified drift or by zones of chemical alteration induced by weathering of the till itself. These layers (pl. 3) represent glacial invasions during successive glacial ages (or subages), separated by time intervals when there were no glaciers and when stream deposits or windblown silt were laid upon the surface, or when the upper part of the drift was slowly decomposed to form soil. In a few places fossils have been found imbedded in the material separating two drift sheets.

Some of these layers are exposed at the surface; others are found in borings. In the latter, especially, correlation of the layers from one place to another is very difficult because of the known variations of any one layer in respect to lithology, texture, and thickness. Accordingly the correlations suggested in this study are tentative only, and are no more than the best guesses that can be made from present knowledge of the glaciation of the entire region. Future study will undoubtedly correct and amplify them in many respects.

The broad southeasterly trend of the outer limit of the drift is part of a regional trend that apparently was determined by the climate prevailing at the time the drift was deposited. The ice flowed westward, a direction in which annual precipitation diminishes and summer temperatures increase at present; presumably similar relations existed during the glacial ages. The ice margin ceased to advance when temperature and precipitation in this region ceased to be favorable.

The lobation of the drift border, superposed upon the regional trend, is controlled by topography. The lobes are coincident with major valleys, in which the flowing ice was able to penetrate farther west than upon the intervening divides.

EFFECT OF GLACIERS ON DRAINAGE

One of the greatest changes wrought by the glaciers in eastern South Dakota is in rearrangement of the drainage. Before the arrival of the ice in one of the pre-Wisconsin glacial ages, probably the Illinoian age, the main streams flowed toward the east. The ice, flowing westward, blocked these streams, ponded them, and forced them to overflow. The overflow water spilled southward and eastward, approximately along the margin of the blockading ice. The escaping water soon intrenched itself into the weak underlying rock, so that when the glacier melted away the runoff remained in its new course. This course is the trench of the Missouri River.

The James River trench was cut mainly by the water escaping from the south end of Lake Dakota, a temporary lake dammed between the shrinking glacier on the north and an ancient divide on the south.

The route of the Big Sioux River was established along the south-trending depression between the Des Moines lobe and the James lobe of the ice sheet. This event certainly took place in Wisconsin time; whether a similar event occurred also during any pre-Wisconsin glaciation is not known.

Thus the drainage of eastern South Dakota, originally eastward, is now predominantly southward. It was turned, in some cases through nearly 90 degrees, in consequence of glacial control of various kinds.

NONGLACIAL DEPOSITS

LOESS

The abundance of silt-size particles in the drift, coupled with the prevailing dry climate and rather strong winds that characterize the region, resulted in the deflation of silt from outwash bodies and even from the till itself, during the melting of the glaciers. The silt, from the outwash, mixed with silt derived from nonglacial sources farther west, was deposited over the surface to leeward of the source areas, as loess. The layers of loess range from thin, barely recognizable veneers to several tens of feet in thickness. They are useful in stratigraphic correlation, for in many areas they separate layers of till so similar in appearance as not to be individually identifiable were it not for the layers of loess between them.

STREAM DEPOSITS

In some parts of eastern South Dakota, generally interbedded with the drift, are deposits of stream-laid gravel, sand, and finer sediments, the lithologic content of which shows that their area of origin was far west of the glaciated region. Some contain the fossilized bones of mammals, from which it has been possible to approximate the dates when they were deposited, and hence by inference the dates of the glacial deposits in contact with them.

Some of these stream sediments may have been laid down during interglacial ages when South Dakota was free of a covering of glacier ice. Others may have accumulated during glacial ages when glacier ice in eastern South Dakota constituted a barrier to the normal eastward flow of streams entering the region from the west.

POSITION AND FORM OF THE BEDROCK SURFACE

The configuration and depth of the surface of the bedrock are inferred partly from the form of the major topographic features of the region, and partly from the logs of drill holes and geophysical prospecting operations. Unfortunately, in South Dakota subsurface data are scanty. In the present investigation the 276 available logs—not nearly enough to afford an accurate idea of the bedrock surface—were obtained from a number of sources, mostly published (Darton, 1896, 1897, 1909; Todd, 1899, 1900b, 1903a, 1903b, 1903c, 1904a, 1904b, 1908, 1909; Todd and Hall, 1903, 1904; Rothrock, 1934, 1946a; Sayre, 1935; Loucks, 1942, p. 50; and written communications from V. A. Means, U.S. Bur. Reclamation, and M. E. Kirby). Many additional holes have been drilled, but the data have never been systematically gathered from drillers, property owners, and municipal and county officials. With only a few exceptions, the logs represent holes drilled prior to 1910 and mostly prior to 1900, and the reliability of interpretation of the materials found varies widely. The locations of the holes were indicated on a map (scale 1:500,000) and beside each were plotted the depth to bedrock and the altitude of the bedrock surface calculated from the curb altitude.

Another source of information lies in geophysical surveying, undertaken principally in the search for additional subsurface water supplies. A resistivity survey, made in an area of 16 square miles at Huron, revealed in some detail the bedrock topography beneath nearly 100 feet of drift (Rothrock and Petsch, 1935). The relief of the bedrock surface in that district is about 70 feet.

If the drift could be stripped away from the Coteau des Prairies, leaving only the bedrock, the topography of this massive highland would be quite different from its present topography. The general form of the Coteau des Prairies and the data from a few deep borings that penetrate hundreds of feet of drift suggest that whereas the main mass of the coteau consists of bedrock, it is considerably dissected, and has been both heightened and smoothed in outline by the accumulation of a large volume of drift. Apparently the successive ice sheets, flowing from the north and northeast and impinging on the high dissected mass of the coteau, flowed into and past the deep coteau valleys and packed them full of clay-rich drift, much as grease is packed into a wheel bearing, until nearly every trace of the valleys was obliterated. No doubt some of the valleys were reexcavated in part by interglacial streams, and were repacked with drift during later glaciation.

The volume of the drift seems to be greater near the northern end of the Coteau des Prairies and along its eastern margin than farther south and west. This distribution finds a reasonable explanation in the narrowness and probably greater dissection of the northern area, and in the greater exposure of the northern and eastern areas to the onflowing ice. The drift carried in the base of the ice can be expected to have been scraped off and caught in the rough topography near the point or prow and along the eastern fringe of the highland, much as mud is scraped from the sole of a shoe by a doorstep scraper. The drift remaining in the ice was carried onward and was plastered over the wider part of the coteau, which, by virtue of its width, probably was also less thoroughly dissected.

In the extreme southern part of the Coteau des Prairies, in the area known as the Newton Hills, thicknesses of drift and loess combined exceed 200 feet in places, as shown by drillers' logs. Probably these great thicknesses occur in valleys cut into the bedrock and wholly masked by Pleistocene deposits.

In the Coteau du Missouri the relation of drift to bedrock is similar, at least in some degree, although the scarcity of subsurface data makes impossible the reconstruction of detail. Subsurface data from areas in Davison, Hutchinson, and Hand Counties suggest that the drift is plastered thickly against the eastern escarpment where the ice impinged obliquely. This relationship is analogous to that on the northeastern escarpment of the Coteau des Prairies. The distribution of bedrock outcrops suggests that in the Coteau du Missouri the drift is thinner than in the Coteau des Prairies. In the western part of the western coteau, in particular, the drift is commonly very thin, and bedrock crops out in wide areas.

Except in a very few places drift blankets the James River lowland completely. The bedrock surface beneath the lowland is gently irregular, and is characterized in places by large elongate depressions, apparently buried major valley systems. Although the present surface of the lowland has a general, very gentle, southward slope from the northern end of the State to the southern, the bedrock surface beneath it increases in altitude from the North Dakota State line to the latitude of Redfield, Spink County. In that latitude bedrock is exposed at the present surface at many places throughout an eastward-trending belt. South of that latitude the bedrock surface declines at a rate slightly steeper than the inclination of the present surface.

These facts suggest that a stream divide antedating the drift crossed the lowland in the latitude of Redfield, and that glacier ice and the melt water flowing from it partly wore down the divide and partly obliterated it by the deposition of drift both north and south of it. A similar belt of exposures of bedrock, trending eastward through Davison and Hanson Counties, suggests the former presence of a second divide that crossed the western part, though not the entire width, of the lowland.

The inferred former divides are here referred to as the Ancient Redfield divide (p. 149; pl. 7) and the Ancient Mitchell divide (p. 151; pl. 7).

PRE-WISCONSIN GLACIAL DEPOSITS

REGIONAL STRATIGRAPHIC SEQUENCE

In the broad region of central United States four glacial stages have been identified, and have been named, from base to top of the Pleistocene, Nebraskan, Kansan, Illinoian, and Wisconsin. In South Dakota the Wisconsin is represented in such preponderant strength that in the discussion that follows it is treated separately, whereas the three underlying stages are treated together and more briefly.

The Nebraskan, the lowest glacial stage in the Pleistocene sequence, was named by Shimek (1909, p. 408) from exposures in the Missouri River bluffs near Omaha, Nebr. Earlier, this drift sheet had been called sub-Aftonian and also pre-Kansan. Drift correlated with the Nebraskan stage by various workers has been reported to have a maximum thickness of 150 feet in Nebraska (Lugn, 1935, p. 40) and Iowa (Kay and Apfel, 1929, p. 181), and to be very thick locally in Minnesota (Leverett, 1932, p. 15).

In Iowa, Minnesota, and Wisconsin the Nebraskan drift, according to Leverett (1932, p. 14–15),

> consists mainly of a nearly black till, in which a large amount of woody material, still present in identifiable species, was incorporated. It seems to contain the black alluvium and dark humus soil of the region over which the ice sheet passed. McGee applied the terms "bituminous" and "carbonaceous" to this till, as noted by him in northeastern Iowa.

Even if we assume that the exposures referred to are assigned to the Nebraskan stage correctly, it seems likely that the "nearly black" hue is due chiefly to the presence of a large quantity of dark-colored clay rather than to the presence of organic matter. Most if not all moist, unoxidized, pre-Wisconsin tills occurring in the central States are very dark in hue.

The next higher glacial stage in the standard sequence, the Kansan, was named by T. C. Chamberlin (1896, p. 872), by transfer to this second drift of the name he had previously applied to the drift now called the Nebraskan. West of the Mississippi River the Kansan drift has been recognized in Iowa, Minnesota, Nebraska, and Kansas. Throughout this region a thickness of 50 to 150 feet has been generally attributed to it (Kay and Apfel, 1929, p. 256; Leverett, 1932, p. 21; Lugn, p. 67–68). However, thickness estimates must be judged in the light of the possibility that not all the till exposures involved have been identified as Kansan correctly.

The third glacial stage, the Illinoian, was named by Leverett (Chamberlin, 1896, p. 874) from the State of Illinois, where this drift is extensively present at the surface. Although known to be present eastward through Indiana, Ohio, Pennsylvania, and New Jersey, and although identified in Wisconsin, this drift has been recognized hitherto in only two districts west of the Mississippi River, namely, southeastern Iowa and southeastern Minnesota.

A body of till, exposed in a Missouri River bluff near Chamberlain, S. Dak., was recognized as probably Illinoian, on a basis of its stratigraphic and erosional relations (Warren, 1951). This confirmed the probable extension of the Illinoian drift westward into South Dakota, in analogy with the Nebraskan, Kansan, and Wisconsin drifts. The strongest direct stratigraphic implication of the presence of Illinoian till is in an exposure in Minnehaha County (locality 17A, p. 35), in which a till (unit 3) antedates Loveland loess and postdates nonglacial sediments similar to though not proved to be the Sappa formation of Nebraska geologists. The probability that this till is Illinoian is high. Further, the presence in Moody County (locality 19, p. 36) of an exposure of a pre-Loveland till underlain successively by nonglacial alluvium and by a still older till suggests that the till first mentioned is Illinoian, though an earlier date is admissible. Stronger evidence of the Illinoian glaciation of South Dakota, although still indirect, comes from the widespread presence of the Loveland loess in Iowa and Nebraska, and, at several localities in South Dakota. These facts imply extensive glaciation in this region during the Illinoian age. Hence the loess and probable age of the tills near Chamberlain and in Moody County stand in mutual support. Evidence of an Illinoian glaciation of South Dakota, derived from drainage relations, is detailed on page 51.

If the probability of the presence of Illinoian drift in South Dakota is admitted, then it is probable that much of the pre-Wisconsin till exposed in South Dakota is Illinoian, simply because the likelihood of survival is greater for this till than for the two older tills. But Nebraska geologists are of the opinion that Illinoian drift is not present in Nebraska because of the stratigraphic relations in northeastern Nebraska.

UNCERTAINTIES IN CORRELATION

In South Dakota internal differences among tills of different dates, revealed by the methods used in this study, are not great enough to permit their correlation with a particular stage or substage, in the absence of independent evidence of date. In other words, in this region there is no "typical" Nebraskan, Kansan, or Illinoian till. Similar difficulty has arisen in other regions, although in western Iowa, Carman (1917, p. 416) was able to distinguish between Nebraskan and Kansan tills in some areas, and in eastern Nebraska there are said to be slight differences between these two tills

(Condra, Reed, and Gordon, 1950, p. 20). The only sure basis of correlation of a till in South Dakota is its stratigraphic relation to some other deposit of known age. On this basis many exposures of till have been identified as Wisconsin because they are seen in contact with loess sheets and paleosols known to belong to the Wisconsin stage.

However, many exposures show no such contact; they show only till without any underlying deposit or paleosol, known or unknown. Not only is the assignment of such a till to a particular stage uncertain, but in some cases it has not even been possible to determine whether it is Wisconsin or pre-Wisconsin.

In regions outside South Dakota pre-Wisconsin tills have been differentiated from Wisconsin tills on a basis of the extent to which they have been altered by weathering. Wisconsin deposits are generally little altered or only moderately altered, whereas pre-Wisconsin deposits are generally considerably altered. Chemical conversion of till to gumbotil, therefore, indicates that that till is pre-Wisconsin. Furthermore accumulations of red iron oxide have been found characteristically developed in soil profiles formed during the Sangamon and other interglacial ages. In accordance with this general relationship, a till altered to a reddish soil in this region is considered pre-Sangamon with a high degree of probability. The implication is that such a till could be Illinoian, Kansan, or Nebraskan.

Removal by erosion of part or all of a soil profile leaves a till with a thin, decapitated soil profile or with none at all. Consequently the observer is in doubt as to how much, if any, weathering actually occurred and can not with certainty assign the till to any one glacial stage. As tills in South Dakota are rarely exposed in visible contact with deposits of known age and soil profiles are altered only locally, the difficulty of satisfactorily correlating till in this region is great.

Fortunately a few exposed tills can be identified as pre-Wisconsin because of their observed stratigraphic relations to Wisconsin sediments. But many more include no exposed evidence of age. Some exposures are considered pre-Wisconsin on the indirect evidence of topographic and erosional features, and still others are believed pre-Wisconsin on a basis of internal evidence. This evidence is applied in the following way:

The internal characters of tills known to be pre-Wisconsin on a basis of stratigraphic evidence are observed to differ somewhat from Wisconsin tills. Tills that possess similar characters, but that are exposed without accompanying stratigraphic evidence of their age, are inferred to be pre-Wisconsin. It should be emphasized that such inferences are tentative and are subject to revision in the light of more detailed investigation than has been possible hitherto.

PHYSICAL CHARACTERISTICS OF PRE-WISCONSIN TILLS

Regardless of age, the tills of South Dakota consist of preponderantly fine-grained sediments, of silt and clay sizes, and, where not leached, are very calcareous. The characters believed to be peculiar to the pre-Wisconsin tills, and to differentiate them from younger tills, are scarcity of large-size rock fragments, pronounced compaction, distinct widely spaced jointing, conspicuous chemical alteration, distinctive hue, and greater thickness.

Scarcity of large-size rock fragments.—Boulders are very few and relatively small; cobble sizes are almost as rare. In most exposures fragments more than 6 inches in diameter are not commonly seen. It is estimated that pebble and larger sizes together constitute only a small fraction of one percent of the entire volume of such a till. This distinction, however, does not seem to extend to the finer grain sizes according to the few mechanical analyses that have been made (fig. 13). The analyses (made by dry screening) suggest that the distribution of sand-, silt-, and clay-size particles is roughly comparable in all tills. Either the dry-screening method has failed to yield the true proportions of clay-size particles, or the impression of finer grain size conveyed to the observer by an exposure of a pre-Wisconsin till is apparently an illusion created by the scarcity of pebbles, cobbles, and boulders.

Pronounced compaction.—Although no compaction tests in the laboratory were made in connection with this study, the firmness of pre-Wisconsin tills is evident in many exposures, with the exception of a surficial zone 3 or 4 feet thick, which has been altered by weathering. A blow with a pick makes only a small dent in an old till; in a Wisconsin till it is likely to cause considerable disaggregation. A conspicuous result of the compact character of pre-Wisconsin tills is that the matrix tends to break around included stones, leaving distinct firm molds.

Although pronounced compaction is not believed to be a criterion of pre-Wisconsin tills, compactness of old tills is believed to be in part a function of time, during which physical settling has occurred. Other possible factors are relative abundance of very fine particles in the till, secondary deposition of mineral matter such as gypsum and calcium carbonate between adjacent grains, and consolidation brought about by the weight of overriding younger glaciers. Probably the last factor is of minor importance in that early Wisconsin tills, overlain by later Wisconsin till and therefore overridden by later Wisconsin ice, are not notably compact.

Distinct, widely spaced jointing.—Pre-Wisconsin tills commonly have clean-cut, deep joints spaced several inches to more than 1 foot apart. When dry these tills do not crumble; they break along the joints, forming massive blocks of irregular shape. In some localities such blocks break with a slightly conchoidal fracture. In this respect the old tills have the properties of a firm rock, whereas Wisconsin tills, in breaking up, generally have the properties of an unconsolidated sediment.

The attitudes of the joints are steeply inclined and are commonly not parallel. Individual joints as much as 15 feet in length have been noted. Some joints are true fissures filled with secondary mineral matter, usually gypsum in platy layers paralleling the fissure walls.

Conspicuous chemical alteration.—Because alteration proceeds from the ground surface downward, its intensity varies in a vertical direction. Thick till exposed to chemical decay during an interglacial age, in an area of nearly level terrain and slow subsurface drainage, has this succession of vertically superposed zones of alteration:

Gumbotil, leached and deoxidized residual clay, largely secondary, representing the alteration or removal by solution of all but the most highly siliceous original materials.
Oxidized till, from which original carbonates have been leached.
Oxidized till.
Fresh, unaltered till.

Weathering profiles of this kind are common in pre-Wisconsin tills in Iowa, Missouri, and Illinois. Although tills known or suspected to be pre-Wisconsin occur at numerous localities in South Dakota, the uppermost, gumbotil zone was observed at only one place (fig. 6, locality 28; p. 37). However, the underlying oxidized zones are exposed in many places. As the pre-Wisconsin tills generally occur in areas dissected by streams, the rarity of gumbotil may indicate merely that the most completely weathered part of the till, being at the surface, has been destroyed by slope wash and other forms of erosion.

The phenomena observed in the oxidized zones in the old tills differ somewhat from those characteristic of the Wisconsin tills. In the upper part of this zone oxides of iron and manganese coat the joint faces; farther down, limonitized fringes of various widths extend inward from the joints, in some places isolating masses of unoxidized till. Generally the Wisconsin tills are oxidized uniformly, irrespective of the numerous, poorly developed joints. The difference in alteration between the two groups of tills may be chiefly a function of the difference in degree of compaction, with resulting differences in ease of penetration by subsurface water.

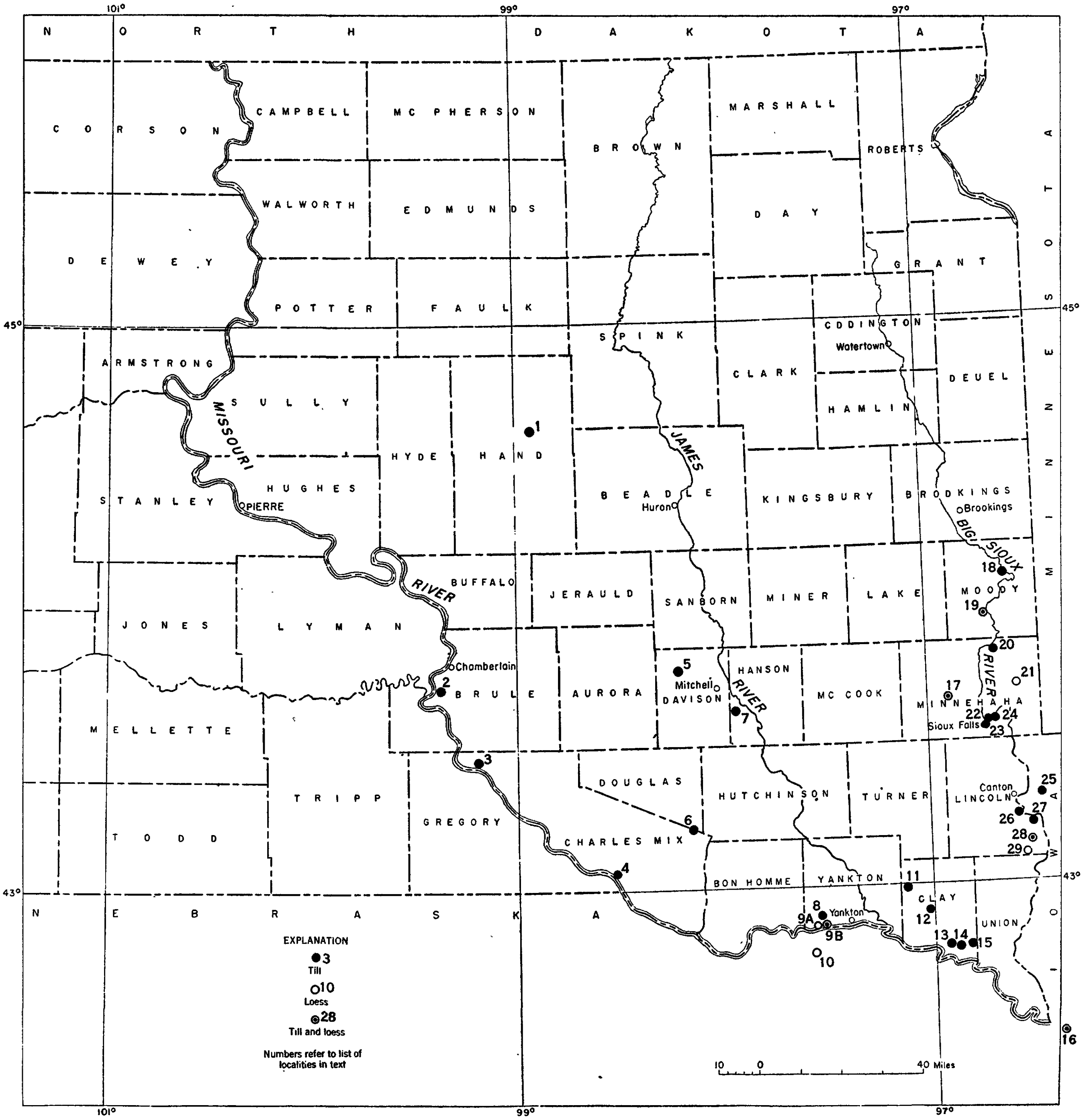
Distinctive hue.—The pre-Wisconsin tills observed in South Dakota, where not obviously oxidized and when wet, tend to show the darkest tones of hue 5 *Y* on the Munsell color scale, approximating olive gray, in contrast with the Wisconsin tills which, under the same conditions, tend to approximate the medium and dark-medium tones of hue 10 *YR*. When dry, both groups of tills resemble each other more closely; yet there is a tendency toward the pale tones of the hue 5 *Y* in the old tills, whereas the Wisconsin tills more commonly show the pale tones of hue 5 *YR*. These statements are based on a considerable number of color-chart comparisons. Aside from them the general impression made on the observer in the field is that the old tills are darker than the Wisconsin tills. This impression is conveyed also in reports from exposures outside South Dakota by statements that the old tills when unoxidized are "dark gray," "black," "blue," and "blue-black," in contrast to a "light-gray" color commonly observed in the Wisconsin tills.

The cause of this difference in hue is not known. The difference may result partly or wholly from differences in the original constituents of the tills. As pointed out on page 162 the James River lowland, which was of prime importance in guiding the direction of flow of the glaciers in Wisconsin time, did not come into existence as such until after the pre-Wisconsin tills had been deposited. Accordingly it is possible that those tills were laid down by glaciers that flowed in somewhat different directions, and hence picked up somewhat different materials, from those carried by the Wisconsin glaciers. Another possible cause of the difference in hue between Wisconsin and pre-Wisconsin tills is the presence, in the former, of oxidation so faint that it is not readily recognizable.

Greater thickness.—It should be added that the average exposed thickness of pre-Wisconsin tills is distinctly greater than that of Wisconsin tills, reaching an extreme at Sioux Falls of 120 feet, with the base not exposed. This difference may be accidental; however, after many more data have been obtained, it may become evident that the tills of the Wisconsin stage are noticeably thinner than those of the earlier stages.

Finally, no attempt was made to compile statistics on the lithologies of stones in the pre-Wisconsin tills. Such a study might aid in discriminating between these and younger tills, but it should be undertaken as part of a more detailed general examination than was possible in the present research.

In summary, the pre-Wisconsin tills in this region are freer from large rock fragments, generally more compact, more conspicuously jointed, more markedly affected by differential secondary mineralization, appar-



Based on U.S. Geol. Survey map of South Dakota

FIGURE 6.—Map showing localities having exposures of till and loess believed to be pre-Wisconsin.

ently darker in hue, and generally thicker than are the Wisconsin tills. These differences are relative, and probably no one of them is in itself an adequate basis for differentiating a till on the spot. However, the combination of these characters may justify the provisional identification of a till as pre-Wisconsin, at least until later more detailed study places its stratigraphic position on a more adequate basis.

DESCRIPTION OF EXPOSURES

The exposures of pre-Wisconsin tills fall into three groups, arranged in order of decreasing certainty of correlation.

TILLS CERTAINLY OR PROBABLY PRE-WISCONSIN BECAUSE OF THEIR STRATIGRAPHIC RELATIONS

The first group, consisting of 9 measured sections or groups of sections, includes tills whose stratigraphic relations imply pre-Wisconsin age. These are numbered 4, 8, 9*B*, 16, 17*A*,*B*,*C*,*D*, 19*A*,*B*, 22, 25, and 28 on figure 6. Each measured section includes one or more tills that can be regarded as pre-Wisconsin with considerable confidence.

In 6 sections (localities 4, 8, 9*B*, 19*A*,*B*, 20, and 28) Illinoian till is believed to be present. In 3 sections (localities 17*B*,*C*, 19 and 25) till underlies sediments believed to correlate with the Sappa formation, as the Sappa is of late Kansan or Yarmouth age (p. 43) the underlying till must be either Kansan or Nebraskan. As both Kansan and Nebraskan tills occur in western Iowa and eastern Nebraska, there can be no doubt that both Kansan and Nebraskan glaciers successively traversed at least part of South Dakota.

The probable Sappa correlatives are dated by fossils at only one locality (25), but at one other locality (17*B*) this horizon is fixed with strong probability by the presence of the Pearlette ash member. In one place (represented by sections from localities 17*A*,*B*,*C*,*D*) a composite section includes pre-Wisconsin tills that may be Nebraskan, Kansan, and Illinoian, respectively. At no locality in South Dakota, however, has a single till been surely assigned to a specific pre-Wisconsin stage, because none occurs between two nonglacial deposits each of which is of certainly known date.

Locality 4. Section north of abutment Fort Randall Dam, exposed in August 1948 during construction. SW¼SE¼ sec. 5, T. 95 N., R. 65 W., Charles Mix County, S. Dak.

	Feet
4. Loess	5.0–12.0
3. Till, silt matrix, crumbles easily; oxidized. (Cary?). Maximum	20.0
Sharp unconformity.	
2. Till, consisting of boulders and cobbles with little fine-grained matrix, numerous contorted lenticular inclusions of sand, silt, pebble gravel, and clay; oxidized. (Iowan?)	3.0–20.0
Unconformity.	
1. Till, olive-gray, compact, coarsely jointed, blocky; included stones rare. Uppermost 3 feet oxidized to yellowish-gray hue. (Pre-Wisconsin, probably Illinoian.) Maximum	23.0
Maximum thickness	75.0
Erosional unconformity with relief of 15 feet at altitude approximating 1,350 feet.	
Bedrock. Niobrara formation.	

This section, revisited in September 1950, had been cut back about 700 feet from the face exposed in 1948. It exposed 90 to 115 feet of till (unit 1), almost entirely free of boulders and so compact that the excavating contractors were blasting it in preference to the use of power shovels. The basal part of the till consists largely of chalk reworked from the Niobrara formation immediately beneath. The great thickness and physical character of this till support the opinion that it is pre-Wisconsin.

Locality 8. Section exposed in gully, October 1949, in NE¼NW¼ sec. 2, T. 93 N., R. 57 W., Yankton County, S. Dak.

[Measured by H. E. Simpson]

	Feet (maximum)
4. Till, consisting of abundant stones in a silt-rich matrix; grayish-orange when dry, moderate yellowish-brown when moist; friable, mealy; structureless; calcareous. (Cary.)	1.7
3. Loess, moderate yellowish-brown when dry, dark yellowish-brown when moist; structureless; calcareous. (Iowan and [or] Tazewell.)	0.8
2. Till, consisting of abundant pebbles in a silt-clay matrix; grayish-orange when dry; moderate yellowish-brown when moist; cut by many closely spaced joints; top 0.2 foot altered to grayish-black Weisenbödenlike soil, noncalcareous; beneath the soil zone the till is calcareous. (Iowan.)	0.9
1. Till, consisting of pebbles in a silt-clay matrix; top 3 feet altered to black Wiesenbödenlike soil, noncalcareous; beneath the soil zone the till is compact, tough, with widely spaced joints along which oxidation is developing. Unoxidized areas are grayish blue; oxidized areas are grayish orange. (Illinoian?)	4.8
Base concealed.	
	8.2

Locality 9B. Shallow gully in draw, altitude approximately 1,400 feet, northeast corner of NW¼NE¼ sec. 13 T. 93 N., R. 57 W., Yankton County, S. Dak.

[Section measured, augered, and interpreted by H. E. Simpson]

	Thickness [1] *(feet)*	
	Exposed	*Augured*
4. Loess, very pale yellowish-brown (10 *YR* 7/2) with light-gray mottling when dry; massive; calcareous. (Iowan and Tazewell?)	0.	5.0
Contact sharp.		
3. Loess, clayey, pale yellowish-brown (10 *YR* 6/2) when dry; massive; leached but containing secondary calcium carbonate. (Loveland.)	2.0	5.0
Contact sharp.		
2. Till, light olive-gray, oxidized to moderate yellowish-brown along joints, massive, calcareous. (Illinoian.)	2.5	5.0
Contact sharp.		
1. Sand, gravelly, fine to coarse, yellowish-gray to grayish orange-pink, contains pebbles and cobbles and lenses and balls of silt and clay, feldspathic granules numerous in some strata. (Pro-Illinoian outwash.)	2.5	5.0
Base concealed.		

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[1] Thicknesses given should not be added horizontally or vertically.

The following section, located a short distance beyond the South Dakota State line, was exposed in a road-building excavation in June 1949 at the east abutment of the highway bridge across the Missouri River at Sioux City, Iowa.

Locality 16. Northwest corner of sec. 31, T. 89 N., R. 47 W., Woodbury County, Iowa

[Examined by R. F. Flint, H. G. Hershey, R. V. Ruhe, and G. D. Smith]

	Feet (estimated)
8. Soil zone, 1 to 2 feet thick, developed in the top of unit 7	9.0
7. Loess, very silty, massive, yellowish-gray, calcareous. (Cary and post-Cary.)	
6. Soil zone, olive-gray to grayish-black, carbonaceous; maximum 2 feet thick; developed in the top of unit 5. (Tazewell and Cary.)	35.0
5. Loess, very silty, massive, yellowish-gray; basal part with yellowish-orange mottling. (Iowan and Tazewell.)	
4. Mature weathering profile extending downward through the full thickness of unit 3 and locally into unit 2. (Sangamon.)	
3. Loess, rich in clay, in part secondary; dark yellowish-brown to grayish-red. (Loveland?)	3.0–10.0
2. Till, consisting of rare pebbles in an abundant matrix rich in clay and silt; compact, tough, conspicuously jointed; strong oxidation along joints. (Kansan? on basis of correlation by Iowa geologists.)	7.0–30.0
Erosional unconformity.	
1. Sand, fine, yellowish-gray; has both parallel and rolling bedding, foreset northeastward; local cut-and-fill stratification. (Kansan?) Maximum	10.0

Locality 17 (Sections A–D). Northeast bank of Skunk Creek and slope above bank in SW¼NE¼ sec. 11, T. 102 N., R 51 W., Minnehaha County, S. Dak.

[Exposed in July 1947]

Section *A*. Trench, 2.5 to 4 feet deep, exposing units 2, 3, and 4 and 1.5-inch auger hole passing through units 1 and 2.

[Trench section measured by R. F. Flint and D. R. Crandell, Auger hole measured by G. D. Smith, F. Riecken, H. G. Hershey and R. F. Flint]

Top of slope.

	Feet
4. Loess, well sorted as to size; upper part oxidized light olive-brown to yellowish-gray, grading downward into gray with brown mottling; calcareous throughout; uppermost 2 feet humified. (Iowan and post-Iowan)	7.0
Sharp contact.	
3. Till, consisting of numerous stones, mostly less than 2 inches in diameter, in clay-rich matrix; not tough; crumbly; faintly jointed; moderate olive-brown when moist; yellowish-gray when dry; iron and manganese oxide coatings on joint and pebble surfaces; matrix in basal part contains reworked underlying silt. (Iowan)	14.5
Contact smeared; indistinct.	
2. Silt, clayey, loesslike; unstratified; well-sorted as to size; very compact; moderate-brown when moist; moderate yellowish-brown when dry; uppermost 2 feet leached. (Loveland)	17.0
Sharp contact.	
1. Till, consisting of stones in clay-silt matrix; tough, compact; dark yellowish-brown when moist; uppermost 4 inches leached. (Loveland)	1.0
Sediments concealed beneath slope, to surface of creek	78.0
	117.5

A layer of volcanic ash is exposed on the slope south of the auger hole and at about the altitude of the bottom of the hole.

Section *B*. In head of gully about 600 feet east of Section A.

[Measured by R. F. Flint and D. R. Crandell].

Concealed to top of slope.

	Feet
3. Volcanic ash, like unit below but mixed with silt in proportions increasing upward, and streaked with yellow iron oxide; noncalcareous; maximum	1.7
Contact gradational.	
Volcanic ash, unstratified; noncalcareous; very light gray to white; apparently unaltered.[1] (Member of Sappa formation)	0.4
Contact sharp; nearly horizontal.	
2. Silt, clayey, poorly stratified, compact; at top olive gray, grading downward to grayish olive mottled with yellow iron oxide; noncalcareous. (Sappa formation.[2] Kansan?)	2.6
Contact sharp.	
1. Till, consisting of stones, mostly small, in abundant matrix rich in silt and clay; tough; light olive-gray when moist; uppermost 3 inches leached. (Kansan?)	1.0
Concealed beneath slope, to creek surface	39.5
	45.2

Section *C*. In head of gully, about 300 feet east of Section B.

[Measured by R. F. Flint and D. R. Crandell]

Concealed to top of slope.

	Feet
4. Till, like till in section A, unit 3. (Iowan.)	1.5
Contact smeared; indistinct.	
3. Silt, with clay content increasing upward; loesslike, nonstratified, very compact, olive-gray when moist in upper half, grading down into moderate brown; lower part noncalcareous; upper part slightly calcareous probably owing to secondary lime derived from overlying till. (Loveland?)	2.7
Contact sharp; nearly horizontal.	
2. Clay, silty, indistinctly laminated, compact; at top olive-gray grading downward into grayish olive, streaked and mottled with yellow iron oxide; faintly calcareous. (Sappa formation; Kansan?)	1.3
Contact indistinct, marked by very thin layer of colluvium(?).	
1. Till, consisting of small stones in abundant clay-rich matrix; tough, distinctly jointed; light olive-gray when moist; oxide coatings on joint faces, faintly calcareous. (Kansan?)	12.0
Concealed beneath slope, to surface of creek	25.5
	43.0

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[1] Pearlette ash (Frye, Swineford and Leonard, 1948, p. 505.)

[2] Condra, Reed, and Gordon, 1950, p. 22.

Section *D*.—In cut bank of Skunk Creek about 500 feet southeast of Section C

[Measured by R. F. Flint and D. R. Crandell, amplified by G. D. Smith]

Concealed to top of slope.

	Feet[1]
3. Till, consisting of small stones in silt-rich matrix; crumbly, moderate olive-brown when moist; some pebbles in colluvium are wind etched	5–25
Contact distinct.	
2. Silt, loesslike, containing rare scattered small pebbles; very tough, brownish-gray, slightly calcareous; uppermost part altered to Chernozem soil; top (glacially?) disturbed	3–13
1. Till, consisting of rare stones in clay-silt matrix; tough, jointed, light olive-brown when moist; no pebbles of carbonate rocks in uppermost 4 feet; calcareous throughout. Uppermost part altered to Chernozem soil and perforated with filled-in crayfish burrows containing shell fragments of the aqueous snail *Limnaea reflexa* Say	12–18
Base concealed at surface of creek.	

Interpretation of section *D* at locality 17:

3. Iowan till.
2. Silt of the Aftonian, Sappa, or Loveland deposits, probably the same date as the burrows, in the underlying till, containing the snail shells. According to Leonard (1950, p. 41) the known stratigraphic range of this snail, which certainly postdates the till, is Pleistocene (Aftonian) to Recent. Insofar as the silt does not resemble the silt of the Sappa formation in sections *B* and *C* or the silt of the Loveland loess in section *A*, it can be considered as most likely Fullerton.
1. Nebraskan, Kansan, or Illinoian till. Least likely Illinoian because the Chernozem soil indicates a post-till, presilt interval and because the overlying silt does not resemble silt of the Loveland. The vertical position of the top of the till, substantially lower than the tops of the basal tills in section *B* and *C*, and the dissimilarity of the silt overlying it to the silt of the Sappa in those sections, suggests that this till is more likely Nebraskan than Kansan.

Locality 19 (Sections A and B). Road cuts 500 feet west of bridge over Big Sioux River in SW¼ sec. 27 and NW¼ sec. 34, T. 106 N., R. 49 W., Moody County, S. Dak.

[Sections exposed in June 1947]

Section *A*. South side of road.	Feet
4. Silt, pale yellowish-brown when moist; light olive-gray to pale yellowish-brown when dry, with very fine sand; streaked with dark yellowish-orange; indistinctly laminated; very tough; irregularly jointed subvertically; noncalcareous except for a few areas far from joints. (Loveland?, probably in part eolian)	10.5
Sharp contact.	
3. Till, light olive-gray when moist; consists of a few stones less than 10 inches in diameter in clay-rich matrix; tough; jointed; blocky; joint faces and stone molds coated with iron and maganese oxides; calcareous. (Illinoian?)	13.5
2. Silt, sand, and gravel. At top, olive-gray silt, indistinctly laminated, grading down into light olive-gray silt interbedded with medium and fine sand and pebble gravel. Pebbles mostly less than 0.5 inch in diameter, and poorly rounded. Uppermost 10 inches noncalcareous. (Sappa formation; Kansan?)	4.2
1. Till, consisting of very few, very small stones in clay-rich matrix; lower part olive-gray when moist, light olive-gray when dry; uppermost 4.5 feet oxidized; extremely tough; blocky; calcareous throughout. (Kansan?)	26.3
Concealed to surface of Big Sioux River	18.0
	72.5

Section *B*. North side of road.	
4. Silt and sand, like section *A*, 4, consisting of a humified silt zone, 0.5 feet; leached silt zone, 1.5 feet; silt zone of secondary carbonates, 3.0 feet; and an oxidized zone of silt and sand, 2.0 feet; (Loveland?, probably in part eolian)	7.0
Contact gradational.	
3. Granule gravel and coarse sand, lithology like that in drift; indistinctly stratified; thoroughly oxidized to dark yellowish-orange. Stream deposits, either outwash or reworked drift, occupying stratigraphic position of Crete formation; (Illinoian)[1]	2.0
2. Stone concentrate	1.0
1. Till[2], identical with Section *A*, 3; (Illinoian?)	11.0
	21.0

Locality 20. Road cut, ditch, and stream bank, exposed in July 1947 in NE¼ sec. 14, T. 104 N., R. 49 W., and adjacent part of sec. 11, Minnehaha County, S. Dak.

[Composite section]

	Feet (maximum)
5. Sand, medium-grained, yellowish-gray; indistinctly and irregularly stratified	6
4. Gravel and sand, little sorted; includes ventifacts	1.5
3. Till, pale yellowish-brown when dry; matrix sandy to clayey; weak and crumbly	8
Concealed	4
2. Clay, silty; yellowish-gray when dry; uppermost 0.2–0.8 feet humified to light olive-gray when dry; indistinctly laminated; contains erratic pebbles and minute mollusk shells stratigraphically not diagnostic but indicating a pond environment; calcareous	2.5
1. Till, dusky-yellow when dry; very few stones, no boulders; very compact; coarsely jointed; blocky	7
Base concealed.	
	29

Interpretation:

5. Eolian sand, Iowan and (or) post-Iowan.
4. Iowan outwash.
3. Iowan till.

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[1] Thicknesses are maxima and minima exposed throughout 250 feet horizontally.

[1] Condra, Reed, and Gordon, 1950, p. 24.

[2] Base of Section *B*, 1 is 6 feet higher than top of Section *A*, 1.

2. Pre-Wisconsin aqueous sediment, probably local.
1. Pre-Wisconsin till, most likely Illinoian.

Locality 22. Road cut on Cliff Avenue, Sioux Falls, in the north bluff of the Big Sioux River trench, southwest corner of sec. 3, T. 101 N., R. 49 W., Minnehaha County, S. Dak.

[Composite section prepared from exposures through a north-south distance of 200 feet, observed in 1947, 1948, and 1949]

	Feet (maximum)
Surface marked by several boulders, which either overlie or project through the loess.	
10. Loess, coarse, noncalcareous; top 1.4 feet humified, lower part brownish. (Wisconsin.)	3.2
Gradational contact.	
9. Silt or loess, very sandy; basal 0.5 foot nearly all sand; nonstratified, noncalcareous, brownish. (Wisconsin.)	2
Sharp contact, marked by discontinuous stone concentrate.	
8. Till, consisting of abundant pebbles in a clay-silt matrix; firm; light olive-brown when moist; oxidized throughout, calcareous throughout; (Tazewell?)	7
Sharp contact.	
7. Loesslike silt,[1] somewhat clayey, even textured; upper part oxidized, lower part gray with brown mottling; calcareous. (Iowan and post-Iowan, either in place or as a large inclusion in till 6 or 8.)	2
Sharp contact, indistinct to southward.	
6. Till, consisting of pebbles in a clay-rich matrix; moderate olive-brown when moist, calcareous. (Iowan?)	16
5. Sand, fine, light olive-gray; parallel bedded in nearly horizontal layers averaging less than 1 millimeter thick, some with dark carbonaceous matter; faintly jointed; coarse and irregularly bedded at south end; uppermost 1 foot noncalcareous; remainder slightly calcareous. (Iowan?)	6
Sharp contact.	
4. Colluvium and Wiesenböden soil zone, consisting of dark-gray clay and silt, indistinctly laminated, containing minute gastropod shells; faintly calcareous in southern part of cut only. (Pre-Iowan)	7.2
Gradational contact.	
3. Till, light olive-gray when moist; with streaks and blotches of moderate brown iron oxide, calcareous, with top 2-foot zone characterized by whitish nodules of secondary carbonates; uppermost 30 feet oxidized. (Pre-Wisconsin)	47.5
2. Concealed	12
1. Till, like unit 3 but lacking secondary carbonates	8
Base concealed at estimated 50 feet above Big Sioux River	
	110.9

The gastropod shells at horizon 4 are of a single species, *Amnicola cincinnatiensis* (identified by A. B. Leonard). Its presence indicates perennial water, but it is of no stratigraphic significance.

A composite section measured in 1927 by Kay (Kay and Apfel, 1929, p. 161) is as follows:

Locality 25. Two miles east of South Dakota State line in SE¼ sec. 14, T. 98 N., R. 48 W., Lyon County, Iowa

	Feet
5. Loess, buff-colored, lowest 1 foot gray and has iron tubules; unleached except upper 3 feet, which is dark brown and leached	14
4. Till, Kansan, oxidized, unleached, has concretions, sand pockets, breaks into irregular shaped fragments, jointed	38
3. Silts, alternating bands of dark-brown, chocolate-colored calcareous silts and lighter colored loesslike silts with no pebbles and highly calcareous and having concretions	30
2. Till, Nebraskan, oxidized and unleached, dark-brown, chocolate-colored stains along many joints, many lines of concretions, breaks into irregular fragments	10.5
1. Till, Nebraskan, unoxidized and unleached, dark gray in color, highly calcareous, has concretions, starch-like fracture	15
	107.5

As stated in the foregoing description, Kay interpreted the two tills as Kansan and Nebraskan, respectively. However, the section was revisited by various geologists in 1947 and 1948. A molluscan fauna collected by Leonard (1950, p. 6, 41) from the silt of unit 3 consists of 8 genera, of which 3 are not known to occur elsewhere than at the Sappa horizon, and the remaining 5 occur in deposits ranging in age from Sappa to Recent. None have been found in pre-Sappa deposits elsewhere. It is therefore likely that the silt is Sappa. It follows that the overlying till (4) can not be Kansan, as Kay believed, but must be post-Kansan. In the writer's opinion this till is Iowan. The lower till (2) may be Nebraskan, as Kay thought, but is more likely Kansan.

Locality 28. Road cut 0.1 mile west of the north quarter corner of sec. 16, and 0.1 mile west of the south quarter corner of sec. 9, T. 96 N., R. 48 W., Lincoln County, S. Dak.

[Exposed in July 1947]

	Feet
4. Loess (Iowan and post-Iowan.)	5.0
3. Concentrate of stones, including ventifacts; lying directly on	
2. Till, dusky-yellow when dry; clay-rich matrix with pebbles, cobbles, and one boulder; calcareous. (Iowan.)	12.0
1. Clay, silty, pale-brown to reddish; weathers with minute hexagonal cracks; checks when dry; grades downward into similar material containing sand-size grains and granules exclusively siliceous; noncalcareous.[1] (Illinoian? till and loesslike silt altered to gumbotil and gumbo silt.)	10.0
Base not reached.	
	27.0

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[1] Occurs in northern part only, pinching out southward, where its stratigraphic position is represented by a thin layer of whitish secondary carbonates.

[1] Only the uppermost 4 feet of unit 1 were exposed. The basal 6 feet of the section were measured by augering.

TILLS BELIEVED TO BE PRE-WISCONSIN ON TOPOGRAPHIC EVIDENCE

The second group includes sections that expose tills believed to be pre-Wisconsin by virtue of their relations to topography, rather than through direct stratigraphic evidence, which is lacking. This group includes five sections, all located in the southern or southeastern part of the State. They are localities 2, 3, 6, 26, and 27 on figure 6.

In this group of exposures the tills, unlike the Wisconsin tills, are unrelated to the existing topography. Clearly they were deposited before the erosion occurred that resulted in the present-day relief. As this relationship has not been observed in the Wisconsin deposits, other than along the immediate bluffs of present-day streams where erosion is now very active, it is believed to indicate pre-Wisconsin dates for the tills concerned.

Locality 2. Exposures in bluff of Missouri River trench in secs. 6, 7, 18, 19, 30, T. 103 N., R. 71 W., Brule County, S. Dak.

[Composite section, from observations by R. F. Flint in 1946 and C. R. Warren in 1949]

	Feet (maximum)
4. Loess, including a soil zone, and overlain by boulders (till equivalent). (Wisconsin undifferentiated.)	10
Sharp contact.	
3. Till, yellowish; consisting of stones in abundant matrix rich in silt and sand; probably reworked from unit 2; maximum thickness estimated. (Iowan.)	10
Contact not exposed.	
2. Till, consisting of stones, mostly pebble size, in abundant matrix of silt and clay, light olive-gray to greenish-gray, compact, cut by widely spaced joints along which oxidation is occurring in upper part, calcareous. (Illinoian?)	120
Sharp contact.	
1. Sand and gravel, largest pebbles about 0.7 inch in diameter; pebbles mostly well rounded; western provenance; stratification not determined because of poor exposure. (Crete formation?)	70
	210

Sharp contact.
Pierre shale.

Locality 3. Road cut at top of northeast bluff of Missouri River trench. West quarter corner of sec. 24, T. 100 N., R. 71 W., Charles Mix County, S. Dak.

[Altitude of top of section approximately 1,900 feet]

	Feet
Till, consisting of sparse stones and one boulder in silt-rich matrix; oxidized dusky-yellow when dry throughout; tough; inconspicuously jointed; contains many inclusions of contorted, stratified and semistratified drift; extensively impregnated with gypsum	36.0

Pierre shale.

Interpretation.—This till, which has the general physical character of the pre-Wisconsin tills and which resembles till 1 in locality 4 (p. 34) is believed to be Illinoian. It is perched on the crest of the bluff, 550 feet above the river; yet no eroded remnants of till occur anywhere between this exposure and the river. This fact suggests that the till antedates the Missouri trench; yet, as explained in the text, there is no evidence that either Nebraskan or Kansan ice reached as far west as this locality. If this reasoning is accepted, the till can be only Illinoian.

Locality 6. In sand and gravel pit on farm of Albert Hieb in NW¼ sec. 23, T. 97 N., R. 62 W., Douglas County, S. Dak.

[Exposed in 1946 and 1947]

	Feet
4. Boulders scattered on dissected surface. (Wisconsin till equivalent.)	
3. Till, consisting of stones and a few boulders in a clay- and silt-rich matrix; light olive-gray when moist; uppermost 10–12 feet oxidized dusky-yellow; contains inclusions of olive-gray clay-rich till and dusky-yellow loesslike silt; in places cut by structures resembling clastic dikes; (Illinoian?) Maximum	22.0
Sharp, flat-lying erosional contact, in places transecting stratification of unit 2.	
2. Gravelly sand, pebble sizes less than 5 percent of total; largest fragments about 1 inch in diameter; mostly medium and coarse sand; grains varyingly rounded; yellowish-gray, locally with a faint pinkish hue owing to presence of abundant pink feldspar; lithology western; cut-and-fill stratification, in courses 12 to 20 inches thick, with foreset beds predominantly sloping northeast; contains fossil vertebrates not later than early Kansan; (Red Cloud formation)[1]	24.0
Unconformity; upper surface of unit 1 faintly channeled.	
1. Silt, grayish-olive when moist; micaceous; compact; indistinctly laminated; 2 feet exposed; 2 feet augered; (Interglacial? alluvium; possibly Fullerton formation)	4.0
Base concealed	
	50.0

Locality 26. Road cuts extending through north-south horizontal distance of about 1 mile in east half of secs. 12 and 13, T. 97 N., R. 49 W., Lincoln County, S. Dak.

[Composite section exposed in June 1947]

	Feet
4. Scattered boulders, foreign, chiefly granitic. (Cary till equivalent at surface.)	
3. Loess, fine-grained, light olive-gray when dry, oxidized, calcareous; includes conspicuous zone of small calcareous nodules in upper part. (Iowan and Tazewell.)	15
2. Till, light olive-gray when moist, mottled in places with dark yellowish-orange; consists of small stones in a clay-rich matrix; conspicuously jointed, blocky, calcareous. (Illinoian.)	98
Sharp, flat-lying contact.	

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[1] Schultz, Reed, and Lugn, 1951.

	Feet	Feet
1. Sand, silt, and clay, proglacial lacustrine and fluvial sediments, mostly horizontally stratified:		
h. Sand, medium; indistinctly laminated	19	
g. Sand, fine, silty; contains large platy calcareous concretions	21	
f. Clay, silty, olive-gray when moist, blocky; contains small gastropods	12	
e. Sand, very fine, interbedded with coarse silt	11	
d. Concealed	20	
c. Sand, medium to fine, with beds of small angular pebbles; crossbedded with foresetting predominantly southward	16	
b. Concealed	31	
a. Clay, light olive-gray, indistinctly laminated, faintly blocky	3	
Total for unit 1		133
Total for section		246

Base concealed in bed of creek near its mouth in Big Sioux River.

Gastropods from horizon 1 *f* were collected by A. B. Leonard, who kindly furnished this list and comment:

Gyraulus, sp. (fragmentary, not identifiable)
Helisoma antrosa
Lymnaea palustris
Lymnaea reflexa

Fragments suggesting additional species also occur. As the species identified are known to occur in deposits from Aftonian to Recent, they do not afford a specific date for these deposits.

The significant fact here is that till 2 is unrelated to the existing togopraphy. Both this till, and the sediments of unit 1 that underlie it, antedate the existing valleys and seem to be related to a former broad valley that drained southwest (pl. 7). As the Wisconsin drift sheets elsewhere in South Dakota are generally related to the present topography, it is inferred that till 2 is pre-Wisconsin. The underlying sediments may well have accumulated in a lake ponded at the margin of the inferred pre-Wisconsin glacier shortly before the ice reached its maximum extent.

Locality 27. In the south bluff of the valley of Big Sioux River. Line separating secs. 16 and 17, T. 97 N., R. 48 W., Lincoln County, S. Dak.

[Section exposed in June 1947]

	Feet
3. Loess, identical with loess of locality 26, unit 3 except that it contains pipelike ferruginous concretions; (Iowan and Tazewell.)	11.0
Sharp, flat-lying contact. Pebbles concentrated at contact, about	0.2
2. Till, identical with till of locality 26 unit 2 except that it is more widely mottled and stained with limonite. (Illinoian.)	128.0
Concealed	5.0
1. Sand and silt, proglacial lacustrine and fluvial; sediments similar to that in locality 26 unit 1 except that little clay is included. (Illinoian?)	85.0
Base concealed beneath floor of valley.	
	229.2

TILLS BELIEVED TO BE PRE-WISCONSIN ON INTERNAL EVIDENCE

Tills described in the foregoing paragraphs possess certain physical characteristics in common that differ from those observed in tills identified, on evidence independent of physical characteristics, as Wisconsin. When such characters are observed in exposed tills without direct evidence of correlation, it is tentatively inferred that the tills are pre-Wisconsin. Exposed tills inferred to be pre-Wisconsin solely because of their physical appearance are found in the following listed 12 localities, which are shown on figure 6. The list is offered with the qualifying statement that the dating is provisional only, and that no basis whatever has been found for assigning any supposed pre-Wisconsin till to any particular pre-Wisconsin stage.

Localities of occurrence

[Locality numbers correspond with numbers on the map, figure 6]

1. NW¼SW¼ sec. 32, T. 114 N., R. 67 W., Hand County. Road cut. Exposed in 1948: 8 feet of till overlain with erosional unconformity by Mankato(?) outwash gravel.
5. SW¼SW¼ sec. 36, T. 104 N., R. 62 W., Davison County. Road cut. Exposed in 1948: 11 feet of till overlain by Mankato (?) outwash.
7. Southeast corner sec. 18, T. 102 N.; R. 59 W., Hanson County. Road cut. Exposed in 1948: 18 feet of till overlain by sand and Mankato(?) till.
11. Northwest corner sec. 5, T. 94 N., R. 53 W., Clay County. Section in creek bank at railroad crossing. Exposed in 1946 and 1947: 22 feet of calcareous till capped by a stone concentrate, base concealed.
12. 0.1 mi. west of the north quarter corner of sec. 6, T. 93 N., R. 52 W., Clay County. Section exposed in 1946: 12 feet of till, with base concealed, and overlain (above a concealed interval) by loess and till, both considered to be Wisconsin.
13. SE¼NE¼ sec. 24, T. 92 N., R. 52 W., Clay County. Section 500 feet long on west side of South University Street, Vermillion. Exposed in 1946 and 1947: 49 feet of calcareous till, with base concealed, overlain by 8 feet of loess believed to be Cary and post-Cary.
14. E½NE¼ sec. 21, T. 92 N., R. 51 W., Clay County. Long road cut in bluff of Missouri River trench. Exposed in 1946 and 1947: 40 feet of till, base concealed.
15. NW¼NW¼ sec. 24, T. 92 N., R. 51 W., Clay County, Long road cut in bluff of Missouri River trench. Exposed in 1946: 30 feet of calcareous till (base concealed) overlain with erosional unconformity (further marked by local stone concentrates) by 5 to 15 feet of loess believed to be Cary and post-Cary.
18. SE¼ sec. 8, and SW¼ sec. 9, T. 107 N., R. 48 W., Moody County. Cuts along road descending south bluff of Big Sioux River trench. Exposed in 1947: 52 feet of till, concealed by colluvium at base of bluff, the uppermost 35 feet of which are oxidized. Overlain by a thin cover of loess believed to be Wisconsin, probably Cary.
20. SE¼ sec. 11 and NE¼ sec. 14, T. 104 N., R. 49 W., Minnehaha County. Stream bank and ditch. Composite section exposed in 1947: 7 feet of till, overlain by aqueous clay and by till thought to be Iowan.

23. Near center of sec. 9, T. 101 N., R. 49 W., Minnehaha County. Below parapet retaining U. S. Highway 77 across a spillway tunnel for the Upper Sioux Valley Drainage Canal. Rothrock and Newcomb (1926, p. 15) reported a section, exposed in 1925, of 120 feet of till. In 1947 and 1949 till about 80 feet thick was exposed, with 40 feet below it concealed by colluvium. The uppermost 30 feet are oxidized dusky yellow; below the oxidized zone the till is light olive-gray when dry.
24. East quarter corner sec. 10, T. 101 N., R. 49 W., Minnehaha County. Great Northern Railway Co. sand-and-gravel pit. Exposed in 1947: 8 feet of till, constituting a massive knob projecting upward into an extensive body of Cary(?) outwash.

DISTRIBUTION OF TILLS

A comparison of localities having exposed tills believed to be pre-Wisconsin (fig. 6) with the general map of surficial deposits (pl. 1), shows that most of the localities are close to major present drainage lines, where dissection and relief are at a maximum. This fact implies that pre-Wisconsin drift occurs, perhaps widely, beneath the more extensive areas of little dissection on the Coteau des Prairies and in the extreme southeastern part of the State. Wide and deep erosion of the James River lowland by Wisconsin glacier ice makes it improbable that much pre-Wisconsin drift is preserved beneath that lowland (p. 154–155).

The only direct inference as to geologic history that can be drawn from the distribution of the tills is that during some glacial age or ages antedating the Wisconsin age, glacier ice covered southeastern South Dakota as far west as the Missouri River in Brule County. More specific inferences as to pre-Wisconsin glaciations, however, can be drawn from other kinds of evidence (p. 52–54).

OTHER POSSIBLE PRE-WISCONSIN DEPOSITS

TILLS FOUND IN BORINGS

The assembled subsurface data on eastern South Dakota reveal very meager indications of pre-Wisconsin tills. Of the 20 borings located on the map (fig. 25) and shown in figure 26 and plate 6, only two (at localities 2 and 8) include units so interpreted, and in each the interpretation is questionable. Both borings are located in prediversion valleys. This fact permits assignment of the tills in question to the pre-Wisconsin dates.

BOULDERS

In many places throughout the glaciated region of South Dakota boulders, mostly granitic, and noticeably roughened by differential weathering, occur on the surface. Roughening appears to have been brought about by alteration of ferromagnesian minerals and feldspars as compared with unaltered grains of quartz. Such boulders are a part of the Wisconsin drift, and are scattered through a vastly greater number of boulders of similar rock types that are fresh and free of differential weathering. This fact seems to preclude the possibility that the weathering postdates the Wisconsin glaciations. Neither can the weathering antedate the Pleistocene glaciation in all cases, because the form of the weathered surfaces of some of the boulders indicates that these were glacially abraded before they were weathered. It is inferred that some and perhaps all of the roughened boulders formerly constituted parts of one or more pre-Wisconsin drift sheets, that they were exposed and weathered during one or more interglacial ages, and that they were then picked up and moved again by Wisconsin glacier ice.

OUTWASH

At four localities (fig 6, localities 9*A*, 9*B*, 19*B*, and 26) represented by measured sections, there are stratified sediments whose stratigraphic positions indicate that they are pre-Wisconsin and whose lithologic character is such that they could represent bodies of outwash. At the first locality (9*A*) alluvium underlies Loveland loess, as shown in the following section, with a contact that is apparently transitional. For this reason it is thought to represent Illinoian outwash—possibly the lateral margin of a valley train of the Missouri River—rather than a sedimentary body of some earlier date.

Locality 9A. Cut on east side of road exposed in 1951. Near center SW¼ sec. 14, T. 93 N., R. 57 W., Yankton County, S. Dak.

[Section measured and interpreted by H. E. Simpson]

	Feet (*maximum*)
4. Loess, very pale yellowish-brown, mottled with light-gray when dry; massive, with prismatic structure; calcareous; contains scattered sand grains and small calcium-carbonate concretions. (Iowan and post-Iowan.)	10.0
Contact sharp to transitional due to reworking of unit 3.	
3. Loess, dark yellowish-brown to moderate yellowish-brown when dry; massive, with prismatic structure; leached; contains secondary calcium carbonate. (Farmdale? of Leighton.)	3.9
Contact sharp.	
2. Loess with soil profile; upper part dark yellowish-brown; massive, with prismatic structure; leached, contains secondary calcium carbonate. Lower part clayey, moderate yellowish-brown when dry; massive, with prismatic structure; leached; contains secondary calcium carbonate. (Loveland.)	5.2
Contact transitional.	
1. Sand, clayey and silty, dark-gray to grayish-black; stratified; leached. (Illinoian alluvium.)	2.0
Base concealed.	
	21.1

At a second locality (26 on fig. 6; see p. 38–39) lacustrine or alluvial sediments underlie a pre-Wisconsin till without intervening weathering or deep erosion, and have a thickness greater than 133 feet. Their predominantly parallel stratification and considerable content of clay and silt indicate that these sediments are lacustrine at least in part, and probably accumulated in a lake in front of a growing ice sheet. As the sediments occur within the area of an abandoned former valley of major size (pl. 7) it seems likely that the lake was created by damming of the ancient valley, on the southwest side, by a pre-Wisconsin James glacial lobe. The lacustrine sediments may have been derived both from that lobe and from the Des Moines lobe on the northeast. The existence of these lobes is assumed by analogy with the clearer record of glacial lobes of Wisconsin age. The lacustrine sediments were later overridden by the advancing ice sheet and were covered with till. Presumably this was the Illinoian glaciation, although proof is lacking that this drift does not pertain to a still earlier glacial stage.

The third locality at which pre-Wisconsin stratified material has been observed is 19 *B* (fig. 6, p. 36). Although the sediment exposed at that place is pre-Loveland alluvium, it lacks features distinctive of outwash; hence its interpretation as outwash is only a possibility. It is separated from the till beneath it by a stone concentrate, which records erosion of the till before the alluvium was deposited. This fact does not preclude the outwash hypothesis; it means merely that the stratified sediment was laid down after the till at that locality had been eroded. Whether this stratified body actually represents outwash remains undetermined.

The three bodies of stratified drift enumerated above have two very different relationships to weathering. The body at locality 19 *B* is thoroughly oxidized, whereas the other two are hardly altered at all. The difference is not significant, inasmuch as each of the two little-altered bodies is overlain by thick sediments, which protected the material underlying them from substantial alteration, whereas the more-altered body was affected by the oxidation that altered the Loveland loess during the Sangamon interglacial age. Degree of weathering alteration, therefore, is not necessarily a measure of relative age.

The scarcity of exposed sediments that even possibly may represent pre-Wisconsin outwash is not remarkable. The widespread covering of pre-Wisconsin drift by Wisconsin drift has been noted already. More significant, perhaps, is the fact that, as shown in a later section, Wisconsin outwash in South Dakota is generally very thin owing to the character of the bedrock; therefore the pre-Wisconsin outwash bodies must, of necessity, have been thin also. Furthermore outwash is commonly deposited along major streamways, where post-outwash erosion is likely to be concentrated. For this reason outwash is a vulnerable kind of deposit; it is not likely to have survived, in quantity, the inroads of erosion during the interglacial ages that succeeded the times of greatest outwash accumulation.

SUMMARY OF PRE-WISCONSIN GLACIAL DEPOSITS

In summary, there are exposed in eastern South Dakota tills known or inferred to represent pre-Wisconsin glacial stages. At certain localities a till underlies deposits believed to be the Sappa formation, and hence is inferred to be either Kansan or Nebraskan, more likely the former. At other localities a till underlies the Loveland loess and hence is Illinoian or pre-Illinoian, more likely the former. In no exposure has either Nebraskan or Kansan till been identified unequivocally, although it is certain that at least one of them is present. However, as both these tills occur in western Iowa and eastern Nebraska, there can be no doubt that both Kansan and Nebraskan glaciers successively travered at least part of South Dakota.

In eastern Nebraska, the Nebraskan drift generally contains little or no Sioux quartzite, whereas the Kansan drift contains abundant fragments of the formation (E. C. Reed, written communication). Possibly this difference is the result of the quartzite body not having been denuded of its Cretaceous cover, and exposed to erosion, until Aftonian time. In South Dakota most of the exposures of pre-Wisconsin drift occur in or south of the area of outcrop (beneath the drift) of the Sioux quartzite. Of these, the ones known or likely to be pre-Illinoian contain quartzite fragments. On a basis of this reasoning the drifts in question may be Kansan rather than Nebraskan.

Much of the pre-Wisconsin till exposed in South Dakota is believed to be Illinoian, but except in the Chamberlain district the evidence is indirect, and hence in most exposures till believed to be Illinoian can not be so dated with entire confidence.

Pre-Wisconsin outwash is scarce; hence the cited record of deposits made by the proglacial streams of pre-Wisconsin glacial ages is very meager indeed.

PRE-WISCONSIN NONGLACIAL DEPOSITS

Pre-Wisconsin nonglacial deposits, like pre-Wisconsin tills, are exposed in South Dakota in only a few places. This fact is not surprising. Probably it is a direct result of Wisconsin glaciation, more extensive in that State than the glaciations of earlier date, having in part destroyed preexisting deposits, and in part concealed them beneath a nearly continuous blanket of Wisconsin drift.

In consequence, knowledge of such features is so fragmentary that reconstruction of a continuous sequence of events in Pleistocene history from them is not possible. On the other hand eastern Nebraska and southwestern Iowa were far less affected by Wisconsin glaciation; therefore the record of pre-Wisconsin events that they preserve is much more nearly complete. For this reason it is desirable to summarize the stratigraphic column already established in this adjacent region, and then to attempt to fit the fragmentary record from eastern South Dakota into that column.

Western South Dakota is underlain extensively by pre-Wisconsin Pleistocene nonglacial stream deposits which include, in places, bones of fossil mammals, and which are commonly related to extensive stream terraces. Mapping and interpretation of this group of related features would add greatly to knowledge of the Pleistocene history of South Dakota. However, as most of these features lie west of the glaciated part of the State, they are beyond the scope of the present report.

STRATIGRAPHIC SEQUENCE IN NEBRASKA AND IOWA

The pre-Wisconsin Pleistocene features of nonglacial origin in Nebraska and western Iowa—stream deposits, loess, and weathering profiles, particularly stream deposits and loess—have been extensively investigated by the Nebraska Geological Survey, by surface methods and by an intensive program of test drilling, and described (Condra, Reed, and Gordon, 1950; Lugn, 1935; Kay and Apfel, 1929; Kay and Graham, 1943). A review of their correlation and significance in Nebraska is essential to an understanding of the somewhat scanty evidence of these features in eastern South Dakota. The term "nonglacial" here refers to the transporting or developing agency rather than to date or source of sediments. It is not meant to imply that a nonglacial feature was necessarily developed during an interglacial age.

STREAM DEPOSITS

The Pleistocene stream deposits in Nebraska include coarse and fine alluvium. Their stratigraphic relations are shown in figure 7.

The coarse sediments consist dominantly of sand and pebble gravel, derived from the west, in part apparently from as far west as the Rocky Mountains. The sand-and-gravel bodies constitute valley fills, in some areas spreading out of the valleys and covering interfluves. The fills reach maximum thicknesses of 300 feet. The stratigraphic relations of these sediments to the Nebraskan and Kansan till sheets and the conspicuous mixing of the western sediments, in the vicinity of those till sheets, with sediments of northeastern, glacial derivation, have led some Nebraska geologists to the belief that some of the sand-and-gravel bodies were deposited in part from the bed loads of western rivers whose downstream segments were in contact with Kansan and Nebraskan glacier ice. The ice deflected the drainage southward.

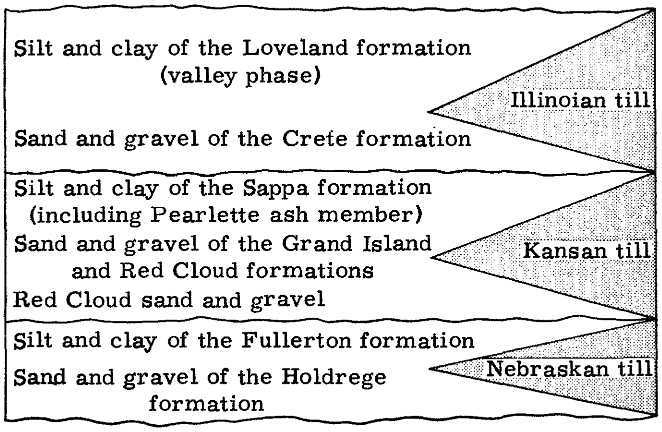

FIGURE 7.—Chart showing generalized stratigraphic relations of pre-Wisconsin Pleistocene deposits in Nebraska. (From Condra, Reed, and Gordon, 1950, p. 12; modified by Schultz, Reed, and Lugn, 1951.)

All these coarse sediments look alike and ordinarily are not separable on a basis of their appearance. They are, however, separable by virtue of their stratigraphic relations to till sheets, and they are in part identifiable through the mammal bones they contain. On this twofold basis four bodies have been recognized as distinct formations (Condra, Reed, and Gordon, 1950; Schultz, Reed, and Lugn, 1951). These are the Holdrege formation (Nebraskan), Red Cloud formation (lower Kansan), Grand Island formation (upper Kansan), and Crete formation (Illinoian). (See fig. 7.)

The Holdrege and Red Cloud formations constitute thick valley fills and are spread widely across interfluves. In contrast the Grand Island and Crete formations are confined to valleys and are less thick. It is inferred, therefore, that considerable dissection occurred during Kansan time, creating valleys to which subsequent deposits of sand and gravel were confined.

The four bodies of sand and gravel contain fossil vertebrates, mostly mammals; these are listed in plate 4. From this list it is apparent that the pre-Illinoian Pleistocene mammal faunas of Nebraska fall into two groups, separated approximately by the horizon of the Kansan till; it is mainly on the basis of this fact that the Red Cloud and Grand Island formations are considered to be two distinct units (Schultz, Reed, and Lugn, 1951).

The mammals of the lower group (antedating the Kansan till) were collected from localities in the western part of the State, from the Lisco member of the "Broadwater formation" of Schultz and Stout (1945, p. 232) and from the Red Cloud formation. They include prongbuck, llama, camels, peccary, horses, mastodonts, saber-toothed cats, skunk, badger, otter, wolf, fox, coyote, ground sloth, and a large variety of rodents.

This assemblage of animals represents a plains environment with a climate possibly somewhat moister than the present climate of the region.

The upper group (postdating the Kansan till) includes a number of immigrants, such as *Castoroides*, *Castor*, *Archidiskodon*, *Parelephas*, *Mammuthus*, *Equus excelsus* and *E. giganteus*, *Mylohyus*, *Cervalces*, *Alce*, *Symbos*, *Ovibos*, *Ovis*, and *Bison*. Of these genera, the mammoth (*Mammuthus*) and the two musk-oxen suggest a cold, possibly tundra, environment; while *Alce* and possibly *Cervalces* suggest a subarctic forest habitat. Not all these animals necessarily lived in Nebraska at the same time, for both the stratigraphy and the implied ecology involved permit their assignment to a wide range of time beginning with the Kansan glacial maximum and extending into Yarmouth time.

The fine alluvium in eastern Nebraska includes, in contrast, laminated silts and clays that are mainly fluvial but that may be in part eolian. Here three stratigraphic units are recognized: the Fullerton formation, the Sappa formation, and the Loveland formation (valley phase). The latter term is used here in the sense of Condra, Reed, and Gordon (1950, p. 24–26), who established the fact that it is not equivalent to the Crete formation, but postdates that unit.

Each of these silt-and-clay units occurs as relatively thin accumulations in former valleys now completely filled with sediments, and as a group these units alternate with the sand-and-gravel units. The top of each of the silt-and-clay formations is marked by a pronounced erosional unconformity. Although suspected previously, these facts were established chiefly through the results of systematic test drilling by the Nebraska Geological Survey (Condra, Reed, and Gordon, 1950, figs. 7, 8).

The Sappa formation contains a molluscan fauna of 65 species collected from 20 localities (Frye, Swineford, and Leonard, 1948, p. 506). This fauna implies a temperature probably no lower than that of today (Leonard, 1950). The vertebrate fauna of the Sappa formation likewise implies a climate no colder than the present climate (C. B. Schultz, written communication). Prominent in this fauna are ground sloths (*Megalonyx* and *Paramylodon*), mammoths (*Archidiskodon* and *Parelephas*), horse (*Equus excelsus*), tapir (*Tapirus*), peccary (*Platygonus*), camels (*Camelops* and *Tanupolama*), deer (*Odocoileus*), four-horned antelopes (*Stockoceros* and *Hayoceros*), and four-horned prongbuck (*Capromeryx*).

Correlation of the Sappa formation is facilitated by the presence in it of a widespread layer of volcanic ash, the Pearlette ash member, said to be petrologically distinctive and therefore recognizable as a key horizon wherever exposed (Frye, Swineford, and Leonard, 1948).

Although the Sappa fauna suggests interglacial conditions, current practice in the Kansas and Nebraska Geological Surveys is to regard the Sappa formation as upper Kansan (that is to say, glacial) and to restrict to the succeeding Yarmouth interglacial stage the deep weathering, soil development, and erosion that succeeded the deposition of the Sappa sediments. In an analogous manner, this practice also regards the Fullerton formation as upper Nebraskan rather than Aftonian, as formerly. This practice, followed in figures 8 and 13 for reasons of consistency, is provisional and for convenience only, and is manifestly permissible pending agreement as to where to place boundaries between glacial stages and interglacial stages in a nonglaciated region. The correlation of fossil-bearing stratigraphic units shown on plate 4 does not coincide in all respects with the correlation mentioned above. This results from unreconciled differences of opinion among geologists in the Nebraska-Kansas region.

LOESS SHEETS

The only pre-Wisconsin loess deposit that has been widely recognized in Nebraska and Iowa is the Loveland loess. Named Loveland by Shimek (1909, p. 405, footnote), from a locality in western Iowa, this deposit was later generally identified as chiefly loess, and, together with noneolian deposits, was incorporated by Kay (Kay and Graham, 1943, p. 63–85) into his Loveland formation. The Nebraska Geological Survey (Condra, Reed, and Gordon, 1950, p. 26–30) recognized this formation as consisting of an upland phase (loess), a valley phase (alluvium) and a slope phase (colluvium).

Mickelson[2] showed that the expanded Loveland formation of Kay included noneolian sediments of different dates, and that at least some of these sediments are referable to the Sappa formation. Accordingly he recommended that the Loveland loess should include only the sediments represented by the type section, as originally named by Shimek, and implied abandonment of the name Loveland formation in the wider sense. For simplicity and convenience this recommendation is followed in the present discussion.

The Loveland loess consists predominantly of silt, with minor amounts of very fine sand.[3] It is generally 3 to 6 feet thick, locally reaching 20 feet in Iowa and 60 feet in eastern Nebraska. It mantles an eroded surface including, in Iowa, the Sappa formation[4] and in

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[2] Mickelson, J. C., 1949, Reclassification of the Pleistocene Loveland formation of Iowa: Iowa Univ., unpublished Ph. D. dissertation, 97 p.

[3] See mechanical analyses, idem, p. 82–85.

[4] Idem, p. 86.

Nebraska the Crete formation, apparently without evidence of post-Crete, pre-Loveland weathering (Condra, Reed, and Gordon, 1950, p. 30). It is overlain by Wisconsin deposits, mostly loess. The date of Loveland loess deposition is thus fixed, at least in places, as post-Crete, pre-Wisconsin. It is deeply oxidized and deeply leached of its carbonates, and this alteration antedates the overlying Wisconsin deposits. Hence, as the sediments constituting the Crete are believed to date from about the time of the Illinoian maximum, the age of Loveland loess deposition could date from late Illinoian to fairly late Sangamon. In 1924 (Kay and Graham, 1943, p. 63–85) the opinion was generally held that the date of the Loveland formation of Kay was late Sangamon. Later, however, evidence began to accumulate that the Loveland loess (in the original sense) was deposited during a glaciation, hence cannot be Sangamon, and hence must be Illinoian. The evidence is as follows:

1. Grain-size distribution is identical with that of younger loesses in the region; hence the Loveland loess is a true loess.[5]

2. Mineral composition in samples from Iowa is similar to that of the same size grades in the (Kansan) till in the same region. Hence the Loveland loess is probably derived from glacial material.[6]

3. Areal distribution is in the form of a belt along the Missouri River from South Dakota to St. Louis, Mo., and on down the Mississippi River (Wascher, Humbert, and Cady, 1947). The total bulk is large. The Loveland loess thins and becomes finer grained with increasing distance from the Missouri River. Hence this loess must be derived from the outwash of a major glaciation, when outwash was being deposited extensively and vegetation on the outwash was at a minimum (Guy D. Smith, written communication).

4. In northern Missouri the Loveland loess is thoroughly weathered to a gumbo loess 3 to 5 feet thick, comparable in character and thickness to the gumbotil developed in the Illinoian till. Hence the major glaciation responsible for furnishing the sediment for the Loveland loess is probably the Illinoian (Guy D. Smith, written communication).

The opinion that the Loveland loess is mostly or wholly Illinoian is now general among geologists in Nebraska, Iowa, and Illinois.

From the time of its earliest recognition the Loveland loess has been described as "red," "reddish," "pink," and the like, although in many exposures it is similar in color to the Wisconsin loess sheets. The opinion has been expressed that this color is original; that is, that the sediment of the Loveland loess was red when deposited. Against that view is the more recent opinion of Nebraska geologists and pedologists that the color is mainly secondary and that it pertains to a well-developed soil profile in areas of good subsurface drainage.

If the latter opinion is accepted, then the "red" color of loess in Nebraska and Iowa is the result of weathering that formed the red iron oxides. It is noteworthy that no loess, proved to be Wisconsin on a basis of its stratigraphic relation to till sheets, shows such features. On the contrary the Wisconsin loess sheets, where oxidized, are paler, being generally yellowish rather than reddish. These implications are consonant with the relative stratigraphic positions of the Wisconsin loesses and the sediments that have been referred to the Loveland loess. The Wisconsin loesses were exposed at the surface during part or all of Wisconsin time, whereas the Loveland loess was subjected to weathering during part or all of the Sangamon interglacial age, which is believed to have been longer, and which certainly was warmer, than the Wisconsin glacial age.

Here it should be noted again that some of the Loveland formation of Kay is in fact pre-Illinoian. By analogy it seems likely that any "red" loess or other sediment that is actually pre-Illinoian owes its color to weathering during either of the two pre-Sangamon interglacial ages. Those were times when climatic conditions are believed to have been favorable to the creation of weathering products similar to those developed during the Sangamon age. Test drilling in Nebraska in 1950 established the presence of "red" loess whose stratigraphic position demonstrates that it is a part of the Sappa formation (E. C. Reed, oral communication).

The Loveland loess, in its original sense, is thought to be Illinoian, and is a true loess in which a distinctive weathering profile developed during the Sangamon interglacial age. The "reddish" hues ascribed to the Loveland are probably the result of oxidation. There seems to be no reason for the belief that such oxidation was peculiar to Sangamon conditions. On the contrary, it developed apparently during earlier interglacial ages, as indicated by published descriptions of deeply oxidized pre-Illinoian deposits. As, however, the latter deposits are rarely preserved, the statistical probabilities are that most of the reported occurrences of deep oxidation are Sangamon, even where direct stratigraphic proof of age is lacking.

WEATHERING PROFILES

A third pre-Wisconsin Pleistocene stratigraphic feature (although not a deposit) that occurs in Iowa and eastern Nebraska consists of gumbotil and related

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[5] Mickelson, op. cit., p. 85.

[6] Idem, p. 86.

weathering products. Gumbotil is a gray, leached, deoxidized clay that is the product of thorough and long-continued chemical decomposition of till under conditions of poor subsurface drainage beneath broad flat uplands. In Iowa gumbotil occurs commonly as the upper parts of pre-Wisconsin till sheets. It has there been found to have average thicknesses of 8 feet on the Nebraskan till, 15 feet on the Kansan till, and 3 feet on the Illinoian till (Kay and Apfel, 1929, p. 133). These gumbotil zones have proved useful in the mapping of the pre-Wisconsin drift sheets in Iowa.

In eastern Nebraska, gumbotil occurs in places but is not common. According to the Nebraska Geological Survey (Condra, Reed, and Gordon, 1950, p. 15) its rarity is the result of erosion, which has removed most of the gumbotil that may have existed formerly. In South Dakota also gumbotil rarely is exposed, probably likewise because of erosion.

Although gumbotil and related weathering products (Ruhe, 1948) constitute the most striking product of interglacial weathering, less thoroughly decomposed products of the interglacial alteration of till are likewise present at many places throughout the Central Lowland. These include weathering profiles in which oxidation of iron-bearing minerals and leaching of carbonate minerals have penetrated to various depths, in some places exceeding 30 feet. Black carbonaceous soils, which developed in poorly drained depressions in the ground moraine and in similar wet spots, are also included.

The weathering profile developed in the Loveland loess, and described in the section preceding is of course a product of chemical alteration. In Kansas (Frye, 1949, p. 480) the soil in the Loveland loess is much thicker than the modern soil at the present surface. Changes in its character between northeastern and north-central Kansas suggest a gradual decrease in precipitation and a change in plant cover from east to west. This change is parallel with, but greater than, the change that occurs in the modern soil through the same distance. The difference in rate of change between the two soils suggests a greater rate of change in mean annual precipitation, east to west, in Sangamon time than at the present time.

STREAM DEPOSITS IN SOUTH DAKOTA

The foregoing summary of pre-Wisconsin nonglacial features in Nebraska and Iowa, where such features are present more widely and have been studied more fully than in South Dakota, constitutes a framework into which the meager information available in South Dakota can be fitted. Exposures within eastern South Dakota are so few and collections of fossils are so incomplete that the correlations suggested in the following discussion must be regarded as tentative until much more information has become available.

The nonglacial stream deposits in South Dakota include both sand and gravel, and clayey silt. Each is described separately.

SAND AND GRAVEL

DISTRIBUTION AND THICKNESS

At various places in eastern South Dakota bodies of sand and gravel of far-western provenance are exposed, apparently identical with the western sediments commonly present in Nebraska. All possess approximately the same characters, which therefore can be described for the group as a whole.

These western sediments occur at various altitudes and in various topographic positions. They occur principally as broad spreads and isolated erosion remnants on high (though not the highest) interfluves, as veneers covering high strath terraces along the Grand, Cheyenne, Bad, White and Niobrara Rivers, and as valley fills (Todd, 1910, map). In all occurrences the bases of the deposits lie well above existing drainage lines. In some places the western deposits are overlain by till.

Although at several localities the base of a sand-and-gravel body is exposed, in all occurrences within the glaciated region the original top has been lost through erosion. In places west of the glaciated region the original tops of bodies of these sediments are preserved. Within the glaciated region, however, the tops of most of the observed sections are erosional; hence original thicknesses are unknown, although probably thicknesses were highly variable. An extreme thickness of 27 feet has been observed in a single exposure in Brule County, and thicknesses of 50 and 81 feet, respectively, have been inferred at two localities.

The occurrence of western sand and gravel on divides and in abandoned or buried valleys implies great modification of the topography since the various bodies of sand and gravel were deposited. (See fig. 10.)

PHYSICAL CHARACTER

The lithologic composition of the sand and gravel is different from that of the stratified drift. North of the White River a large proportion of the pebbles consist of carbonate rock types and various kinds of chalcedony. South of the White River 20 to 50 percent of the pebble-size fragments consist of pink feldspar, with subordinate pegmatites, white and brown quartzites, volcanic rocks, and chalcedony. In the glacial drift these constituents are negligible or absent. Most of the constituents mentioned could have been derived from the Black Hills and possibly in part from the Rocky Mountains in Colorado (Wanless, 1923, p. 262).[7] The presence of chalcedony and fragments of fossil mammal bones characteristic of various Cenozoic strata in the Great Plains region indicates that some of the material of the sand and gravel was picked up east of the Black Hills and Rocky Mountains.

The sand and gravel contain, in addition to the fossils derived from older deposits, mammal bones and teeth that are not abraded and that are believed to belong to animals that lived at the times of deposition of the western sediments. The fossils are scattered through the sediments so sparsely that they have generally been collected only where concentrated by screening or washing operations at sand pits. These operations concentrate the fossil fragments, but also they make it impossible to determine the exact position of any particular fossil within the deposit.

Grain-size distribution in samples from extreme southern South Dakota is shown by histograms (fig. 8). It is apparent that the sediments are predominantly of sand size, with minor amounts of pebbles, mostly of small diameter. North of the White River cobbles are present, the largest having a diameter of 10 inches.

Individual grains larger than silt particles show some degree of rounding. In a series of three samples collected from Gregory County, and Charles Mix County, S. Dak., and Cedar County, Nebr., respectively, together embracing an east-west distance of about 80 miles, grain size decreases eastward, and the extent of sorting and rounding increases in the same direction. (Laboratory report by S. S. Oriel on samples collected by R. F. Flint.)

Stratification is of the lenticular, cut-and-fill type, with individual courses several inches to about one foot in thickness. The foreset laminae have a pronounced easterly dip that is consonant with the western origin of the sediments.

DESCRIPTION BY LOCALITIES

Bodies of western sand and gravel have been mapped wherever observed east of the Missouri River trench, and west of but near the trench in the drainage basins of the Bad and White Rivers. The areas or points of outcrop are shown on a map (fig. 9) and are listed, together with what is known about the contained fossils, in the following paragraphs. The map and list do not include distinct terraces along the Grand, Cheyenne, and White Rivers, on which western sediments occur commonly as discontinuous coverings, nor do they include localities at which western sediments, mixed with sediments of glacial origin, are believed to have been reworked by glacial and postglacial streams.

Locality 1. Secs. 10 and 12, T. 8 N., R. 27 E., and secs. 11 and 12, T. 7 N., R. 27 E., Stanley County. Two remnants capping buttes on the high ground south of the mouth of the Cheyenne River, at altitudes of 2,100 to 2,200 feet (700 to 800 feet above Missouri River). A horse tooth was collected by Mr. D. R. Crandell from the exposure in section 10, but remains unidentified.

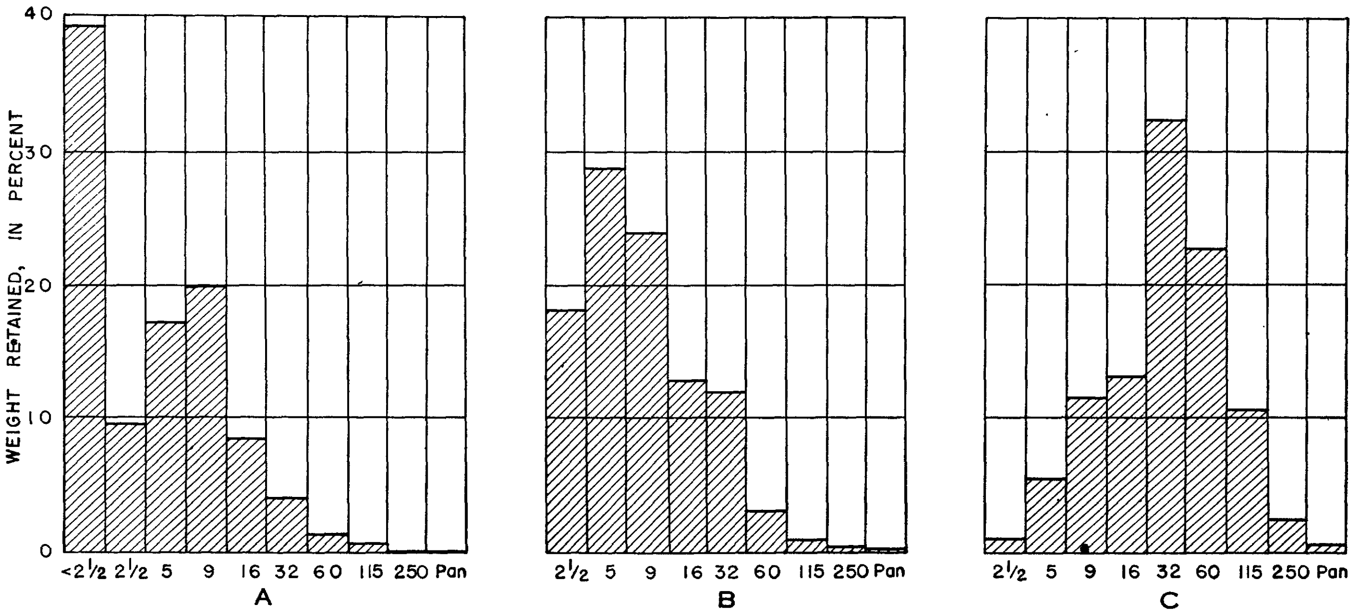

FIGURE 8.—Histograms showing frequencies of grain sizes smaller than cobble size in 3 samples of sand and gravel of western provenance. Numbers at bases of columns are Tyler screen mesh numbers. *A*, Bonesteel, Gregory County, S. Dak.; *B*, Pickstown, Charles Mix County, S. Dak.; *C*, Hartington, Nebr. The histograms suggest that in such sediments the mean grain size decreases toward the east.

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[7] Oral communications from E. B. Eckel, Lincoln Page, and James Norton of the U. S. Geological Survey, and E. L. Tullis, of the South Dakota School of Mines. These four persons kindly examined specimens of the pebble-size fractions of the material.

Based on U S Geol. Survey map of South Dakota

FIGURE 9.—Map showing localities in and close to the glaciated region at which sand and gravel of western origin, not mixed with glacial deposits, have been observed.

Sections 11 and 12, described by Crandell[8], yielded three fossil specimens which were identified by Dr. C. W. Hibbard in 1949 and 1951, as follows:

Part of vertebra centrum of Proboscidean
Neural arch of vertebra of Proboscidean
Fragment of lower molar of equid, possibly *Hippotigris* (=*Plesippus*), which has a known range from Upper Pliocene to the lower part of the Yarmouth.

The tooth fragment was examined again in 1951 by Dr. C. B. Schultz, who compared it favorably with examples from the upper part of the Ogallala formation in Nebraska. As the tooth fragment shows abrasion, it may antedate the deposit from which it was collected.

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[8] Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, p. 99–101.

Locality 2. Southern half of Stanley County. Twenty-eight erosion remnants north of the Bad River, ranging in altitude from 1,700 feet to 2,100 feet (250 to 650 feet above Missouri River). Crandell[9] interpreted them as remnants of a belt of coarse alluvium deposited by an ancestral Bad River (fig. 10). One remnant, in the NW¼ sec. 26 and center of sec. 22, T. 5 N., R. 29 E., yielded 2 groups of fossils collected by Mr. Crandell:

One group, identified by Dr. C. W. Hibbard in 1951, includes teeth of *Equus excelsus* or *E. niobrarensis.* This form has a stratigraphic range from upper Kansan to Wisconsin.

The other group consists of fossils examined by Dr. C. B. Schultz. He identified them as bison, camel, proboscideans, raccoon, and horse. The horse, represented by 5 teeth, was referred by him to *Equus excelsus.* He correlated this species tentatively with one from an horizon within the Grand Island or a higher one, possibly as high as the Illinoian stage.

Locality 3. Sec. 34, T. 107 N., R. 79 W., and NW¼ sec. 8, T. 106 N., R. 78 W., Lyman County. Remnants on the high interfluve between the Bad River and Medicine Creek, at an estimated altitude of 2,000 feet. No fossils are known from these deposits (D. R. Crandell, written communication).

Locality 4. Center of sec. 30, T. 107 N., R. 75 W., Lyman County. Cap on butte, altitude about 1,980 feet (700 feet above Missouri River). Fossils collected by D. R. Crandell were identified by Messrs. C. B. Schultz and W. D. Frankforter as parts of a Pliocene deer (mineralized and waterworn, indicating reworking from an older deposit), a phalanx of a camel, probably Pleistocene, and a phalanx and calcaneum of *Equus*, also Pleistocene (C. B. Schultz, written communication).

Locality 5. Secs. 16, 17, 20, 21, 28, and 29, T. 105 N., R. 72 W., Lyman County. Continuous cover over flat interfluve at about 1,800 feet (450 feet above Missouri River). Its extent west of the area designated above is unknown. No fossils have been found.[10]

Locality 6. Secs. 6, 7, and 19, T. 103 N., R. 71 W., and sec. 4, T. 102 N., R. 71 W., Brule County. Occupies abandoned prolongation of the valley of White River, and is overlain by thick till. Altitude of lowest part, about 1,470 feet (115 feet above Missouri River). No fossils have been found. (C. R. Warren, 1951.)[10]

Locality 7. SW¼ sec. 10, T. 102 N., R. 71 W., Brule County. Forms knoll on upland. Altitude of base of sand and gravel, about 1,800 feet (500 feet above Missouri River). (C. R. Warren, 1951).[10] A suite of fossils collected from this deposit were identified as follows:

Edentata: *Megalonyx* sp. Ground sloth
Carnivora: Felid, large. Large cat, size of *Smilodon* (too incomplete for generic identification)
Proboscidea: *Parelephas* cf. *jeffersoni* (Osborn). Mammoth. (Too incomplete for definite specific identification)
Perissodactyla:
  Equus excelsus Leidy. Horse
  Equus cf. *giganteus* Gidley. Large horse
Artiodactyla:
  Camelops kansanus Leidy, referred. Camel
  Camelid, larger than *C. kansanus.* Large camel
  Antilocaprid, similar to *Stockoceros.* Four-horned antelope
  Platygonus sp. Peccary
  Mylohyus sp. Peccary

Messrs. Schultz and Frankforter, who identified the fossils, expressed the opinion that this suite is probably of Yarmouth age, less probably as young as Sangamon (C. B. Schultz, written communication).

Locality 8. Vicinity of Burke, Herrick, St. Charles, and Bonesteel, Gregory County. Continuous cap, at least 25 miles long, on broad interfluve. Altitude 2,000 to 2,200 feet (at least 700 feet above Missouri River). Extent southeastward in Nebraska is unknown. No fossils from this area have been identified.

Locality 9. NE¼ sec. 2, T. 94 N., R. 65 W., Charles Mix County. In high area much dissected by Missouri River tributaries. Altitude 1,738 to 1,771 feet (about 500 feet above Missouri River). Exposed in the Gaspar sand and gravel pit, the sediment varies in thickness from 23 to 81 feet, and is overlain by till.

Fossils collected by H. E. Simpson were identified by C. B. Schultz and W. D. Frankforter (written communication):

a. Proximal end of the radius-ulna of a giant camel, cf. *Gigantocamelus* (Fullerton formation—Broadwater fauna—of western Nebraska).
b. Proximal end of radius-ulna. Same identification as above.
c. Proximal end of metacarpal of a small camel, cf. smaller (*Tanupolama*-like) forms of camel from the Fullerton formation (Broadwater fauna). Not diagnostic; may be Upper Pliocene, but we think it to be lower Pleistocene.
d. Fragment of antler of a large cervid, probably *Cervus.* Unknown in upper Pliocene or lower Pleistocene of the central Great Plains.
e. Dorsal vertebrae of a mastodont. Not diagnostic.
f. Fragment of proximal end of right ulna of a mastodont. Not diagnostic.
g. Fragment of carapace of a giant turtle (*Testudo*). Not diagnostic.

A later collection, made by Messrs. Schultz and Frankforter, was listed by them as follows:

Proboscidea: Mastodont (compares favorably with *Stegomastodon,* but additional material is needed for specific identification).

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[9] Op. cit., p. 104.

[10] Warren, C. R., 1950, Preliminary report on the geology of part of the Chamberlain, S. Dak. quadrangle: U. S. Geol. Survey, manuscript on open file, 30 p.

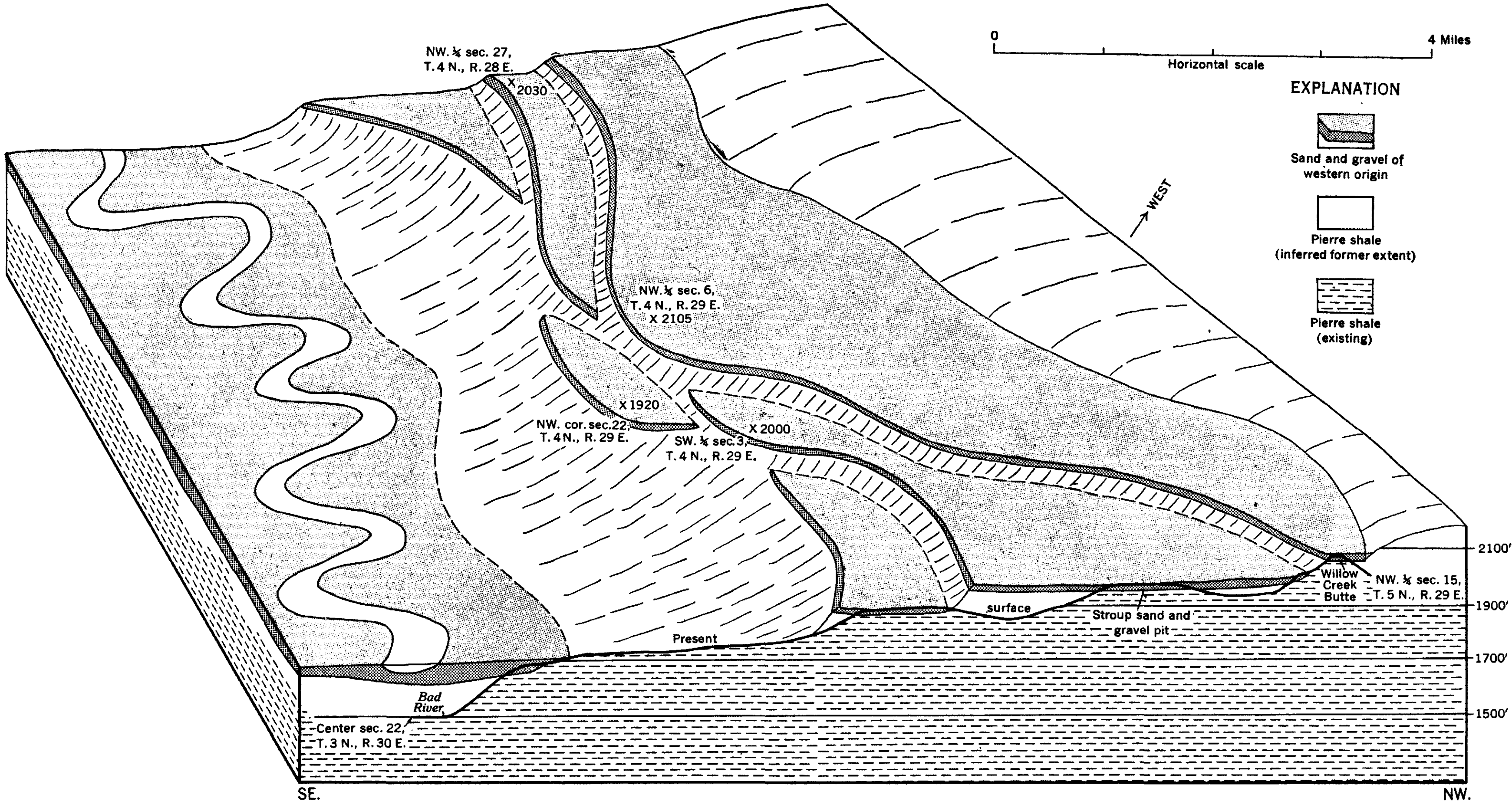

FIGURE 10.—Sketch showing relation of present surface to inferred former surface along the Bad River near its mouth. Diagrammatic reconstruction of the southern half of the Oahe quadrangle, showing the probable origin of bodies of western alluvium as covers of sand and gravel deposited on Pierre shale straths during lateral planation and downcutting by the Bad River. Probably the original terrace scarps were less steep and less distinct than those in the diagram. The Bad River is shown flowing on a fill thought to have been graded to glacier ice or outwash of Iowan(?) age in the Missouri River trench. Spot locations indicate existing sand-and-gravel exposures with their altitudes in feet. (D. R. Crandell, 1951.)

Artiodactyla:
  Sangamona sp. Large deer, similar to example from Locality 10, but larger.
  Gigantocamelus fricki Barbour and Schultz referred. Giant camel.

Messrs. Schultz and Frankforter (written communication) expressed the opinion that this assemblage suggests an Aftonian or early Kansan age.

In addition to the fossils listed above, others were collected from the same deposit that are differently mineralized and consist of forms characteristic of the Ogallala formation (Ash Hollow formation of Ogallala group, of Nebraska geologists). Obviously they were reworked from Ogallala deposits.

Locality 10. NW¼ sec. 23, T. 97 N., R. 62 W., on Charles Mix-Douglas County line. In abandoned high-level valley; capped with till. Altitude about 1,475 feet (225 feet above Missouri River). Fossils collected and identified by Messrs. Schultz and Frankforter (written communication):

Rodentia:
  Procastoroides sweeti Barbour and Schultz. Giant beaver
  Procastoroides sp. Large species, probably not described
Proboscidea: Mastodont (compares favorably with *Stegomastodon*, but too incomplete for specific identification)
Perissodactyla: Equid (near *Plesippus* sp. Based on palate with 12 cheek teeth; also 4 incisors and one addtional cheek tooth). Horse.
Artiodactyla:
  Odocoileus sp. Deer
  Sangamona sp. Large deer
  Capromeryx sp., referred. Antilocaprid
  Gigantocamelus fricki Barbour and Schultz, referred. Giant camel

> The above list indicates that the fauna is not later than early Kansan and is probably Aftonian in age. The fauna is similar to the one we find beneath the Kansan till in northeastern Nebraska and also to our Broadwater fauna in western Nebraska. This fauna is much more diagnostic than the one from Locality 9.
>
> In addition to the forms listed . . . Ash Hollow (Ogallala group) species appear. The specimens representing Tertiary forms are mineralized differently from the lower Pleistocene forms.

Locality 11. Sec. 28, T. 93 N., R. 60 W., Bon Homme County. In abandoned high-level valley; capped with till. Altitude of base of sand and gravel, about 1,365 feet (175 feet above Missouri River). No fossils are known from this deposit.

Locality 12. Irregular area capping part of Yankton Ridge, chiefly in secs. 2, 3, 10, and 11, T. 93 N., R. 57 W., Yankton County, and secs. 12 and 13, T. 93 N., R. 58 W., Bon Homme County. Altitude of lowest exposure of sand and gravel, about 1,500 feet (330 feet above Missouri River). Highest exposure is at 1,590 feet (H. E. Simpson, written communication). Sediments from this area have been reworked and incorporated into pro-Illinoian outwash, shown in unit 1, locality 9*B*, page 34.

Fossils collected by H. E. Simpson were examined in 1951 by Dr. Schultz and Mr. Lloyd Tanner, who identified them as follows (written communication):

Perissodactyla: *Equus excelsus*, referred.
Artiodactyla:
  Sangamona, referred. Giant deer.
  Gigantocamelus fricki, referred. Giant camel.
  Titanotylopus nebraskensis, referred. Camel.

Messrs. Schultz and Tanner stated their belief that the camels suggest correlation with the Holdrege, Fullerton, and Red Cloud formations, whereas the horse and deer suggest correlation with the Grand Island and Sappa formations. It is not known whether all the specimens were collected from their original places of deposition, or whether the stratigraphically older ones had been reworked.

Locality 13. Near the northeast corner of sec. 13, T. 95 N., R. 54 W., Yankton County. On Turkey Ridge, at altitude about 1,440 feet (270 feet above Missouri River). Sand and gravel are overlain by till. No fossils have been found.

CONDITIONS OF DEPOSITION

The western provenance of the sediments, their east-west linear distribution, their decrease in grain size and increase in rounding in an eastward direction, and the easterly dip of their foreset stratification point to the inference that these deposits were made by streams flowing eastward from sources hundreds of miles west of the glaciated region of South Dakota. The cut-and-fill stratification indicates further that the streams were braiding streams carrying full bed loads. The spreads of sediment across interfluves suggest that the streams responsible for such deposits either had aggraded their (probably shallow) valleys to the point of obliteration and were depositing wide, thin mantles of sediment across the plains surface between the valleys, or were occupying shallow, high-level valleys the present positions of which are represented by interfluves (fig. 10).

The western sediments are exposed only a short distance inside the glaciated region, although they have been seen incorporated in the glacial deposits in the Missouri River trench and at various localities in Brule and western Aurora Counties not far east of the trench. These facts may mean that some of the western sediments were never widely deposited east of the Missouri River, owing to early blocking and diversion of eastward-flowing streams by glacier ice. It seems more likely, however, that western sediments were deposited in the region east of the Missouri, and that they were later in part buried beneath glacial drift and in larger part plowed up by glacial erosion and eroded by streams and mass wasting during nonglacial intervals.

AGE AND CORRELATION

Evidence drawn from the fossils combined with evidence from topographic and stratigraphic relations indicates that the western sand and gravel in South Dakota represent at least three episodes of stream deposition: an episode antedating the Kansan glacial maximum, an episode postdating that maximum, and an episode of early Illinoian age.

Only the first two of the episodes named are inferred directly from the faunal identifications in the preceding section. The fossils suggest that the deposits at localities 9 and 10 antedate the Kansan maximum and probably are to be correlated with the Red Cloud sand and gravel and (or) the Holdrege formation in Nebraska. On the other hand the fossils from localities 2, 7, and 12 postdate the Kansan maximum and suggest correlation with the Grand Island formation.

The correlation of one of the bodies of sand and gravel with Illinoian deposits is based on evidence drawn from locality 6. There the body of sand and gravel occupies the floor of the abandoned prolongation of the valley of White River. It is exposed in the eastern wall of the Missouri River trench, and is overlain by till more than 100 feet thick. The floor of the former valley, and therefore the base of the sand and gravel that cover it, lies 115 feet above the Missouri River, which transects it nearly at right angles. These relations, including also the position of locality 7, are shown in cross section in figure 11. The western sediments in the abandoned valley segment were first observed by the writer in 1946, and were later examined in detail by C. R. Warren (1951) who constructed the cross section and established the probable correlation of the overlying till.

The western sediments exposed in the abandoned valley are believed by Warren to be younger than the two high-level bodies described above. Warren's reasoning is this:

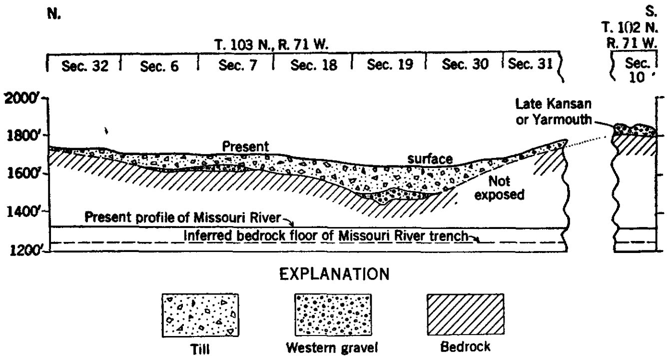

FIGURE 11.—Cross section showing inferred stratigraphic relations exposed in east side of Missouri River trench opposite the mouth of the White River. (After C. R. Warren, 1951.)

1. The sediments at locality 7 have an exposed thickness of 27 feet and a maximum inferred thickness of 50 feet. Either figure is too great to be attributed to the normal covering of alluvium on a planation surface. Hence the sediments probably represent a fill within the valley of the Ancient White River, which, indirect evidence suggests, may have been 15 to 20 miles wide.

2. These sediments contain fossils which, as already stated, have been identified as probably late Kansan or early Yarmouth.

3. The base of the sediments at locality 6, occupying the floor of the abandoned White River valley, lies 350 to 380 feet lower than the base of the sediments at locality 7, and 425 feet lower than their top. Hence 425 feet of erosion, at least 350 feet of it in the shale underlying the higher sand and gravel, took place between the two episodes of deposition. This erosion created a low-level valley, about 6 miles wide, incised below a much wider high-level valley. The alternative to this view, the hypothesis that both occurrences of sand and gravel are parts of a single giant-size fill at least 425 feet in maximum thickness and perhaps 15 to 20 miles in width, is so improbable that it is not considered further. In the low-level valley a new generation of western sand and gravel was deposited, by a river flowing eastward across the path of the present Missouri River. Later the valley was invaded by glacier ice and the eroded remnants of this sand and gravel were buried beneath till 125 feet thick.

4. The thick till was eroded. Later, during a new glacial invasion, it was covered by till at least 12 feet thick, probably of Iowan age. In the interval between the two episodes of till deposition, the Missouri River was created and cut a trench at least 170 feet lower than the floor of the low-level valley of White River.

5. The low-level western deposits, then, are much younger than a sand and gravel of late Kansan or early Yarmouth age, but are in turn overlain by a thick till that long antedates an Iowan(?) till and hence is pre-Wisconsin. The thick till therefore can only be Illinoian, and the western deposits immediately beneath it must also be Illinoian (or very late Yarmouth).

The low-level sand-and-gravel body in the abandoned valley of White River is more likely Illinoian than Yarmouth, because no coarse-grained sediments of Yarmouth age have been recognized elsewhere in South Dakota, in Nebraska, and in western Iowa. The physical character and apparent stratigraphic position of the sand-and-gravel body are identical with those ascribed to the Crete formation. Accordingly it is considered likely that this low-level body is the correlative of the

Crete formation. If so, then at least three of the four western sand-and-gravel units recognized in Nebraska are present in South Dakota as well.

In connection with the Crete formation, attention is drawn to a measured section exposed in Moody County (locality 19*B*, p. 36). In that section Loveland loess is underlain by a thin body of sand and granule gravel, which in turn overlies till, from which it is separated by a residual concentrate of stones like those in the till. Possibly the sand and gravel represent outwash, but the presence of the underlying concentrate points to erosion intervening between deposition of the till and that of the stratified sediments. Accordingly it seems more likely that the latter represent reworking of the till, and redeposition of sand and granules from it, by a local stream (possibly the prediversion river shown in plate 7 as traversing Moody County) before the deposition of at least some of the Loveland loess. The stratified sediments occupy the stratigraphic position of the Crete formation and correspond with the description of that formation as given by Condra, Reed, and Gordon (1950, p. 24–25).

CLAYEY SILT

In comparison with the sand-and-gravel bodies described above, the occurrence of bodies of clayey silt is even more restricted. At only three localities have such sediments been found in stratigraphic positions such that they are known to be pre-Wisconsin.

The most closely dated occurrence is near Hartford, Minnehaha County (localities 17*B*, p. 35 and 17*C*, p. 35). At that place the clayey silt underlies the Loveland (?) loess and overlies a till. It is 2.6 feet thick, olive gray, and indistinctly laminated. Its stratigraphic position, supported to some extent by its physical character, justifies correlation with the Sappa formation (Condra, Reed, and Gordon, 1950, p. 22). This correlation is strengthened by the occurrence in this section, conformably overlying the clayey silt, of a layer of volcanic ash. On a basis of microscopic characteristics the ash was correlated (Frye, Swineford, and Leonard, 1948, p. 505) with the Pearlette ash member of the Sappa formation of Kansan age, which is stated to occur at many localities in the territory stretching from Nebraska to Texas. If the ash bed is a petrologically distinctive unit, then the correlation of the associated clayey silt at the South Dakota locality is assured.

A second exposure of pre-Wisconsin clayey silt occurs in Moody County (locality 19*A*, p. 36). In that exposure olive-gray clayey silt, indistinctly laminated, is interbedded with coarser sediments near its base. It is 4.2 feet thick, and no volcanic ash is present. It underlies a till that in turn underlies Loveland loess, and is underlain by a still older till. These relations strongly suggest, although they do not prove, correlation with the Sappa formation.

The third exposure occurs south of Delmont in Douglas County (locality 6, p. 38). There a minimum of 4 feet of grayish-olive silt, indistinctly laminated, underlies a thick section of sand and gravel of western origin. As the age of the western sediments is fixed, by Schultz and Frankforter, on a basis of contained fossils, as not later than early Kansan, the underlying silt may be referable to the Fullerton formation, or may be even older.

LOVELAND LOESS IN SOUTH DAKOTA

Like the pre-Wisconsin stream deposits described in the preceding section, loess or loesslike silt of pre-Wisconsin age has been seen exposed in few places within South Dakota. Specifically such sediments have been noted at 8 localities in southeastern South Dakota and at 2 additional localities, 1 in Iowa and 1 in Nebraska, very close to the South Dakota State line.

All these localities are represented by measured sections on the map, figure 6. They are localities 9*A* (p. 40), 9*B* (p. 34), 10 (p. 52), 16 and 17*A* (p. 35), 19*A* and 19*B* (p. 36), 21 (p. 52), 28 (p. 37), and 29 (p. 53).

Locality 10. Cut on east side of road, exposed in July 1948, in northwest corner of sec. 7, T. 32 N., R. 2 E., Cedar County, Nebr.

[Section measured by H. E. Simpson]

	Feet (*maximum*)
2. Loess, dusky-yellow when moist, yellowish-gray when dry; massive except for a zone 2.5 feet thick, which is laminated; firm, calcareous. (Iowan and post-Iowan.)	12.0
Contact distinct; very irregular.	
1. Loess, dark yellowish-brown when dry, dusky yellowish-brown when moist; compact, noncalcareous except for secondary calcium carbonate in topmost 12 inches. (Loveland.)	5.0
Base concealed.	
	17.0

Locality 21. Section exposed in east bank of West Pipestone Creek, July 1947, near center sec. 26, T. 103 N., R. 48 W., Minnehaha County, S. Dak.

[Measured by G. D. Smith, F. F. Riecken and R. F. Flint]

3. Loess, yellowish-gray when dry, calcareous. (Iowan and post-Iowan.)	4.0
2. Till, yellowish-gray when dry; consists of pebbles and boulders in an abundant silt-rich matrix; faintly fissile; ventifacts present in slope wash though not seen in place; basal 5 feet include unoxidized masses and thin streaks and smears of the underlying silt; olive-gray when moist; calcareous. (Iowan.)	30.0

	Feet
Contact somewhat smeared.	
1. Silt, clayey, dark yellowish-brown to grayish-purple when dry; jointed, blocky; noncalcareous except for secondary calcium carbonate accumulation in uppermost 3 feet; contains secondary colloids. Exposed 7 feet down to surface of creek; 3 feet augered below creek. Base not reached. (Loveland.)	10.0
	44.0

Locality 29. Cuts on north-south road in SE¼ sec. 31 and SW¼ sec. 32, T. 96 N., R. 48 W., Lincoln County, S. Dak.

[Measured by G. D. Smith, F. F. Riecken, and R. F. Flint. Only the loess exposed; underlying sediments measured by use of spade and auger]

	Feet
4. Loess, yellowish-gray when dry, calcareous. (Iowan and post-Iowan.)	<11.0
3. Sand, medium-grained, faintly and irregularly stratified, dark yellowish-orange when dry, pinches out toward south. (Iowan.) Maximum	1.0
2. Till, yellowish-gray when dry; consists of pebbles in an abundant clay-rich matrix; many pebble ventifacts at upper contact; calcareous. (Iowan.)	3.0
1. Gumbo silt, dark yellowish-brown to grayish red-purple when dry; contains secondary colloids; checks when dry; noncalcareous. Base not reached.[1] (Loveland?)	6.0
	21.0

The loess or loesslike silt exposed in these sections is dark yellowish brown and in places has the purplish hue found in the oxidized Loveland loess in adjacent States. As stated earlier, this color may have developed through weathering during any one of the three interglacial ages; hence it is not diagnostic of Sangamon weathering. On the other hand, the stratigraphic position of the loess or silt in all these sections permits correlation with the Loveland loess, if that unit is, as it is now generally considered to be, Illinoian. For example, at 4 localities (17*A*, 21, 28, 29, fig. 6) the loess or silt underlies the Iowan till and is therefore pre-Iowan. At 5 localities (10, 16, 17*A*, 19*A*, 21, fig. 6) it overlies a till believed, on independent physical evidence, to be pre-Wisconsin. One locality (17*A*, fig. 6) is common to both groups; the exposure at that place affords the closest dating of this loess that has been seen thus far in South Dakota.

On a basis of these considerations the dark yellowish-brown loess or silt at the localities listed is correlated tentatively with the Loveland loess.

In the ten exposures listed, the thickness of this material ranges from 5 to 17 feet. These rather substantial thicknesses, together with the considerable area embraced by the localities of occurrence, are consonant with the evidence from other parts of the Central Lowland that this loess probably was derived from the outwash resulting from a major glaciation.

The data from one of the 276 recorded well logs examined during the present investigation suggest the presence of Loveland loess. This well (5 on fig. 25) is in the SW¼ sec. 15, T. 95 N., R. 64 W., Charles Mix County. The log (Rothrock, 1946a, p. 20) reads:

4. Drift	20
3. Reddish-brown clay	10
2. Blue clay	10
1. Gray shale.	

It seems likely that unit 4 is Cary drift, 3 is Loveland loess, and 2 is pre-Loveland till The distinctive color is what makes this interpretation likely; but the thickness is within the observed range of the Loveland loess in South Dakota, and the location, a short distance northeast of the Missouri River, is optimum for the occurrence of a loess deposited later than the major drainage diversion described on pages 139–143.

If the observed distribution of the Loveland loess represented the actual distribution, it could be said to be consistent with the concept of wind-deposited silt derived from outwash in the valleys of the Missouri and Big Sioux Rivers. However, in view of the repeated Wisconsin glaciation of southeasten South Dakota, it is not at all certain that what we now see is representative of the original distribution of this loess. Accordingly it seems best not to draw inferences from the areal pattern of the known exposures.

WEATHERING PROFILES AND BURIED SOILS

In South Dakota, gumbotil has been identified thus far at only a single locality (28 on p. 37; fig. 6). Although detailed study would undoubtedly disclose other gumbotil localities in South Dakota, it is believed that such localities are actually few, and that in this scarcity at least two factors are involved.

One factor is that the whole of the glaciated part of South Dakota was overridden by glacier ice during the Wisconsin glacial age, thus extensively removing by erosion or covering up pre-Wisconsin materials. The comparable effect of Wisconsin glaciation in the State of Iowa is strikingly evident in two maps published by Kay and Apfel (1929, p. 128, 129) showing the distribution of exposures of gumbotil of Nebraskan and Kansan age respectively. Although abundant outside the area of Wisconsin glaciation, such exposures are few in the area covered by the Iowan ice and are almost nonexistent in the area covered by the post-Iowan ice.

The other factor is dissection. The southeastern part of South Dakota is traversed by major valleys of both prediversion and postdiversion dates. It is therefore

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[1] O. F. Scherer (written communication), some years earlier, penetrated 15 feet of this unit with an auger, ending in the same material.

likely that this region was subject to considerable dissection in the vicinities of these major valleys. As dissection increases, the combined area of broad flat upland surfaces—the sites of gumbotil development—decreases.

Where mature weathering profiles in till are exposed in Iowa, ordinarily oxidation has penetrated farthest below the surface, leaching of carbonate less far, and conversion to gumbotil least far. In permeable till oxidation proceeds more or less uniformly through its mass; in less permeable till oxidation penetrates along the joints and works inward from them. This is illustrated at locality 8, page 34, where tills 2 and 4 are permeable and oxidized, whereas till 1 is oxidized only along and close to the joints. With the exception of this one occurrence the pre-Wisconsin tills exposed in South Dakota show only a part of this profile. Either the unaltered till, or the oxidized zone, or the zone that is both oxidized and leached, extends to the top of the till now exposed, regardless of whether the till is or is not overlain by some younger deposit. From this fact it may be inferred that following or during the weathering process, erosion removed a part of the till, thereby destroying a part of a weathering profile already made, or preventing a profile already in process of development from reaching maturity. Tills exposed beneath slopes of about 15 degrees or more are calcareous, indicating that on such slopes, in this climate, surface erosion proceeds at least as rapidly as chemical alteration of the till.

All that can be said about the general process of oxidation, leaching, and gumbotil formation during pre-Wisconsin Pleistocene ages is that the occurrence of altered deposits, overlain by less-altered or unaltered deposits of Wisconsin age, indicates that pre-Wisconsin intervals of weathering did occur in South Dakota. Better evidence of the extent and character of those intervals, however, exists outside the State, in the region not overrun by glacier ice during the Wisconsin age.

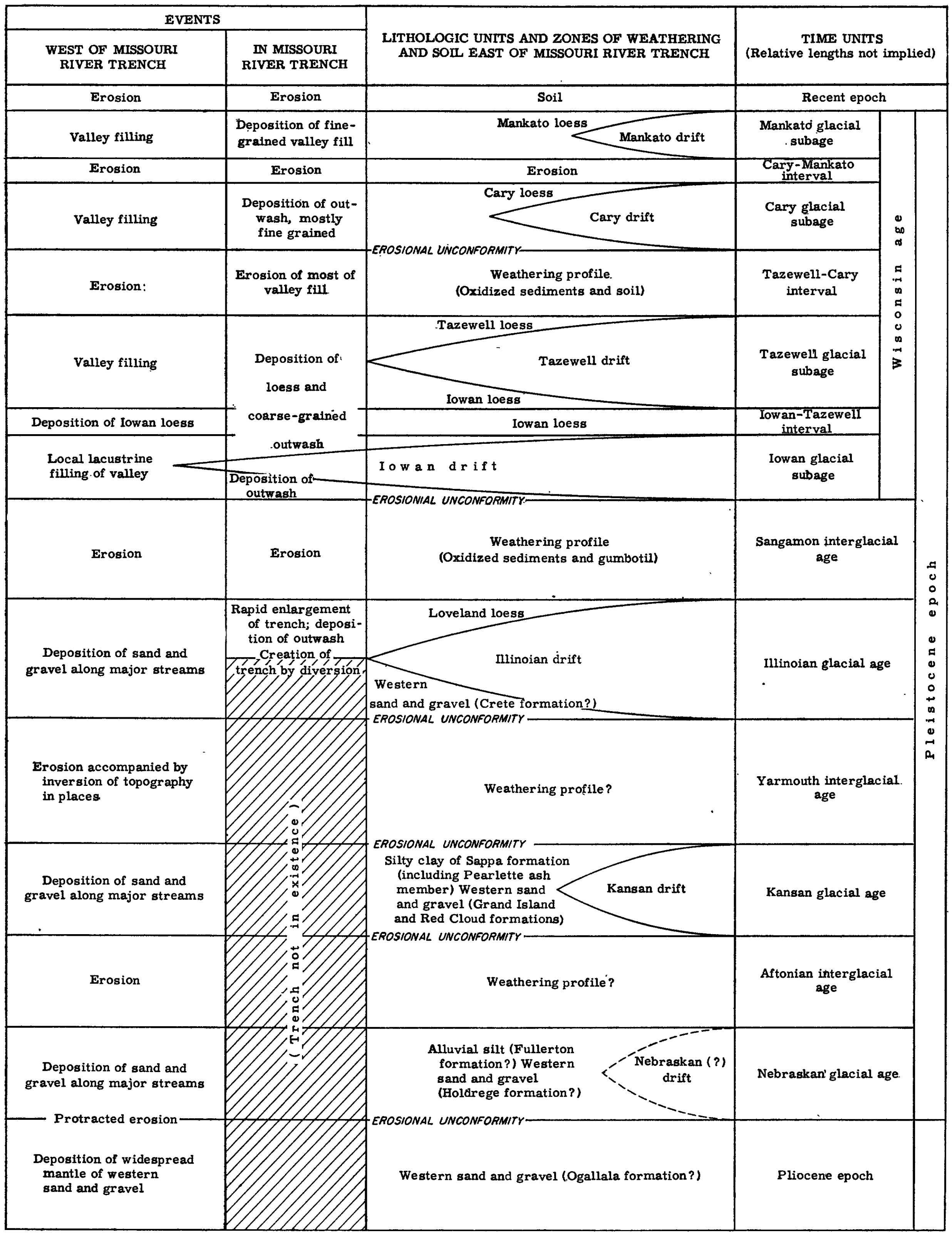
At three localities weathering of a till prior to deposition of a till of Wisconsin age is recorded principally by humification; that is, by the accumulation of dark-colored organic matter in the uppermost part of the older till. These are localities 8 (p. 34), 17*D* (p. 36), and 22 (p. 37). The dark-colored accumulations are in part Chernozem soils and in part Wiesenböden soils. In at least one locality (22) the organic matter has been augmented by the accumulation of colluvium, and in another (17*D*) it is perforated with filled-up crayfish burrows.

None of these occurrences necessarily demands a very long time interval between the first exposure of the pre-Wisconsin till and the deposition of the overlying Wisconsin deposits. Hence they are treated here merely as phenomena that developed in interglacial ages rather than as evidence of interglacial conditions.

The leached, thoroughly oxidized character of the Loveland loess exposed in South Dakota denotes a weathering profile developed through extensive alteration during the Sangamon interglacial age.

SYNTHESIS OF PRE-WISCONSIN STRATIGRAPHY

The known and inferred relations that have been discussed in the foregoing pages are assembled in the form of a chart (fig. 12). In it the drift sheets are represented as wedge-shaped bodies thinning toward the west, and the relation of the nonglacial sediments to them is necessarily based in part on analogy with similar relations established in Nebraska. The whole pre-Wisconsin sequence as depicted in the chart is consistent with the few and inadequate data obtained in South Dakota and with the more satisfactory data assembled in Nebraska. It is believed to be correct in its essentials, but it must be regarded as tentative and as subject to revision in the light of future information.



EVENTS		LITHOLOGIC UNITS AND ZONES OF WEATHERING AND SOIL EAST OF MISSOURI RIVER TRENCH	TIME UNITS (Relative lengths not implied)		
WEST OF MISSOURI RIVER TRENCH	IN MISSOURI RIVER TRENCH				
Erosion	Erosion	Soil	Recent epoch		
Valley filling	Deposition of fine-grained valley fill	Mankato loess Mankato drift	Mankato glacial subage	Wisconsin age	Pleistocene epoch
Erosion	Erosion	Erosion	Cary-Mankato interval		
Valley filling	Deposition of outwash, mostly fine grained	Cary loess Cary drift EROSIONAL UNCONFORMITY	Cary glacial subage		
Erosion:	Erosion of most of valley fill	Weathering profile. (Oxidized sediments and soil)	Tazewell-Cary interval		
Valley filling	Deposition of loess and coarse-grained outwash	Tazewell loess Tazewell drift Iowan loess	Tazewell glacial subage		
Deposition of Iowan loess		Iowan loess	Iowan-Tazewell interval		
Local lacustrine filling of valley	Deposition of outwash	Iowan drift EROSIONIAL UNCONFORMITY	Iowan glacial subage		
Erosion	Erosion	Weathering profile (Oxidized sediments and gumbotil)	Sangamon interglacial age		
Deposition of sand and gravel along major streams	Rapid enlargement of trench; deposition of outwash Creation of trench by diversion	Loveland loess Illinoian drift Western sand and gravel (Crete formation?) EROSIONAL UNCONFORMITY	Illinoian glacial age		
Erosion accompanied by inversion of topography in places	(Trench not in existence)	Weathering profile? EROSIONAL UNCONFORMITY	Yarmouth interglacial age		
Deposition of sand and gravel along major streams		Silty clay of Sappa formation (including Pearlette ash member) Western sand and gravel (Grand Island and Red Cloud formations) Kansan drift EROSIONAL UNCONFORMITY	Kansan glacial age		
Erosion		Weathering profile?	Aftonian interglacial age		
Deposition of sand and gravel along major streams		Alluvial silt (Fullerton formation?) Western sand and gravel (Holdrege formation?) Nebraskan (?) drift	Nebraskan glacial age		
Protracted erosion		EROSIONAL UNCONFORMITY			
Deposition of widespread mantle of western sand and gravel		Western sand and gravel (Ogallala formation?)	Pliocene epoch		

FIGURE 12.—Chart showing provisional correlation of lithologic units and weathering zones in eastern South Dakota with standard time units and with inferred events in and west of the Missouri River trench.

The inconsistency in showing events in and west of the Missouri River trench in contrast with lithologic units east of the trench is intentional. The western limits of the several drift sheets are necessarily much generalized because their limits change depending on latitude.

PHYSICAL GEOLOGY OF THE WISCONSIN STAGE

The Wisconsin drift is the youngest of the four major drifts generally recognized in northern North America. In South Dakota it is the most extensive of the four; it covers up the pre-Wisconsin drifts everywhere except in those places from which it has been locally removed by erosion. Therefore, within the State, the area of the Wisconsin drift is coextensive with the glaciated area, which approximates 34,000 square miles. Most of the thousands of road and railroad cuts east of the Missouri River expose only the ubiquitous Wisconsin drift; hence most travellers across the eastern part of the State never see the pre-Wisconsin drifts at all. In fact the older drifts are so rarely exposed, and their outcrop areas are so small, that they can not be shown practicably on the map, plate 1.

The Wisconsin stage, a time-stratigraphic term, includes the deposits laid down during the Wisconsin glacial age, not only by glacier ice and its melt waters but also by nonglacial streams and by the wind. Furthermore in Wisconsin time the ice smoothed and striated the bedrock in places, and although the bedrock markings are not strictly a part of the Wisconsin stage, they have a strong bearing on it and must be considered along with it.

GLACIAL MARKINGS

EXPOSURES AND PRESERVATION OF MARKINGS

In southeastern South Dakota, bedrock and boulder pavements are exposed on which can be seen, at one place or another, highly polished surfaces, striations and grooves, and crescentic marks made by the passage of glacier ice across rocky surfaces. The first two are the direct result of abrasion; the third consists of related though somewhat different features resulting from the movement of former glaciers.

Exposures of these features are confined to three areas: Sioux quartzite in the southeastern part of the State, a boulder pavement in Beadle County, and granite in Grant County. They are among the very few areas in which firm, resistant materials are known to be exposed. The friable character of the Codell and Fox Hills sandstones, the solubility of the chalk strata, and the softness and ease of erosion of the various shales make such strata unsuited either to receive such markings or to retain them, once made.

The vast majority of the markings mentioned are preserved on the Sioux quartzite, a rock type ideally suited to the preservation of striations and related features. The map (plate 5) shows the striations and grooves recorded on this rock. The areal bunching of the markings reflects the spotty distribution of "windows" in the drift, through which the underlying quartzite is exposed. Most, though not all, of the quartzite exposures occur along the larger streams, which once carried proglacial melt water laden with silt. In consequence, although many exposures show ideally the effects of glacial abrasion, others have been scoured by streams so effectively that they have lost their glaciated surfaces. The presence of glacial markings on nearly all the exposed quartzite surfaces not glacially quarried nor subsequently scoured by streams invites the belief that if the overlying drift were stripped away, the quartzite would be seen to be so marked nearly universally.

POLISHED SURFACES

The facies of the Sioux quartzite most commonly exposed in South Dakota takes a beautiful polish. Indeed many of the quartzite surfaces are so smooth that they reflect sunlight brilliantly even when they are dry. Following a rain some of them are dazzling.

The polish on some surfaces has some of the characteristics of wind-abraded surfaces; such polish is believed to be eolian. However, on other surfaces the polish lacks these characteristics, and no clear evidence of age sequence as between striations and polish was noted. Such surfaces are believed to have been polished by glacier ice.

Many surfaces are both striated and polished. The striations and grooves are clearly the result of abrasion by sand grains and larger-size particles, whereas the polish could only have been made by finer particles. In southwestern Finland, Edelman (1949, p. 132) found striations generally confined to surfaces inclined upstream, and polish present generally on surfaces inclined downstream. His explanation, that the ice had failed to bear down upon the lee slopes, does not apply to the Sioux quartzite surfaces, which are mostly flat lying, with little relief. Although in some localities (notably E½ sec. 6, T. 101 N., R. 58 W., Hanson County, and the vicinity of Dell Rapids, Minnehaha County) the quartzite possesses relief, with gentle upstream slopes and steeper downstream slopes, the polish does not seem to be confined to the downstream slopes.

In view of these facts it seems more likely that the presence of both striations, and polish of apparently glacial origin, on the same surface is related to the character of the glacial loads in this region. The clay-rich composition of the till indicates that the basal loads of the glaciers consisted principally of clay. It seems possible that the clay was responsible for the polish, and that the striations were made contemporaneously by the rarer fragments of larger size carried in the base of the ice.

STRIATIONS AND GROOVES

The striations and grooves have no essential differences except as to size. The striations are fine to coarse scratches, mostly less than one-sixteenth of an inch in average depth, whereas the grooves are mostly as much as one inch in depth and several inches in breadth. Nearly all are straight, but few of either kind seem to have a linear continuity exceeding a few yards. Probably they were made by the same mechanism, at the same time, with tools that varied in coarseness.

Nearly all the striations in southeastern South Dakota trend southeast. Like most striations in other regions they do not in themselves indicate which of the two possible directions was the one toward which the ice flowed. The actual direction must be determined from other features, such as the provenance of the overlying drift and the orientations of end moraines that mark various positions of the glacier margin. From such evidence it is clear that in this area the ice flowed generally from northwest to southeast.

At individual localities some striations diverge from others, but the divergences are not large, nor do they show any apparent order or system in their arrangement. Most of the divergences seem best explained as the result of small local variations in direction of flow during a single movement of ice, almost certainly the latest ice that flowed across each locality. However, good indications of the presence of two sets of striations were observed at two localities. One is in the SW¼ sec. 35, T. 101 N., R. 48 W., near Rowena, Minnehaha County. At that place a set trending southeast seems to cut an older set trending south-southeast. The other is in secs. 21 and 22, T. 102 N., R. 47 W., northeast of Sioux Falls, where again a set trending southeast cuts a south-southeast set. According to Brewster Baldwin (written communication) the south-southeast set is less plain, restricted in occurrence, and found on high parts of the surface together with the southeast set, whereas the southeast set occurs on low parts of the surface without the south-southeast set. At neither of these localities was evidence seen that the two sets were separated from each other by more than a short interval of time.

In this connection attention is drawn to the observation by Leverett (1932, p. 17) at localities in Pipestone and Rock Counties, Minn., not far from the South Dakota State line, of two sets of striations, an earlier set bearing south and a later one bearing south-southwest. At the south edge of the SW¼ sec. 16, T. 103 N., R. 45 W., Rock County, Minn., Brewster Baldwin (written communication) confirmed Leverett's observation by noting the truncation of a southward-trending set by a set at S. 45° W.

The Minnesota localities are related to the Des Moines glacial lobe on the east side of the Coteau des Prairies, whereas the Rowena locality is related to the James lobe on the west side of the coteau. All are in the area last glaciated during the Iowan subage. It seems quite possible that all these examples represent variations in local direction of flow occasioned by thinning of the ice with consequent increased response, in the direction of flow of each lobe, to the regional topographic barrier consisting of the coteau itself.

The opinion was stated above that at each locality the striations were probably made by the ice that last invaded the locality. This reflects the rather general opinion that a glacier able to produce a good set of striations on a given surface is likely to have been able to erase the striations made earlier. If this is assumed to be the case in southeastern South Dakota, then a useful inference can be drawn from the relation of the striation directions to the areal pattern of the drift sheets. Comparison of plate 5 with the map, plate 1, shows that part of the striated Sioux quartzite district was last glaciated in Iowan time, part was last glaciated in Cary time, and part was last glaciated in Mankato time. Yet the general orientation of all the striations is about the same, namely, southeast, as though the scratches had been made beneath the peripheral zone of a lobe of ice flowing southward down the James River lowland, and spreading outward near its margin in the fashion common to all lobate glaciers. If we assume the scratches to have been made in each locality by the latest ice, then some of them are Iowan, some are Cary, and some are Mankato. It then follows that the direction of flow of each was, in this district, about the same; that the high-standing mass of the Coteau des Prairies induced a similar lobation in all. That this was indeed the case is evident from the lobate pattern of the borders of the Cary and Mankato drift sheets in South Dakota, and from that of the Iowan drift sheet in northwestern Iowa as shown on the map by Ruhe (1950). There is thus general agreement between the striations on the one hand and the pattern of the drift sheets on the other.

An alternative explanation is that all or most of the striations were made by the Iowan ice, and that the later glaciers, being somewhat thinner, failed to erase them and to leave new scratches in their place. This seems unlikely because the post-Iowan glaciers carried large volumes of drift in their basal zones and flowed vigorously enough to build this drift into massive end moraines. It is probable that such glaciers would be competent to abrade effectively the bedrock beneath them.

Striations are far fewer on the granite outcrops in Grant County than on the Sioux quartzite, possibly because of the coarser texture and variable hardness of the polymineral rock. They consist principally of broad, shallow grooves, cutting a low boss of the granite in the SW¼ sec. 7, T. 120 N., R. 46 W., east of Milbank. Their trend is about S. 15° W. As the area is generally covered with Mankato drift, probably the grooves were made in Mankato time. They are roughly normal to the trend of the outer limit of the Mankato drift sheet in that vicinity.

The striations in Beadle County, in the James River lowland, are of interest because they occur not on bedrock, but on a boulder pavement. They were well exposed in June 1949, in the SE¼SE¼ sec. 26, T. 113 N., R. 60 W., in the west side of the valley of Shue Creek. At that place till 8 feet thick overlies a different till, at least 12 feet thick, the upper surface of which is a boulder pavement. The upper till is dusky yellow when dry, has a silt-rich matrix, and is friable. The lower till is light olive gray when dry, and has a clay-rich matrix containing many large pieces of Pierre shale and pockets of gravel in which chalk is an important constituent.

Both tills contain boulders, but boulders are concentrated at the surface of the lower till to such a degree that they form a nearly continuous pavement, which stands out as a pronounced lithologic bench in the valley side. The exposed boulders range from 1 to 5 feet in diameter; most of them exceed 3 feet. They include many kinds of igneous and metamorphic rocks; two are Paleozoic limestones. The boulders are planed down so that their tops are flush. They are not, however, fitted together like a mosaic, but are separated slightly from each other by the inclosing till. Many boulders seem to have lost as much as half their bulk through glacial abrasion.

Many of the planed surfaces are striated with fine, well-marked parallel scratches, and one boulder possesses two strings of nested crescentic fractures, the strings paralleling the striations. Although many striated boulders were seen, only six had surely not been displaced by soil creep. On these six the striations have a uniform bearing of S. 16° E. to S. 21° E. This direction parallels the axis of the James River lowland in the latitude of the locality, and is at right angles to the crests of the end moraines in the vicinity. There seems to be no basis for doubt that the striations are as reliable an indication of the latest movement of glacier ice over this area as though they had been inscribed on bedrock.

As the till immediately overlying the boulder pavement is of Mankato age, the till that incloses the boulders is either Mankato or pre-Mankato. The fact that the lower till is notably bouldery suggests, however, that it is Wisconsin. If Wisconsin age is accepted on this basis, it follows that glacial downcutting, by abrasion alone, amounting to at least 1–2 feet, was accomplished during one or more of the Wisconsin glacial invasions. Indefinite as it is, this is the only possible quantitative measure of the rate of glacial erosion that has been found in South Dakota.

Boulder-pavement exposures in Beadle County were noted in 1904 and 1905 by Todd (1909, p. 5) in the SW¼SW¼ sec. 9, T. 113 N., R. 60 W., and in the northeast corner of sec. 8, T. 113 N., R. 61 W. He recorded southeast bearings for the striations at both localities, but, at both, the bearings are more easterly than at the locality described above. Both places were visited by the writer in 1949, but although there are many surface boulders, no boulder pavement was observed. At the latter place four surface boulders with flat facets bearing parallel striations were seen; probably these were derived from the pavement exposed in 1904 and 1905. At the former place some of the boulders showed wind cutting, but none with plane facets or parallel striations were observed.

At several other localities throughout the townships named, however, planed and parallel-striated boulders were seen lying on the surface, mostly on the side slopes of small draws. These are believed to have been derived from a boulder pavement that was extensive in this district.

The presence of a pavement on till implies concentration of boulders through the removal of the finer grain sizes by a selective agent of erosion, probably running water. The presence of boulder concentrates on the Mankato till, in places along the James River, ascribed elsewhere in the present paper to melt-water streams, suggests that the pavement described above may have been concentrated in a similar manner.

CRESCENTIC MARKS

In some places the striations and grooves on bedrock surfaces are accompanied by crescentic marks. Marks of this kind have been described repeatedly in the literature, which has been summarized by Harris (1943). Of the four distinct types that have been recognized, three are shown in figure 13. All four are alike in that they are commonly lunate, are oriented at right angles to the direction of glacial flow, are as much as several inches in individual length, and are generally arranged in nested series or strings. The four types, however, differ among each other in these ways:

Crescentic gouges are concave upstream and consist of two fractures, from between which the rock has been removed.

Lunate fractures resemble crescentic gouges except that they are concave downstream.

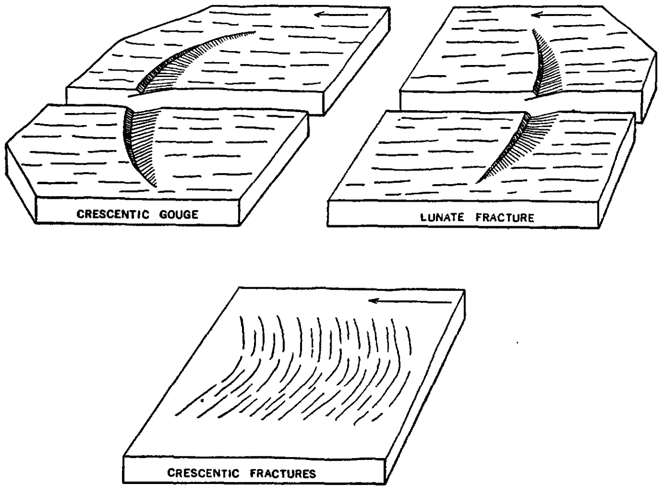


FIGURE 13.—Crescentic gouge, lunate fracture, and crescentic fractures shown diagrammatically. Greatest diameters of all features shown are about 4 inches. Arrows indicate direction of flow of glacier.

Crescentic fractures are concave downstream and consist of a single fracture only, without removal of any rock.

Chattermarks occur only within large grooves, are concave downstream or not concave at all, are made by the removal of a chip of rock, and possess no fracture that extends deeper than the scar left by removal of the chip.

Of these types, crescentic gouges and crescentic fractures occur commonly on striated surfaces of Sioux quartzite. Maximum individual diameters are about 4 inches; depths range from one-sixteenth to one-eighth inch; nested series vary to as much as 12 inches in length, with component marks spaced 1 inch to 1½ inches apart. In each case the long axes of the series parallel the striations on the same surface.

According to Harris (1943, p. 258) the principal fracture in the first three types dips into the rock in the forward or downstream direction. At only two localities, however, was it possible to check this statement in the field, owing to lack of exposures of vertical rock surfaces cutting the fractures. At one locality (SW¼ sec. 14, T. 102 N., R. 48 W., Minnehaha County) a set of six crescentic gouges, paralleling well-developed grooves trending S. 42° E., are seen to possess downstream-dipping fractures. At the other locality (east quarter corner sec. 22, T. 104 N., R. 45 W., Rock County, Minnesota) fractures observed by D. R. Crandell in 1947 and later sectioned in the laboratory include a crescentic fracture that dips 85° upstream and a crescentic gouge that dips 30° downstream. Hence it appears that not all the fractures associated with crescentic marks do dip downstream. Consequently neither the direction of concavity of the mark, nor the direction of dip of its fracture seem to be reliable criteria of the direction of glacial flow. If this is true, then crescentic markings afford little directional information in addition to what can be inferred from the associated striations and grooves.

Some of the marks observed on the Sioux quartzite may be chattermarks, but in the absence of vertical sections this could not be established.

THICKNESS OF DRIFT

The thickness of the Wisconsin drift in South Dakota is extremely variable within short distances. In the James River lowland it is believed to be, on a rough average, between 50 and 100 feet. In some places near the margins of the coteaus it probably exceeds 300 feet. In many areas along the eastern and northern sides of the Missouri River trench this drift is only a few feet thick. West of the trench, with few exceptions, and in western Buffalo County the Wisconsin drift can not properly be said to possess thickness, for it consists almost entirely of widely scattered stones and boulders, generally lying directly on the surface of the bedrock itself.

Although, without a great number of closely spaced borings, it can not be established that the till is thicker on slopes that faced the oncoming glacier ice than on flats and on slopes facing downstream, nevertheless the thicknesses exposed in these three situations lead to the belief that such is the case. A similar relationship has been observed elsewhere than in South Dakota.

Well records in end moraines at points along the flanks of the coteaus indicate that at those places the drift is generally thicker than it is in the James River lowland. The greater thickness of the drift along the flanks of the coteaus is not attributable entirely to the fact that massive end moraines are present there, because drift thicknesses exceed the heights of the moraines above their bases. This fact indicates that exceptional accumulations of drift were built at these places during episodes of glacial deposition that antedated the building of the existing end moraines.

Aside from the coteaus and the few other bedrock features described earlier, the topography of the eastern part of the State is determined almost entirely by the surface of the Wisconsin drift. Furthermore most of the earth fill, sand, and gravel used in the construction of roads, dams, and other structures, and most of the domestic water supplies obtained through shallow wells are derived from the Wisconsin drift. In all these ways, therefore, the Wisconsin drift is of major importance.

TILL

GENERAL CHARACTER

Within the area of outcrop of any one kind of bedrock the several Wisconsin tills are much alike in physical character. In fact the lateral change in character of a single till, as the character of the bedrock beneath it changes, is commonly more conspicuous than the differences between successive Wisconsin tills in any one district. In consequence it is difficult if not impossible to distinguish Wisconsin tills from each other on a basis of their physical character.

Certain general characteristics of the Wisconsin tills, however, seem to distinguish them from the pre-Wisconsin tills. The most obvious is that pebbles, cobbles, and boulders are more abundant relative to the finer size grades. Wisconsin tills are less compact, disaggregating easily when dry and quite commonly feeling mealy between the fingers. Joints, where present, are less continuous and more closely spaced. Probably because of their looser texture, oxidation is more uniformly developed in them, imparting a more nearly uniform hue to any exposure. Finally, in many places the Wisconsin tills possess weak fissility parallel with their upper surfaces.

In some localities Wisconsin tills seem to differ from older tills, and to differ among themselves as well, as to friability. However, mechanical analyses (fig. 14) show very small differences among them as to the proportion of silt and sand (which would make them friable) to clay-size particles. The differences observed in the field are believed to result from differences in moisture content. When moist, a small lump of till is plastic between the fingers, but the same till, when quite dry, may be friable. Therefore differences in friability are not necessarily differences inherent in the tills themselves.

The tills of three Wisconsin substages in northwestern Iowa have been shown by Ruhe[11] to differ among themselves only slightly; the similarity among Wisconsin tills therefore appears to be general throughout a wide region.

BOULDERS

Rock fragments of pebble, cobble, and boulder size are more abundant, relative to finer size grades, in Wisconsin tills than in pre-Wisconsin tills. In the present reconnaissance study no statistical data on pebbles and cobbles were accumulated, but the distribution of boulders, which are numerous, large, and easily seen, was noted. The largest boulder observed has a maximum diameter of more than 10 feet. Waring (1949) recorded a boulder 17 feet in diameter on the James River lowland.

Two facts about the distribution of boulders, seen in exposures of till and on the surface, are apparent. The first is that there is a close relationship between angle of local slope and frequency of boulders at the surface. The steeper the slope, the more frequent the boulders. This can only have resulted from the residual concentration of boulders through the removal, by rainwash, of the finer matrix that formerly inclosed them. The relationship is clearly evident at the northeast end of the most easterly butte in the Bijou Hills, centering in the northeast corner of sec. 26, T. 101 N., R. 69 W., Brule County. Till mantles the comparatively flat country around the base of the butte, and no section was seen in which two tills are exposed. But on the butte itself, with a slope averaging about 25 degrees, no till was observed. Instead the surface is littered with stones and boulders. The strong suggestion here is that on both flat and slope only one till is represented, and that on the slope the till has been converted into coarse residuum. In other words the critical factor is not time but angle of slope. This interpretation very probably applies in part to the Wisconsin drift both in the Missouri River breaks and in the dissected country west of the river. In those districts the drift is represented chiefly by scattered boulders rather than by till. However, as stated on pages 85–87, there are reasons for believing that in the latter district, at least, the till was scanty even at the time when it was deposited.

The second fact apparent in boulder distribution is that boulders are generally more abundant in end moraines than in ground moraine. Undoubtedly their abundance on the surfaces of end moraines is in part the result of residual concentration owing to the removal of a large bulk of fines on the relatively steep slopes that characterize those moraines. But as the frequency of boulders exposed in place in end moraines is substantially greater than their frequency in ground moraine, the difference is in part original. Even in end moraines with steep slopes, however, one segment may have many surface boulders whereas an adjacent segment may have very few. An example is the outermost Mankato end moraine along the western flank of Turkey Ridge in Hutchinson and Yankton Counties Commonly surface boulders are more numerous on the distal slope of an end moraine than on the proximal slope. This may result from repeated lodgment of till against the proximal slope, thus covering up the water-washed surface of that slope.

The greater original concentration of boulders in end moraine than in ground moraine must involve some concentrating process within the ice itself. Two possibilities are suggested. The operation of melt-water streams of all sizes on and in the terminal zone of the ice would tend to remove fines and to leave a residual concentrate of coarse pieces—a concentrate that should be evident even after the drift had been rearranged by glacial flow before it was finally deposited.

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[11] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation, fig. 5.

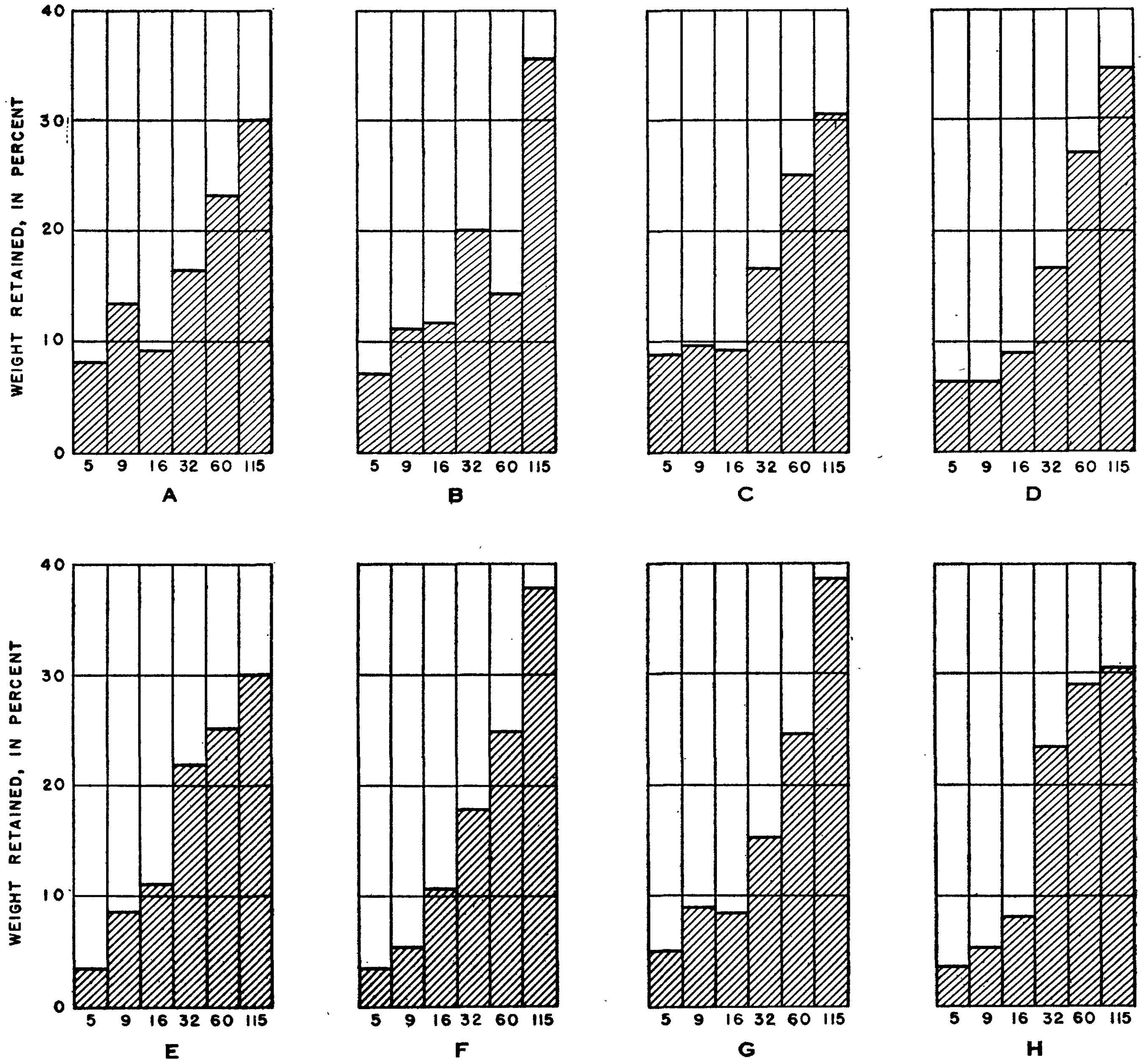

FIGURE 14.—Histograms showing frequencies of grain sizes smaller than pebble size in representative till samples. Numerals at bases of columns are Tyler screen mesh numbers. Laboratory analyses by H. E. Simpson and R. J. Ordway. *A*, Mankato till, southwestern Aurora County; *B*, Illinoian(?) till, northwestern Brule County; *C*, Cary till, northwestern Clay County; *D*, pre-Wisconsin till, northwestern Clay County; *E*, Illinoian(?) till, northwestern Charles Mix County; *F*, Illinoian(?) till, southeastern Douglas County; *G*, Mankato till, southeastern Sully County; *H*, Mankato till, northwestern Yankton County.

The other possibility concerns the fragment sizes yielded by glacial erosion in South Dakota and to the north, and the vertical positions of the fragments while in glacial transport. Whereas ground moraine in South Dakota is believed to consist principally of drift carried in the basal part of the glacier, end moraines must include not only basal drift, but most of the englacial drift as well. Boulders carried great distances can be expected to have been more numerous in englacial positions than in the base of the ice because attrition, during long-distance transport in the base of the glacier, should have reduced such boulders to smaller size. By this reasoning, end moraines in South Dakota should contain, per unit volume of drift, a larger proportion of boulders (most of which in this region are far travelled) than should ground moraine, because ground moraine consists mainly of debris from more local rocks, yielding chiefly fines, plus the fine-grained products of the attrition of basally carried far-travelled coarser fragments.

Long observation has led the writer to the belief that even in the ground moraine the distribution of boulders is by no means uniform. This belief is based not only on surface-boulder distribution, but, more reliably, on exposures of till in road ditches created by new construction. Commonly, in a traverse of new construction 3 or 4 miles long in a single till body having uniform topographic expression, 1 mile may reveal numerous boulders still in place or thrown out during excavation, whereas the next mile may reveal few boulders or even none at all. Differences in local bedrock can not explain this fact, because the boulders consist of rock types derived from beyond the limits of the State. Possibly some factor related to movements of the glacier ice, such as concentration by upward shearing in the terminal zone, may be involved. No satisfactory explanation has yet been found.

In an area within the James River lowland in South Dakota, Waring (1949) counted more than 1,500 surface boulders having long diameters between 4 and 9 feet, measured the diameter of each, and grouped the diameters into half-foot groups. He found the number of boulders in each group decreases, with increasing diameter, in a systematic manner, and suggested that a logarithmic law of distribution may be involved.

In a few localities the Wisconsin tills include blocks or lumps of older till. A particularly good example of this relationship, exposed in 1947, is in the southeast corner of sec. 12, T. 100 N., R. 54 W., Turner County, where Mankato till contains blocks of an older, possibly pre-Wisconsin, till.

In the eastern wall of the Missouri River trench are a few exposures of till, apparently Wisconsin, in which cobbles and boulders constitute a large proportion of the whole mass, instead of the very small proportion commonly observed. Such deposits, consisting essentially of rubble, seem to require a condition of deposition in which the fines, normally present in the glacier in great abundance, could be selectively carried away by melt water. The removal can not have been postglacial, because the fine-grained matrix is still present between the closely packed cobbles and boulders. The relation of these rubbles to the eastern wall of the trench suggests that perhaps ice at the glacier margin was breaking up and part falling, part flowing into the trench. Such conditions should permit the flushing away of a large proportion of the fines, leaving a till unusually rich in large-size fragments. Good examples were well exposed as recently as 1949 in a cut near the northeast abutment of the Oahe Dam, in the NW¼ sec. 6, T. 111 N., R. 79 W., and in a series of road cuts in the S½ sec. 18, T. 108 N., R. 74 W., both in Hughes County.

CONTORTED STRUCTURES

Exceptionally numerous boulders are not the only characteristic that distinguishes the till of end moraines from the till of ground moraine. In nearly all ground-moraine exposures the till seems to show a nearly random distribution of its components of various size grades. Many end-moraine exposures, however, have distinct local concentrations of particular size grades, as well as conspicuous related structures. The concentrations take the form of lentils and pockets of sand, silt, and gravel, ranging in horizontal diameter from a few inches to several tens of feet. Clearly these are the result of sorting of the drift by water. The structures are evident in the attitudes of many of the lentils, which are warped and contorted; yet others seem entirely undisturbed. The whole effect is like that seen in a slice of marble cake. The contortion seems to be the result of the drag effects of glacial flow; if so, the water sorting of the sediments in the lentils occurred before the ice ceased to flow and hence occurred, presumably, beneath or within the basal part of the ice.

The inference of washing and sorting followed by contortion finds support in the common occurrence of such sections in end moraines which mark terminal glacial positions. Instead of having been lodged or plastered upon the ground by flowing ice, this drift may have come to a halt while still incorporated in thin, stagnating ice near the margin of the glacier. Trickling melt water may have created the sorted lentils which became separated from each other by slumping as the melting ice released more drift. The deformation may have been brought about by overriding of the drift, during and after release from the ice that contained it, by the thrust of thicker ice from upstream.

The explanation suggested above is for this case only, and can lay claim to no accuracy; it merely seems a reasonable explanation of the facts observed. Of the many sections of contorted till observed, the following are easily accessible, being located mostly on paved highways:

Brule County: Cut on southwestern side U. S. Highway 16, in the NE¼ sec. 22, T. 104 N., R. 71 W., in Illinoian(?) till.

Charles Mix County:

- Cut on east side U. S. Highway 281, in the NW¼SW¼ sec. 1, T. 99 N., R. 66 W., in Cary till.
- Cut on road at brink of Missouri River trench, in the NW¼SW¼ sec. 24, T. 100 N., R. 71 W., in Iowan(?) till.

Hutchinson County: Road cut 0.1 mile east of the northwest corner sec. 19, T. 98 N., R. 60 W., 1 mile west of State Route 37, in Mankato till.

Minnehaha County: Cut on south side State Route 38, in the SE¼ sec. 16, T. 102 N., R. 51 W., in Cary till.

Potter County: Gravel pit, center SE¼ sec. 22, T. 118 N., R. 78 W., 1.5 miles west of U. S. Highway 202, in Iowan or Tazewell till.

Yankton County: 0.1 mile north of the west quarter corner of sec. 4, T. 94 N., R. 55 W., in Mankato till.

Another section, 0.2 miles west of the north quarter corner sec. 30, T. 115 N., R. 60 W., Spink County (in east slope of valley of Foster Creek, 0.3 miles east of State Route 37), is peculiar in that it shows 4 feet of Mankato till overlying 10 feet of deformed Pierre shale. The strike of the shale, N. 10° E., nearly parallels the axial trend of the local end moraines; its dip is about 12° SE. The rarity of structures in the bedrock exposed in this region, and the parallelism of strike to end-moraine axes, suggest that the deformation of the shale is the result of thrust by glacier ice, probably at the time the moraines were built. A similar cause has been attributed to local bedrock structures in other regions. (See references in Flint, 1947, p. 171–173.)

STRATIFIED DRIFT

CLASSES

Stratified drift has its origin in till as well as in the drift contained in glacier ice. Ideally, stratified drift is distinct from till in that it has been both sorted and stratified by melt water after or in some cases before its release from the ice. In nearly every glaciated region, however, stratified drift grades into till in one place or another, so that some of it is not stratified, even though it is partly sorted. In consequence the line dividing the two kinds of drift is arbitrary.

Stratified drift can be subdivided in two ways. In terms of the medium by which it was deposited it can be classified into stream deposits (outwash) and deposits made in ponded water. In terms of relationship to glacier ice, as indicated by its surface form and internal character, stratified drift can be classified into ice-contact deposits (laid down upon or against glacier ice) and ice-free deposits. These two kinds of subdivision overlap and to some extent grade into each other. For convenience in discussion, the second is here subordinated to the first.

OUTWASH

In eastern South Dakota there are many bodies of outwash. Most, however, are neither thick nor areally extensive, nor, from the utilitarian point of view, do they meet the standards required for concrete aggregates and for some other industrial uses. The majority of these deposits are the despair of engineers in search of concrete aggregate because of the character of the till in this region and, more remotely, the nature of the bedrock from which all the drift was derived.

Scarcity of outwash in other regions has been attributed to a preponderance of evaporation over melting in the ablation of glacier ice. The relatively small proportion of outwash in eastern South Dakota is not believed to be attributable to such a cause, because the channels of ice-marginal and proglacial streams are present in great abundance. It is therefore evident that there was no lack of melt water; it is only the sediments deposited by such streams that are meager. Not only the small quantity but also the industrially poor quality of the outwash are attributable to the character of the bedrock.

The fact that most of the bedrock immediately underlying the drift in this region consists of shale, with chalk a poor second, accounts for the overwhelmingly large proportion of clay- and silt-size particles in the till. The glacial melt-water streams that flowed away from the ice separated these fine particles from the little coarse material that the drift contained. The silt and clay particles were small enough to be taken into suspension and kept there; consequently the great bulk of such fine material was exported entirely from South Dakota and is now little represented in the stratified drift. On the other hand the sand- and larger-size fragments, being heavy, constituted the bed loads of the melt-water streams, and were therefore deposited in the upstream parts of the proglacial stream courses. However, the coarse, bed-load sediments were so scanty that they now rarely constitute thick deposits. The typical small outwash body in this region (fig. 15) consists of a maximum of 2 to 10 feet of crossbedded sand and pebble gravel capping a low paired terrace that stands a few feet above the modern flood plain. Clearly the outwash was thin to begin with, and much of it was removed by downcutting that followed outwash deposition. The sand grains tend to be angular, and the

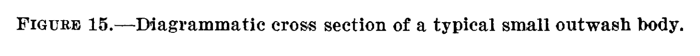

FIGURE 15.—Diagrammatic cross section of a typical small outwash body.

pebbles, although waterworn, are mostly poorly rounded. These facts indicate that the melt waters did not carry their bed-load sediments far from the glacier; rather they deposited the sediments after transporting them only a short distance.

As shown in figure 15, the parts of the original outwash bodies that are now preserved as terrace remnants are parts that were thin. Greater thicknesses existed in the central parts which have been removed by post-outwash incision. However, most of the outwash-bearing valleys were shallow before incision, and hence thicknesses even in their vanished central parts were not great.

Because of its small scale, the map (pl. 1) does not differentiate outwash from younger alluvium. In general, however, considerably more than half the combined area mapped as outwash and alluvium is underlain at the surface by alluvium, related to the outwash as shown in figure 15.

Although pebbles are commonly the coarsest fragments seen in outwash in this region, cobbles and boulders are exposed in some places, usually near the heads of outwash bodies at the points where streams emerged from the glacier. They seem to have been moved very little from their former positions in glacier ice or till. Good examples are a road cut in the SE¼ NE¼ sec. 6, T. 95 N., R. 65 W., Charles Mix County, which in 1946 exposed 25 feet of boulder gravel, and a pit in the southeast corner sec. 8, T. 99 N., R. 53 W., at Parker, Turner County, which in 1947 exposed lentils of cobbles and boulders in sand and gravel.

In some places, where gradients were steeper or where stream discharge was greater than usual, a proglacial stream was competent to carry virtually its entire load of sediment without depositing even the coarse pieces. Nevertheless the stream accomplished a good deal of lateral erosion, widening its channel in the till through which it was flowing, and removing all the eroded material except the boulders. The result was a broad flat underlain by till and strewn with residual boulders, and in most cases incised by later stream trenching so as to constitute a pair of terraces. Such "till shelves" are numerous. A conspicuous example, readily accessible, parallels Twelvemile Creek for 4 miles in Davison and Hanson Counties. It extends from sec. 26, T. 102 N., R. 60 W., into sec. 8, T. 101 N., R. 59 W., cutting Mankato till.

Here and there in some outwash bodies are patches of till whose flat tops are flush with the general surface of the outwash and are marked by scattered boulders. Probably these are low knobs or hills of till whose tops were planed down by flowing melt water while outwash was being deposited. Such till patches are exposed in the Cary outwash body between Madison and Chester in Lake County.

So much for the small bulk of the outwash. Its poor quality, from the practical point of view, again lies in the character of the local bedrocks. Except for the Sioux quartzite, these rocks simply do not yield hard, durable pebble-size fragments. The shales, the chalks, and the ferruginous concretions concentrated from the Pierre shale possess neither strength nor durability. Accordingly the principal firm rock types found in the outwash deposits are the far-travelled species—Paleozoic limestones and igneous and metamorphic rocks from far to the north and northeast—and as has been shown these are few even in the till. Where concentrated in the outwash they are too few to make a good showing.

In general outwash is more deeply and thoroughly oxidized than is till of the same age; in some exposures, indeed, it is stained completely brown with limonite. The difference is the result mainly of the open texture of sand and gravel, which readily permits the descent of water. In this region, at least, the extent and intensity of oxidation is not a reliable guide to the age of a deposit of drift.

To the generally small quantity and poor commercial quality of the outwash sediments, there are exceptions where, owing to special circumstances, thicker accumulations of better commercial quality are found. The chief exception is the outwash in parts of the valley of the Big Sioux River and that of Skunk Creek, one of its larger tributaries. North and west of Sioux Falls, along these streams, are accumulations of outwash that are 30 feet thick through the 15-mile segment between Baltic and Sioux Falls, and 50 feet thick in the valley of Skunk Creek near its mouth. The sediments are not exposed in terraces for they occur beneath present flood plains. Their thicknesses are known as a result of a well conceived plan of test drilling (Rothrock and Otton, 1947) undertaken for the improvement of water supplies for the city of Sioux Falls. These exceptional accumulations of outwash sand and gravel were localized by preexisting basins, created apparently by blockades of till across valleys in the underlying Sioux quartzite. The exceptional volumes of coarse sediment available for deposition in these basins seem to have resulted from the interlobate position of the proglacial Big Sioux River. It is evident from the map (pl. 1) that in Cary time, at least, this stream flowed down the narrow ice-free belt between the Des Moines glacial lobe on the east and the James lobe on the west. Throughout this distance in Cary time it was fed by many short tributaries leading directly from the ice on both sides. In consequence the Big Sioux had an unusually abundant bed load of gravel and sand, which could be deposited wherever a trap was available.

In addition to the thin outwash caps on terraces and the more impressive outwash bodies along major valleys such as the Big Sioux, outwash masses occur buried beneath till, with no apparent relation to present topography. These masses are revealed in 72 of the 276 well logs assembled for study. Their presence is suggested also by the results of geophysical prospecting for local water supplies (Rothrock, 1941).

Although discussed in more detail hereafter, the relation of outwash bodies to end moraines and drift borders deserves mention at this point. Along the outer margins of some major end moraines outwash occurs as elongate aprons, paralleling the trends of the moraines. Examples, easily seen on the map (pl. 1) are the outer Cary moraine in Potter County and the outer Mankato moraine in Clark and Kingsbury Counties. Such aprons were built largely by water flowing down the distal slopes of the moraines themselves. More commonly outwash bodies take the form of long narrow valley trains, following either intermoraine depressions (such as those which contain the outwash in Miner County) or premoraine valleys leading directly away from the moraines (such as Platte Creek in Charles Mix County and Medicine Creek in Hughes County). However, many long sectors of the border of the drift whether marked by end moraine or not, lack outwash. The outer Mankato moraine in Day County and the broad Mankato moraine in central McPherson and central Edmunds Counties are examples. Long sectors apparently devoid of outwash imply that the glacial drainage originated, not at the glacier margin, but farther back upon or within the ice, issuing at the margin only at hydrologically favorable points after considerable integration of stream flow had occurred.

OUTWASH-MARGIN LAKE DEPOSITS

One other feature of outwash bodies in eastern South Dakota should be noted. At some points, most of them close to the ice margins from which the streams emerged, outwash valley trains are flanked by fine-grained ponded-water deposits that extend laterally up tributary valleys. These deposits very nearly reach the altitudes of the outwash surfaces at the mouths of the tributaries, and in favorably situated exposures the outwash sediments (where still present) are seen to grade into the much finer-grained ponded-water deposits. Evidently aggradation of the outwash valley trains blocked the tributaries and created lakes in them. The parallel-bedded silts and clays are the floor deposits in such lakes, contributed by lateral discharge from the valley trains as well as from up the tributaries.

Two striking examples occur beyond the western margin of the Mankato drift. One is the lacustrine fill (silt, clay, and fine sand) in the valley of South Medicine Creek above its junction at Blunt, Hughes County, with the capacious valley of North Medicine Creek. Although the North Medicine Creek outwash has been extensively removed, enough remnants exist to indicate that this was the master stream, and that South Medicine Creek received only a subsidiary discharge of melt water from the Mankato ice front.

The other example is in northwestern Douglas County. There Platte Creek, depositing outwash at the margin of the Mankato glacier, formed a dam across the mouth of an unnamed depression that extends eastward for several miles through the northern parts of T. 100 N., R. 65 W., and T. 100 N., R. 66 W. This resulted in the accumulation of laminated silt. A third example, in Minnehaha County east of Sioux Falls, has been briefly described by Rothrock and Newcomb (1926, p. 31).

Lacustrine deposits such as these are not true glacial-lake deposits because they were not accumulated in water bodies held in by dams of glacier ice. They are, strictly speaking, outwash-margin lake deposits.

GLACIAL LAKE DEPOSITS

Distinct from outwash and outwash-margin sediments is the stratified drift, mostly fine grained, accumulated in temporary lakes held in basins that formed where the ground sloped toward a glacier margin.

As might be expected, such lakes were more numerous in the well-dissected coteaus than on the lower ground. Most of the lake deposits identified are at the surface; the emerged lake floors are still visible. Some, however, are inferred from well logs. An example is the mass of clay and silt, free of stones and 78 feet thick, found in a boring (fig. 25, locality 8) at Bristol, Day County. This sediment lies buried beneath more than 225 feet of overlying drift.

However, the area covered by glacial-lake sediments in the James River lowland is greater than the area of all other lake sediments combined, because conditions in the lowland permitted the ponding of a very large lake which extended into North Dakota and continued to be maintained from the north for some time after South Dakota was freed of ice.

Glacial-lake features are discussed specifically on page 122.

ICE-CONTACT STRATIFIED DRIFT

Ice-contact stratified drift, showing by its internal character and external form that it was deposited in contact with wasting glacier ice, is common in many glaciated regions. It includes elongate sinuous eskers, knoll-like or buttelike kames, valley-side kame terraces with short projecting fingerlike crevasse fillings. Also in this category are the heads of outwash bodies pitted with steep-sided kettles made by the melting of masses of buried ice, and bodies of collapsed stratified drift built entirely over ice and let down irregularly as the ice melted.

In a broad sense the development of ice-contact stratified drift depends on thin ice wasting into many separated masses. This relationship is inferred not merely from the drift left by former glaciers, but also from observations on existing glaciers, where such drift is actually seen in process of development. The terminal zone of a shrinking glacier, in some cases through many miles behind its extreme outer margin, thins to such a degree that it can no longer flow under its own weight. In consequence it lies inert, and if melt water and drift are present in sufficient quantity, the water sorts and deposits the drift upon, beside, and beneath the ice, penetrating crevasses, enlarging them by melting, and filling them with sediment. Separation and melting of the ice, coupled with the deposition of stratified sediments, thus give rise to a wide variety of topographic forms which, taken together, create a complex and virtually endless series of combinations.

Although topographic forms are varied, the range of internal characteristics is much the same within all of them. These characteristics include pronounced lenticularity, abrupt change of grain size, and structures recording disturbance of stratification by subsidence, faulting, folding, and sliding. Ordinarily there is a close correlation between the internal characteristics and an outer form that is predominantly constructional, composed principally of knolls and basins.

Two factors promote the development of ice-contact drift. The first is a thin glacier; the second is a subglacial surface with pronounced relief, providing cleats and pockets that favor the separation of masses of marginal ice. Accordingly ice-contact features should be found more commonly in drift left by the Mankato and Cary glaciers (which, as shown hereafter, were relatively thin) than in the drift of the thicker Tazewell and Iowan glaciers. This is, in fact, the case. It follows also that such features should be most abundant where predrift relief is greatest, namely, in prediversion valleys and in the more dissected parts of the coteaus. This, also, is the case.

However, the overall bulk of ice-contact stratified sediments in eastern South Dakota is small in comparison with their abundance in drifts of comparable age in Minnesota or Wisconsin. The comparatively poor display of ice-contact stratified drift in South Dakota probably can be attributed to the fundamental fact that the bedrocks of this region yield predominantly clay and silt rather than fragments of larger size, and hence do not produce much stratified drift of any kind.

Most of the ice-contact deposits in South Dakota consist of kettle-pitted or collapsed outwash in prediversion valleys. Apparently short minor lobes of thin ice remained in these relatively deep, protected furrows. Melt-water streams, following these same low-level routes, deposited outwash around and upon the ice, while separation and collapse progressed. Such occurrences are identified on the map, plate 1, by stippling superposed on the color designating outwash and alluvium. Although many exist, only four of the largest and most conspicuous areas of pitted and collapsed outwash are mentioned here. The first three are developed in the Mankato drift; the fourth dates from Cary time.

1. An area 25 miles long by as much as 6 miles wide in Campbell and Walworth Counties, extending northward from near Selby through Mound City and Herreid nearly to Pollock.
2. An area 15 miles long and as much as 5 miles wide, centering at the town of Long Lake in northern McPherson County.
3. A discontinuous and patchy area 20 miles long and as much as 8 miles wide centering at Pickerel Lake in northeastern Day County and including adjacent parts of Marshall and Roberts Counties.
4. An area 16 miles in maximum length and 7 miles in maximum width lying northwest of Watertown, Codington County, and extending into Clark County.

Kame terraces are far less common in South Dakota than are collapsed and pitted outwash bodies. The most conspicuous example is found in Yankton County, flanking both sides of the James River, and centering in sec. 32, T. 94 N., R. 55 W. The terraces, standing more than 100 feet above the river, lie within the jaws of a pincers formed by a conspicuous Mankato end moraine. As they are partly covered by a thin deposit of till, they antedate at least the latest readvance of the glacier lobe over the area. It is likely that they were built, possibly as the proximal part of an outwash valley train, shortly before the construction of the conspicuous moraine.

With the possible exception of some very small discontinuous elongate ridges in secs. 19 and 30, T. 96 N., R. 53 W., and the center of T. 96 N., R. 54 W., on the summit of Turkey Ridge, no eskers were seen during the field study, and it is probable that few if any exist in this region. A ridge, about 1 mile long and 25 feet high, in sec. 22, T. 122 N., R. 60 W., in southeastern Brown County, was mapped by Todd (1909) as an esker. However, it trends southwest, parallel with local end moraines, and has a steep northwest slope exposing till and a less steep southeast slope exposing gravel. In view of these facts the ridge seems better explained as an end moraine—probably a push moraine—with an apron of outwash covering its distal slope.

Other steep-sided ridges, with or without gravel covers, are mapped in the literature of the State as eskers, but as all of them parallel the local end moraines, and as all those examined consist largely or wholly of till, they are here regarded as end moraines.

In a few localities isolated, steep-sided conical hills project sharply above the general surface. These hills expose sand and gravel; but whether any or all of them possess cores of bedrock or till is not known. Some of them are undoubtedly kames. A conspicuous example, only 50 feet high but visible for several miles, is the mound, locally known as Garfield Peak, in the S½ sec. 3, T. 115 N., R. 68 W., Hand County, in an area of Mankato drift.

Similar isolated knolls occur in many places on high parts of the Coteau des Prairies in eastern Minnehaha and Moody Counties, in the Iowan drift area, and in similar positions in eastern Brookings County, in the area of Tazewell drift. These knolls are less steep and less conspicuous than those in younger drifts, owing mainly to a blanket of loess that is thicker at the bases of the knolls than at their tops. The mounds, some of which have been opened by gravel pits, are two or three hundred to two or three thousand feet in diameter, and are therefore too small to be represented on the scale of the map, plate 1. Those in Minnehaha County are well shown on a map of larger scale published by the South Dakota Geological Survey (Rothrock and Newcomb, 1926, fig. 8).

The apparently random occurrence of the knolls on high stream divides, where the wasting Iowan and Tazewell ice sheets should have been thinnest, suggests an explanation of their origin. They may have formed at the intersections of crevasses and other openings in places where the wasting ice was so thin that glacial flow had almost ceased. Some such explanation seems necessary in order to account for the preservation of the knolls, which, beneath a vigorous flowing ice sheet, would have been greatly modified or destroyed.

The shallow depressions with depths ranging to several feet and with lengths ranging to 1 or 2 miles, occurring in the floors of the shallow valleys of minor intermittent streams throughout the entire drift-covered region, are not kettles and are apparently unrelated to ice-contact stratified drift. They occur only in areas where very gentle slopes are the rule. They are visible on many of the standard air-photo contact prints, scale about 1:20,000, imparting to a valley the appearance of a string of beads of varying sizes. They are inclosed by till, with or without a covering of silt and clay deposited by the streams at times of continuous flow or in lakes and ponds at times of little or no flow.

It seems probable that the depressions are a part of the original morainic surface created beneath the glacier ice, having survived whatever small discharges of water have crossed them since their exposure by deglaciation. The basins have been partly integrated into strings by streams trenching through the intervening swells during wet times, and have been partly filled with lacustrine clay and silt. However, it is quite likely that during dry times the basins have been accentuated by the deflation of these partial fillings; the wind may even have removed fines from the underlying till itself.

BASINS IN THE DRIFT

Many glaciated regions include large numbers of basins, mostly small and mostly in areas of stratified drift. These are generally described as having been localized by residual blocks of glacier ice that became wholly or partly buried in the drift and whose subsequent wastage created the basins. They are referred to as kettles.

Although it might be supposed that the lake basins of eastern South Dakota, apparently surrounded by drift, originated in the same manner, this is not believed to be the unqualified origin of most of them. The great majority seem to be related to former stream valleys partly blocked or largely buried by glacial drift. This origin of many basins was first recognized in Minnehaha County by Rothrock and Newcomb (1926, p. 27) and was later recognized in counties farther north by Searight and Moxon (1945, p. 4, 8). Probably some basins do represent former masses of residual ice isolated within valleys that antedate the glacial encroachment. Others, however, seem to be no more than areas of nondeposition by the ice, hemmed in on two sides by the sides of an ancient valley and on the other two sides by accumulations of drift. The kettlelike appearance of such basins derives from their round or ovate form and from the steepness of their side slopes. In most basins, however, these features are the result of wave erosion by lakes that occupied them formerly or that occupy them still, steepening the shores and smoothing the plans of the basins. It is noteworthy that the rounder and steeper basins occupy low positions in the local terrain; thus they would benefit most from rise of the water table. Most of the basins in higher positions resemble normal ground-moraine swales and lack the lacustrine features described.

According to the explanation set forth above, masses of isolated residual ice are not implied in explanation of all kettlelike basins. Technically, some of the basins seem to be kettles whereas others are not, and in a great many cases it can not be affirmed whether or not a basin is a kettle. The distinction is somewhat academic; what is important is the inference that most of the basins are related to ancient valleys.

Three facts support this inference: The majority of the basins occur in chains, with a linear alignment that in some cases is a series of curves like those of a winding stream valley; the basins tend to be individually elongated parallel with the axis of the chain in which they occur; some of the chains are extensions of obvious former stream valleys in areas of strong relief where the drift fails to mask the bedrock surface. Examples are the well-marked chains at the head of the Spring Creek drainage north and south of Long Lake, McPherson County, and the chains at the heads of several creeks that drain the western slope of the Coteau des Prairies in Clark County. This last fact seems to constitute virtual proof of the origin suggested. Absolute proof could be had from detailed data on the configuration of the bedrock surface beneath the drift, but such information is lacking.

In the light of the explanation above, it is clear why lake basins are largely confined to the two coteaus and are very rare in the intervening James River lowland. The relief of the bedrock surface is many times greater in the coteaus than in the lowland, the valleys are correspondingly deeper, and the likelihood that glacier ice would create conspicuous basins by blocking the valleys was increased accordingly.

Ancient valleys traversing the lowland are marked by linear groups of relatively small, shallow depressions rather than by a few large and deep ones. Examples are the clusters of lakes in southwestern McCook County and in the southwest corner of Miner County, both shown on plate 1. These appear to be true kettles, formed by the collapse of drift over buried residual ice. The drift, however, is not stratified drift, but till.

LOESS

Loess can be defined, for the purpose of the present discussion, as a sediment, commonly nonstratified and commonly nonconsolidated, composed dominantly of silt-size particles, ordinarily with accessory clay and sand, deposited primarily by the wind. In South Dakota, as elsewhere, loess consists chiefly of particles of quartz and feldspar.

As in the discussions of till and stratified drift, only the physical aspects of loess, as distinct from the stratigraphic aspects, are mentioned at this point. Separate treatment of the two aspects is the easier in that the various loess sheets of different ages seem to be much alike in physical character and hence in the factors that determined their areal distribution and grain size. This fact is brought out in a series of histograms showing the results of mechanical analysis of various loess sheets (figs. 16–19), of a single loess sheet at various levels in a single exposure (figs. 20, 21), and of a nonglacial silt (fig. 22) for comparison. As the Loveland loess has already been briefly described, it is mentioned only for comparison in the following discussion, which is concerned principally with the loess sheets of the Wisconsin stage.

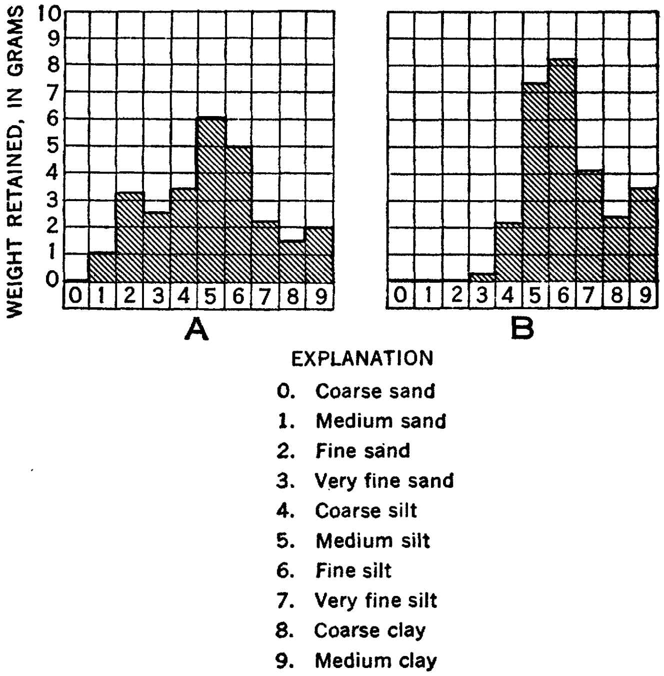

FIGURE 16.—Histograms showing grain-size frequencies in two samples of Loveland loess. *A*, NE¼ sec. 11, T. 102 N., R. 51 W., Minnehaha County, S. Dak.; *B*, Fullerton, Nance County, Nebr.

COLOR AND ALTERATION

In the literature generally, loess has been described as "yellowish." Loess takes on a yellowish hue as it becomes oxidized, and this hue is what is nearly always seen, owing to the facts that loess, being permeable, is subject to rapid and deep oxidation, and that most exposures are comparatively shallow. Indeed, unoxidized loess was observed at only a few places in South Dakota, all of them in the basal parts of relatively thick sections. Unoxidized loess in this region is light olive gray when dry; slightly darker when moist. Oxidized loess is colored various shades of yellowish brown and yellowish orange. Where drainage is good, as in the upper and middle parts of thick sections, the yellowish hue is even and uniform. Where drainage is poor, as immediately above a clayey till or shale, the color is unevenly distributed, producing a distinctly mottled effect.

In the western part of the glaciated region the loess, even where oxidized, is paler in hue than farther east.

Probably this is the result of the distinctly drier climate, which slows the rate of oxidation and promotes the accumulation of much secondary carbonate, whose pale-grayish hue is apparent in many exposures.

Beneath surfaces having little slope, loess is commonly leached through a superficial zone varying from a few inches to two or three feet in thickness. Below this zone is a zone in which carbonates leached from above have accumulated as whitish powdery interstitial fillings or as small white nodules. Beneath slopes the loess commonly lacks these zones, because there erosion of the loess keeps pace with subsurface alteration.

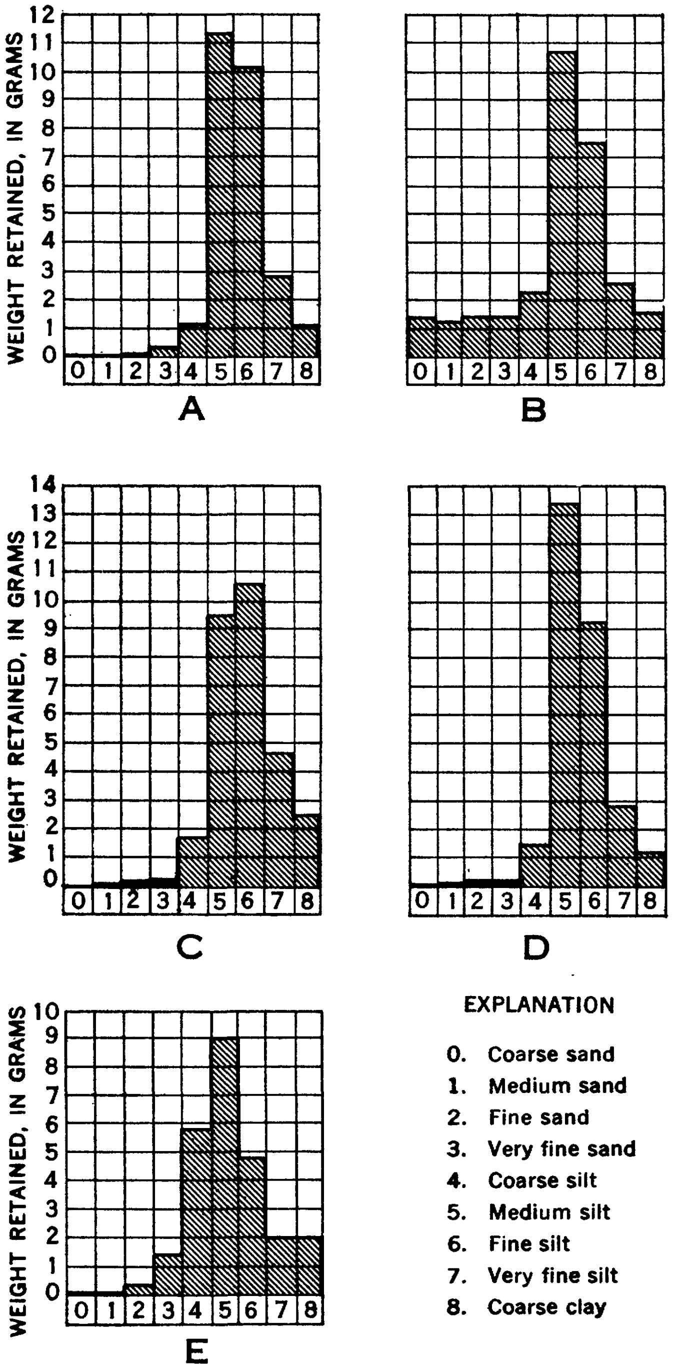

FIGURE 17.—Histograms showing grain-size frequencies in five samples of Iowan and post-Iowan loess. *A*, SE¼ sec. 19, T. 94 N., R. 50 W., Union County; *B*, NE¼ sec. 14, T. 96 N., R. 50 W., Lincoln County; *C*, NW¼ sec. 6, T. 103 N., R. 50 W., Minnehaha County; *D*, NW¼ sec. 11, T. 102 N., R. 51 W., Minnehaha County; *E*, SE¼ sec. 24, T. 21 N., R. 26 E., Corson County, S. Dak.

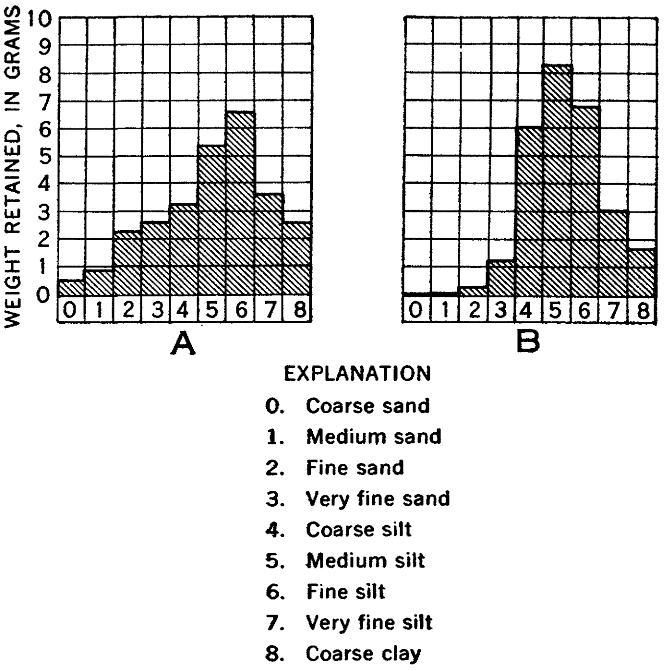

FIGURE 18.—Histograms showing grain-size frequencies in two samples of Tazewell and post-Tazewell loess. *A*, NW¼ sec. 30, T. 116 N., R. 50 W., Deuel County; *B*, NE¼ sec. 26, T. 114 N., R. 50 W., Deuel County, S. Dak.

STRATIFICATION

Most of the loess is apparently nonstratified although mechanical analyses show that variations in grain size in the vertical direction are visible at least locally. In places near the Missouri River trench, however, such variations are expressed as conspicuous subparallel stratification, in which layers of sand and silt of various sizes are clearly distinguishable. The two most striking examples seen are exposed just outside the region mapped. One is in a draw in the Missouri River bluff within the limits of Sioux City, Iowa, about 2 miles east of the South Dakota State line. The other[12] is exposed in cuts on State Route 12, in the N½ sec. 21, T. 32 N., R. 5 W., Knox County, Nebr., 3 miles southeast of the State line.

At these localities the stratification is probably eolian rather than aqueous, because in both exposures massive layers of varying thickness are conformably interbedded with laminated layers. This relationship has

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[12] Described in detail by Simpson, H. E., 1951, Geology of the Yankton district, S. Dak.: U. S. Geol. Survey open-file manuscript report.

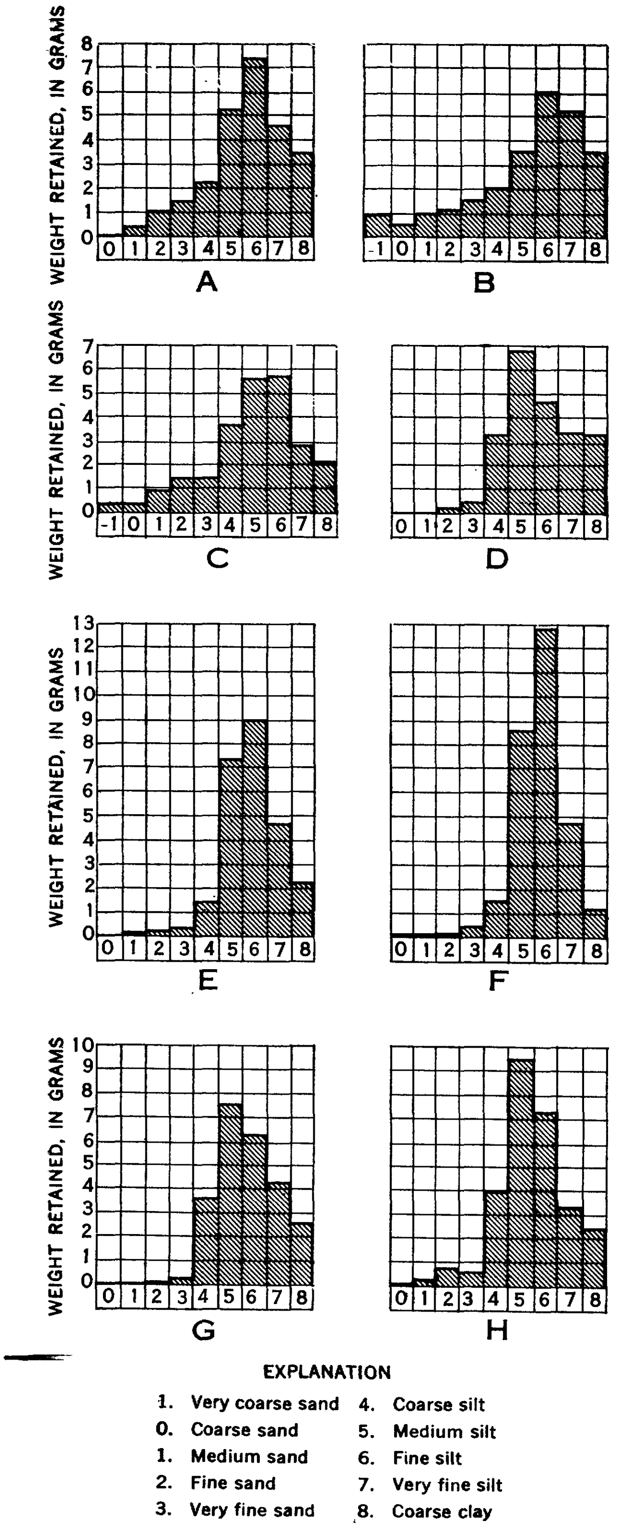


FIGURE 19.—Histograms showing grain-size frequencies in eight samples of Cary and post-Cary loess. *A*, southeast corner of sec. 19, T. 99 N., R. 50 W., Lincoln County; *B*, southeast corner of sec. 12, T. 100 N., R. 54 W., Turner County; *C*, SW¼ sec. 36, T. 102 N., R. 52 W., Minnehaha County; *D*, NW¼ sec. 35, T. 103 N., R. 69 W., Brule County; *E*, NW¼ sec. 15, T. 105 N., R. 52 W., Lake County; *F*, NE¼ sec. 22, T. 108 N., R. 55 W., Miner County; *G*, SE¼ sec. 14, T. 108 N., R. 55 W., Miner County; *H*, center of sec. 7, T. 120 N., R. 52 W., Grant County, S. Dak.

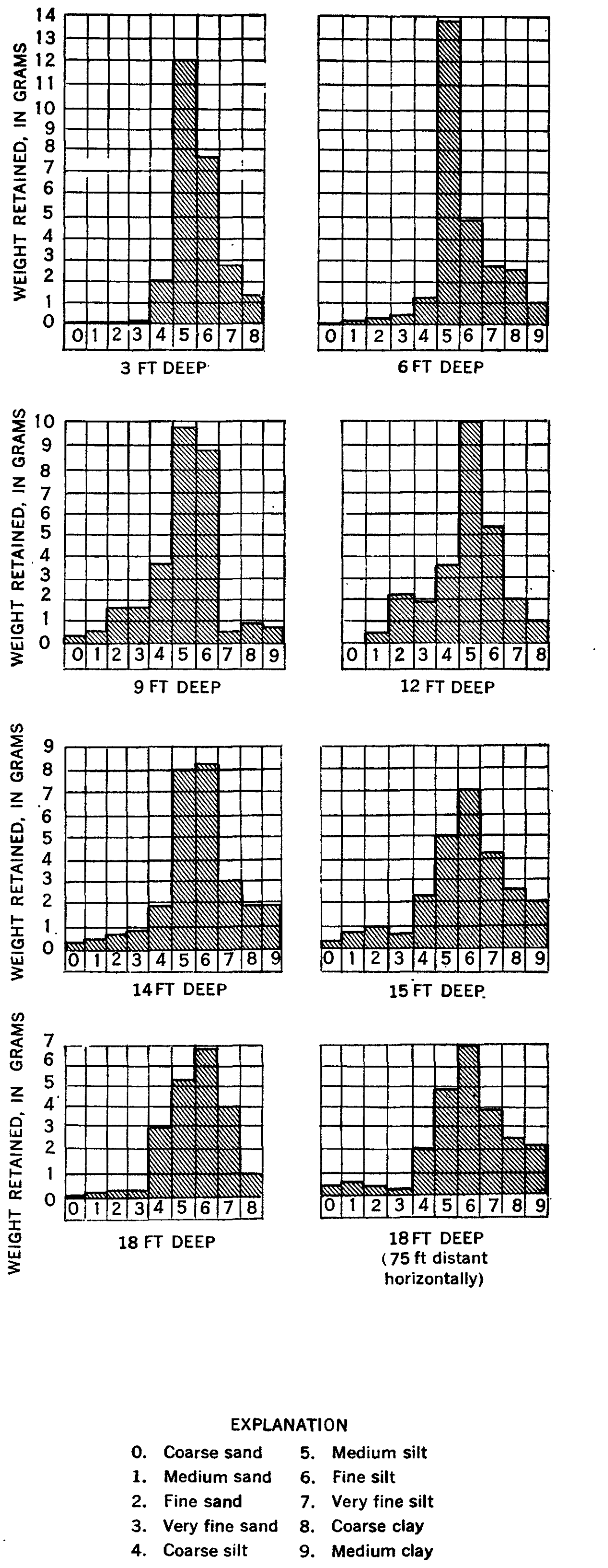


FIGURE 20.—Histograms showing grain-size frequencies in eight samples of Iowan and post-Iowan loess from various depths at a single locality in the center of sec. 19, T. 102 N., R. 50 W., Minnehaha County, S. Dak.

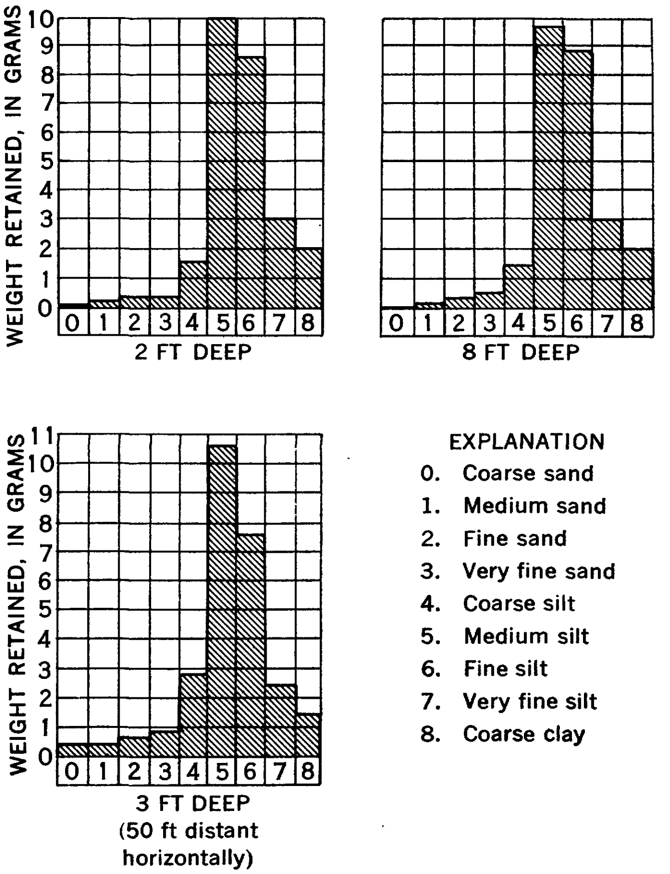


FIGURE 21.—Histograms showing grain-size frequencies in three samples of Iowan and post-Iowan loess from various depths at a single locality in NE¼ sec. 6, T. 101 N., R. 48 W., Minnehaha County, S. Dak.

not been reported in sections known to be aqueous. Furthermore the altitudes and topographic positions of the stratified material preclude the likelihood that water bodies formerly existed at those places.

An occurrence within the region mapped is in the SW¼ sec. 1, T. 105 N., R. 71 W., Brule County, in cuts along State Route 47.

At localities within the Missouri River trench in Hughes County, loess, including exceptional proportions of fine-sand sizes, is not only stratified but also cross laminated.

This stratification, if eolian, must reflect variations in competence of the wind. Such variations should have been frequent close to the glacier margins. With a varied assortment of grain sizes in the source material—chiefly outwash valley trains of major size—such stratification is expectable. It is surprising that stratified loess in similar positions has not been widely reported in the past.

In contrast with stratification believed to be eolian, some exposures of loess in relatively low topographic positions have vague, indistinct stratification. Prob-

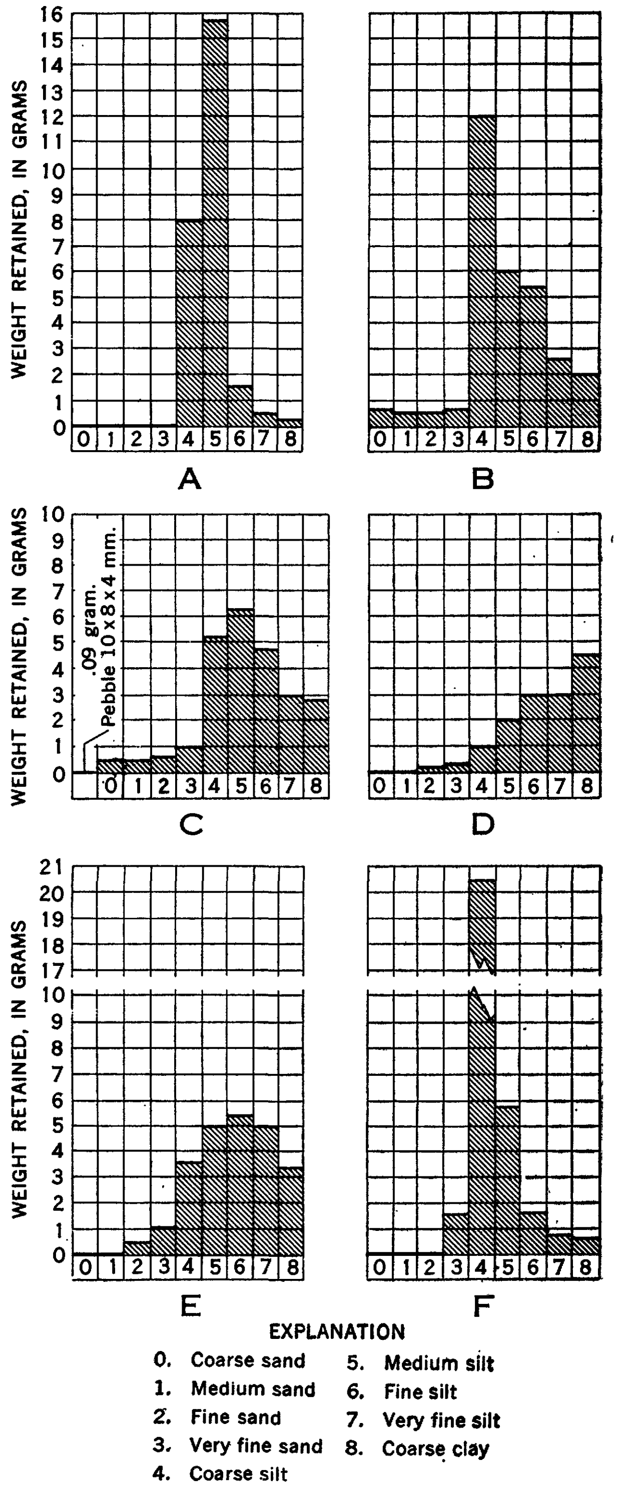


FIGURE 22.—Histograms showing grain-size frequencies in five samples of loesslike silt, probably aqueous, and in 1 sample of nonglacial sediment, probably part of the Ogallala formation. *A*, aqueous(?) silt, NE¼ sec. 12, T. 99 N., R. 49 W., Lincoln County; *B*, aqueous(?) silt, SW¼ sec. 36, T. 102 N., R. 52 W., Minnehaha County; *C*, aqueous (?) silt, southwest corner of sec. 3, T. 101 N., R. 49 W., Minnehaha County; *D*, aqueous (?) silt, south quarter corner of sec. 7, T. 124 N., R. 55 W., Day County; *E*, aqueous or colluvial silt, southwest corner of sec. 3, T. 101 N., R. 49 W., Minnehaha County; *F*, Ogallala formation(?), SE¼ sec. 26, T. 122 N., R. 76 W., Walworth County, S. Dak.

ably this arrangement of the loess particles is secondary, having been produced by colluvial and alluvial activity during and since the eolian accumulation of the loess. The interpretation of such stratification as secondary is one of long standing. Loess having stratification of this kind has been referred to as valley-phase loess, in reference to its occurrence in low-lying positions. The indistinctness of the stratification can be attributed perhaps to the fact that the loess particles, having been already sorted by the wind, include only a narrow range of grain sizes and hence lack a physical basis for conspicuous lamination.

A remarkable example of this material was exposed in 1948 in a big ditch, 350 feet long and 23 feet deep, in the southwest corner of sec. 5, T. 123 N., R. 78 W., Walworth County. Grayish-yellow silt, derived from loess and mostly laminated, is there interbedded with olive-gray colluvium evidently derived from the Pierre shale, the local bedrock. The section records either successive eolian incursions separated by times of rainwash, or wholly colluvial accumulations derived from lithologically distinct, very local sources.

STRUCTURE

Two facts about the structure of loess have been reported so widely that they are accepted as common knowledge. One is the presence of conspicuous vertical jointing and the other is the persistent tendency of loess to stand in steep slopes, even in places where joints are not conspicuous.

Observations of loess in eastern South Dakota furnished no data inconsistent with the view that the joints were caused by settling and compaction of the sediment, a hypothesis frequently appealed to by students of loess. In a large number of exposures, however, the steep angle of repose of this material is independent of visible joints. Possibly this fact is related to the properties of silt grains as compared with sand grains, as indicated by Bagnold (1937, p. 435), as a result of laboratory experiments:

> The physical properties of quartz particles, such as feel, angle of repose, and behavior in a wind, change abruptly as the grain size falls below 0.01 cm. Below this diameter the angle of repose rises sharply, and clean dry grains of 0.005 cm. will stand in vertical cliffs like those produced in flour and other fine powders. The presence of such grains in a mixture of coarser sand will also have the same effect. Since microscopically the grains are very little different in shape from the larger grains of dune sand, it seems that true cohesion must be the cause.

The same worker (Bagnold, 1937, p. 436) put forth data that may explain the stability of loess once it has been deposited, even where a protective cover of vegetation does not enter in:

> . . . there is distinct evidence that the wind required to move grains smaller than those of 0.01 cm. begins to increase . . . as the size is reduced. The probable cause is that the wind has now to overcome not only the friction due to the grain's weight, but also the coherence force attaching it to the other grains on the surface . . .

Bagnold's experiments showed that

> . . . a layer of fine particles of smaller size than 0.005 cm. once deposited by sedimentation out of the air will not be moved by the wind—unless bombarded by larger grains—and will not therefore drift into dunes. It is of interest to note that the peak diameter of loess particles is of just this magnitude.

THICKNESS AND TOPOGRAPHY

The true thickness of loess at any one place is difficult to measure accurately, because the material, being unconsolidated, creeps and slumps down the slopes. This is especially true within a few miles of the Missouri River in the extreme southeastern part of the State, where loess is generally thickest and where the dissected surface that underlies it has maximum relief and maximum slope. Loess is draped like a mantle over this surface, and the upper part of this mantle is in slow process of shifting down the many slopes toward the streamways. For this reason apparent thicknesses measured vertically on slopes are likely to differ from true thicknesses.

True, unexaggerated measurements can be obtained through auger borings on broad, flat, nondissected uplands. By this method a maximum thickness of 25 feet was obtained at one point in Union County (NW¼ sec. 1, T. 95 N., R. 49 W.) A thickness of 34 feet was determined by auger in the N½ SW¼ sec. 14, T. 93 N., R. 57 W., Yankton County (H. E. Simpson, written communication). An apparent thickness of 50 feet is exposed in the bank of Brule Creek in SE¼ sec. 1, T. 92 N., R. 50 W., Union County, but the true thickness is believed to be smaller. What is thought to be a nearly true thickness of 49 feet was exposed in 1949 in the Missouri River bluff at the east end of the highway bridge in Sioux City, Iowa, a few miles southeast of the South Dakota State line. Exposed thicknesses of as much as 100 feet have been reported from localities farther south along the Missouri River bluffs (Kay and Graham, 1943, p. 196).

Todd (1908, p. 8) cited well logs that show greater thicknesses than any determined from exposures or auger borings. A hole in SW¼ sec. 20, T. 93 N., R. 49 W., Union County, passed through 60 feet of loess before entering till, and another in SW¼ sec. 4, T. 94 N., R. 49 W., revealed 90 feet of loess overlying till. Todd mentioned a well in Dixon County, Nebr., close to the Missouri River bluff opposite Vermillion, S. Dak., that passed through 130 feet of loess.

Where loess is 20 feet or more thick, as in the extreme southeastern corner of the State, it is present not only on nearly flat surfaces, but also on fairly steep slopes, although it is obviously in process of removal by rainwash. Where thinner, loess tends to be absent from the steeper slopes. There seems to be no single critical slope angle above which loess is absent, but the general statement can be made that where a slope exceeds a very few degrees, little or no loess is present. Of course loess is being removed from slopes by present-day processes, but it is probable that a part, perhaps much, of the removal dates from the episode of accumulation, and that many slopes lost their cover, through mass wasting and sheet erosion, nearly as fast as the silt was deposited on them by the wind.

Outside the Mankato drift, most of which never received a mantle of loess, the loess-free areas are mainly on the flanks of the Coteau des Prairies, in the breaks of the Missouri River in the central part of the State, and on end moraines with steep slopes. In the area of nondifferentiated Iowan-Tazewell drift and in the western part of the area of Cary drift it is not unusual to find a loess-free end moraine surrounded by loess-covered ground moraine. The presence of loess-free end moraines constitutes a local restriction on the general principle that drift sheets in this region can be correlated by means of their relation to intervening loess sheets. In such correlation topography and slope must be taken into consideration.

Although the relationship can not be firmly established without a fine network of auger borings, the exposures observed lead to the belief that loess thicknesses are greatest near outwash valley trains, and that they are greater on easterly than on westerly sides of such bodies. This relationship, if true, points to derivation of loess from outwash by means of winds of generally westerly origin. It is noteworthy that the two areas of thickest loess in South Dakota, in southern Union County and eastern Minnehaha County, occur immediately east of major bodies of outwash. Other factors influencing thickness, notably the time available for accumulation, enter into the problem. But the loess in both areas is of the same age (Iowan and post-Iowan), and relation to westerly winds is believed to have been an important factor. This factor has long been recognized elsewhere in the Central Lowland region; the data have been summarized by Smith (1942, p. 152).

The relation of the thickness of Cary and post-Cary loess to the Missouri River trench, the greatest source of outwash in southeastern South Dakota, is illustrated by the fact that at Vermillion, in Clay County, exposures and borings give a thickness of about 16 feet at the crest of the river bluff, and that this diminishes to less than 5 feet at a distance of 3 miles northeast of the bluff. This same loess is thicker in Clay County, where the bluff trends southeast, than it is in Yankton County, where the trend is slightly north of east; the difference again suggests the agency of westerly winds.

Along both sides of the Missouri River trench between the North Dakota State line and the vicinity of Chamberlain, loess that is probably Tazewell and post-Tazewell is 8 to 18 feet in thickness. Westward it thins rapidly to an average of less than 3 feet and becomes very patchy. Eastward it thins less rapidly, and on flat surfaces as much as 25 miles east of the river it averages about 5 feet thick.

The Cary and post-Cary loess is irregular in thickness and is locally patchy, but its average thickness does not depart far from 30 to 36 inches throughout its wide area of outcrop. In places at the western border of the Cary drift this loess reaches 6 feet in thickness. It is believed to have been derived from many local sources. The Mankato loess is developed only locally, principally in the vicinity of major outwash bodies. Where it occurs it is mostly too thin (less than 2 feet) to be readily mappable, although close to the Missouri, in Bon Homme and Yankton Counties, it is 3 or 4 feet thick.

East of the Missouri River, in western Iowa, loess is so thick that it possesses a constructional topography resulting from differential heaping of sediment by the wind (Carman, 1917, p. 342; 1931, p. 116). Topography of this kind has not been recognized in South Dakota, even in those areas where loess is thickest, except on a very small scale. However, in this region loess generally has the effect of reducing the local relief and coarsening the texture of the topography. Away from the most conspicuously dissected areas along major streams there is a close correlation between loess thickness, relief, and topographic texture. Loess only a few feet thick erases minor topographic swales and thus reduces the irregularity of the surface. This effect is particularly evident in the contrast between the respective surfaces of the Cary drift, generally loess covered, and of the Mankato drift, generally loess free.

The only topographic features peculiar to loess in this region are small basins. Most of them are a few tens of feet in diameter and a foot or two in depth. They occur on broad uplands. A few, however, are larger. The largest one observed is in the center of sec. 6, T. 92 N., R. 49 W., Union County, and is shown by contours in the Elk Point topographic quadrangle of the U. S. Geological Survey. It is about 1,500 feet in diameter and has a closure of 25 feet. Its gently sloping floor is covered with colluvium. The maximum relief of the area of its occurrence exceeds 200 feet.

It may be that some of the minor shallow basins are the work of deflation, although the stability of loess particles, mentioned earlier, argues against such an origin. It is believed that the large basins, and possibly the small ones as well, are sinks developed by the mechanical removal of loess by subsurface drainage. The permeability of loess and the considerable local relief would favor downward percolation of rainwater along a short steep streamway in the buried subloess terrain, and emergence at a low point nearby. Saturation of the silt along the subsurface route would cause its removal by flowage, thus creating a subterranean tube through which mechanical transport from the point of intake could be effective. The mechanism, a mechanical analog to the chemical development of sinks in soluble rocks in the zone of aeration, was described by Cockfield and Buckham (1946), who observed active sinks in lacustrine silt in British Columbia. In eastern Nebraska the writer has observed small loess basins with active, open holes in their centers, and although most of the basins seen in South Dakota lack such outlets, small ones exist along the Missouri River trench in Brule County (C. R. Warren, written communication). The excavation of many of them has ceased, at least for the time being, for they seem to be now filling with colluvium washed down from their gently sloping sides.

AREAL EXTENT

Each of the loess sheets in South Dakota can be regarded as a complex of wedges, locally discontinuous and in places overlapping and intertonguing, each wedge beginning at a source of sediment and thinning away from it. As inferred in the discussion of loess thickness, the principal sources of sediment were bodies of outwash, of which the successive valley trains in the Missouri River trench probably were chief. To some extent, however, fines blown from the surfaces of till newly exposed by glacial melting may have contributed to loess. Any primary clay in loess very likely came from this source, because the outwash bodies now exposed contain little or no clay. To some extent, also, contributions were made by alluvium of nonglacial origin along the streams in the western part of the State.

Each of the loess sheets except that on the Mankato drift lies beneath a sheet of till. Therefore it is possible to determine accurately the extent of only that part of each loess body which remains free of a covering of till. As loess is identified in very few of the well logs assembled, it is not known to what extent its failure to appear in them is due to lack of original loess deposition, removal by later glacial erosion, or inaccuracies in the logs.

From direct observation of exposed surfaces east of the Missouri River, however, it can be said generally that loess covers the Iowan, Tazewell, and Cary drift sheets, and is present on the Mankato drift only in very restricted areas close to major sources.

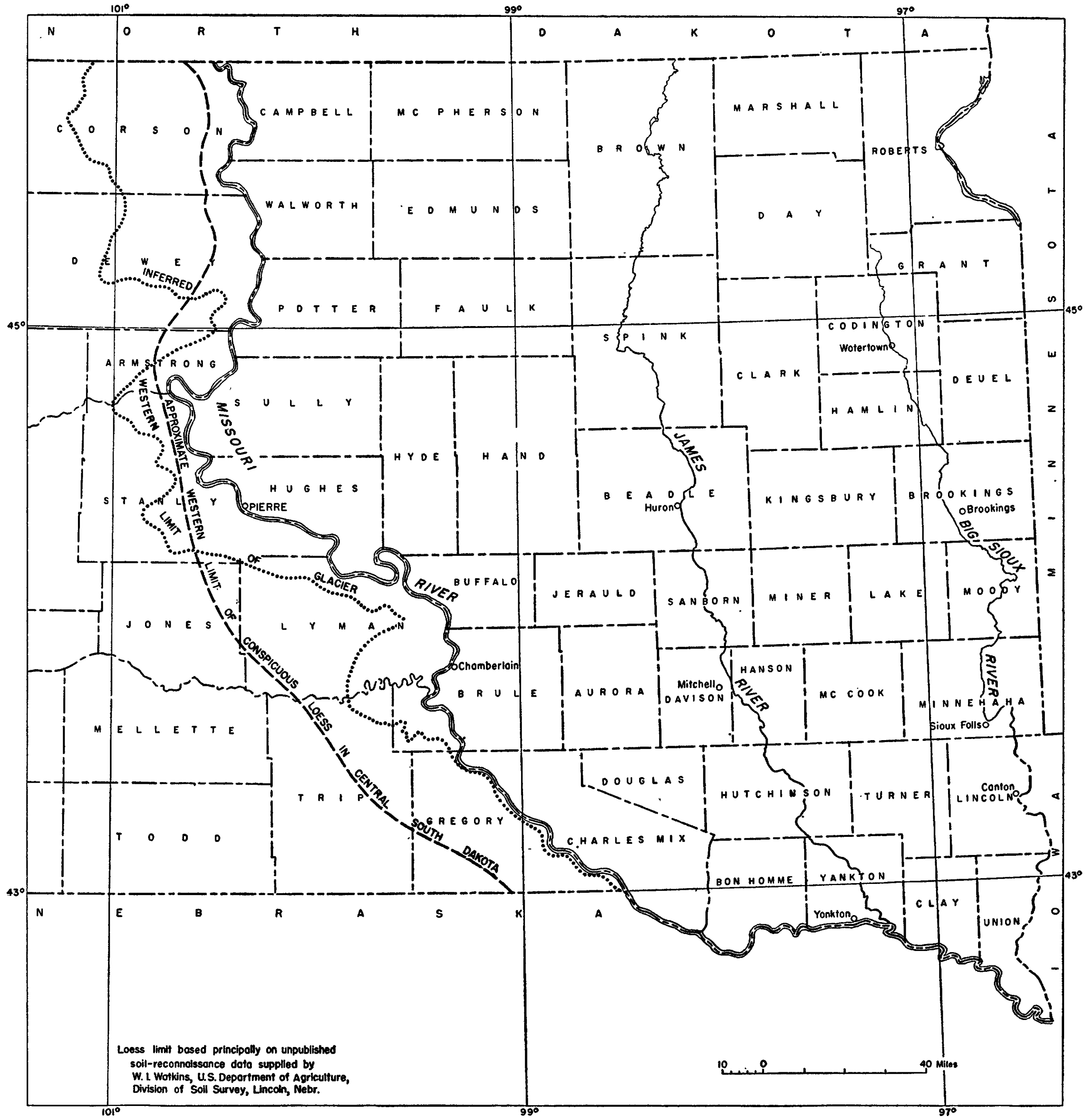
The loess west of the Missouri River presents a special problem. It occupies a belt of country 5 to 30 miles wide, as determined in soil surveys (fig. 23). This belt roughly parallels both the general trend of the river and the general trend of the outer limit of the drift. As the terrain is considerably dissected and as the loess is mostly very thin, loess is present there only in patches. West of the western limit shown on the map loess is found in places along the major stream valleys, mostly as caps on terraces of coarse alluvium, and east of the Black Hills in areas not yet mapped.

The Pleistocene geology of the region west of the Missouri River is so little known that the ages and sources of the bodies of loess present there are not known. However, as the loess is coarsest in the Missouri River trench itself, and as it thins toward the west, the inference seems justified that much of it was derived from sediment, probably outwash, in the trench. On the other hand the occurrence of loess along the western rivers strongly implies that it was derived, at least in part, from their alluvium. Finally, the loess in Gregory and Tripp Counties may have received considerable contributions from sediments of the Ogallala formation and overlying Pleistocene western alluvium; both bodies are widely present in those counties. In Corson and Dewey Counties wide outcrop areas of Fox Hills sandstone may have furnished contributions to the loess, and elsewhere the Mobridge member of the Pierre shale may have contributed particles of calcite and clay to the loess.

It is worth noting that, west of the Missouri River in South Dakota, loess is both thinner and less extensive than in the same belt of longitude in Nebraska, where the loess cover is virtually continuous. The difference can hardly be attributed to glacial phenomena, inasmuch as only the extreme eastern part of Nebraska is underlain by glacial drift. The explanation must be sought among nonglacial sources. Western Nebraska is widely underlain by alluvial deposits of western origin and of various Cenozoic epochs including the Pleistocene. These deposits include abundant sediments of the sizes that figure importantly in loess. In contrast, the unit having the greatest outcrop area in western South Dakota is the Pierre shale, a rock type that could have contributed only in a very minor way to the accumulation of loess. It may be that the poorer development of loess in western South Dakota than in Nebraska is the result of this lithologic contrast.

FOSSIL CONTENT

There exists a sizable literature on the terrestrial gastropods found as fossils in loess in the Central Lowland region. Although by no means abundant, such fossils



Loess limit based principally on unpublished soil-reconnaissance data supplied by W. I. Watkins, U.S. Department of Agriculture, Division of Soil Survey, Lincoln, Nebr.

Based on U.S. Geol. Survey map of South Dakota

FIGURE 23.—Map showing approximate limit of conspicuous loess in central South Dakota.

occur in South Dakota. However, no special effort was made to collect and study them, as this was considered to be outside the scope of a reconnaissance survey.

GRAIN SIZE

An excellent example of what can be learned from detailed study of grain sizes in a loess sheet is a publication on loess in Illinois by G. D. Smith (1942). Such a study, however, can be carried out successfully only after the stratigraphic framework of the drift sheets and loess sheets has been established in the area to be studied. As the stratigraphic relations in eastern South Dakota were almost unknown at the outset of the present study, systematic mechanical analysis of the loesses could not have been made effectively even if time had been available.

It is believed that with the present report as a background, systematic loess studies could be undertaken with the certain expectation of important results. During the field work leading to this report, however, the loess samples collected had to be selected to some extent blindly; in consequence the results of mechanical analysis offered here are spotty and have only a general significance.

Thirty-four samples of loess and loesslike sediments collected during 1946 and 1947 were mechanically analyzed by D. R. Crandell at Yale University. The results are shown in the series of histograms appearing in figures 16–22. From a comparison of the histograms the following inferences can be drawn. It should be emphasized that the inferences pertain only to the area sampled and that in any case they are tentative. No firm conclusions can be expected without detailed, systematic sampling.

1. The loess sheets, known to be of different ages because of their stratigraphic relations, are apparently not distinguishable from each other on a basis of their grain-size frequencies, nor do they seem to differ in any consistent way from loesslike silts believed to be of aqueous origin.
2. Comparison of the field samples with the histograms derived from them suggests that most of the differences among the various histograms are too slight to be readily detected by inspection of the sediments themselves.
3. Samples collected from a single exposure at short vertical intervals (fig. 20) tend to increase in grain size toward the top without, however, any discontinuity between adjacent samples. This may record merely variations in wind velocities; on the other hand it may indicate changes in the source of sediment, such as the arrival of a new flood of outwash related to a new glacial substage.
4. Three samples from another single exposure (fig. 21) show no significant differences among themselves.

Systematic size-frequency differences in South Dakota loesses may exist, yet may have been obscured, in the samples analyzed, because of multiplicity of sources. The source relationships in South Dakota appear to be more complex than those of the area in Illinois studied by Smith (1942).

Detailed mechanical analysis could be accompanied, possibly with profit, by the study of heavy minerals aimed at isolating the various regions of provenance of the loess. During the present undertaking no attempt at mineralogic examination of loess was made.

Aside from its eolian components the loess in South Dakota, as elsewhere, includes a few erratic fragments too large to have been transported by the wind. These fragments, mostly of pebble size, are believed to have been emplaced by creep and rainwash during the sedimentation of loess on relatively steep slopes. At two places pebbles were seen in abundance in loess, forming actual lentils inclined in the same direction as the present erosional slopes. Possibly a few pebbles may have been brought up into loess from underlying till, by frost heaving and by burrowing animals.

SUMMARY OF LOESS CHARACTERISTICS

Review of the physical character of loess in this region leads to five principal conclusions. The loess locally includes conspicuous stratified phases, believed to be eolian. It was derived chiefly from outwash bodies, although other sources contributed to it. Its thickness is a function chiefly of nearness to source. The winds effective in its sedimentation seem to have had a westerly component. The several loess sheets do not seem to differ from each other in the frequencies of their component grain sizes.

STRATIGRAPHY OF THE WISCONSIN DEPOSITS

HISTORY OF STRATIGRAPHIC SUBDIVISION

The Wisconsin drift was named by T. C. Chamberlin in the Central Lowland region. He originally called it East-Wisconsin (Chamberlin, 1894a, p. 763) but soon shortened the name to its present form (Chamberlin, 1895, p. 275). As the term was understood by Chamberlin it did not embrace all the drift now included in the Wisconsin stage; it excluded the Iowan drift in most areas and excluded both Iowan and Tazewell drifts in some others.

From 1895 to the present time, field studies by many geologists have resulted in continued refinements in the definition of the Wisconsin stage. Three contributions to these refinements are outstanding. The first was the subdivision of the Wisconsin drift, by Leverett (1899, p. 317), into two units, Early Wisconsin and Late Wisconsin. The second was Leverett's substitution of a threefold classification of the Wisconsin drift into Early, Middle, and Late units (Leverett, 1929a, p. 18), while viewing the Iowan drift as probably distinct from the Wisconsin. The third was the establishment (Leighton, 1933) of the classification and terminology now in use. These are set forth here for comparison with the classification used by Leverett in 1929. The region in which this stratigraphy was developed centers in the Lake Michigan basin, and includes the States of Illinois, Wisconsin, Minnesota, and, in part, Iowa:

Leighton (1933)	*Leverett (1929)*
Wisconsin stage	Wisconsin drift
4. Mankato substage	Late Wisconsin
3. Cary substage	Middle Wisconsin
2. Tazewell substage	Early Wisconsin
1. Iowan substage	Iowan drift (age and rank debatable)

According to the classification of Leighton the Wisconsin stage[13] is subdivided into four substages,[14] each of which marks a conspicuous expansion of the Wisconsin ice sheet. The substages higher than the Iowan substage mark interruptions that temporarily reversed the long process of deglaciation. That glacial reexpansions took place is demonstrated by the evidence, as all now agree. Furthermore the intervals between successive reexpansions are known to have involved less extreme changes than did the pre-Wisconsin interglacial ages, on the evidence of slight weathering of the various Wisconsin drift sheets. For this reason these drifts are considered substages rather than stages. However, comparatively little is known about the extent of deglaciation between any two succeeding expansions and about the relative lengths of the corresponding time units.

No more than two of the four Wisconsin substages are seen in contact in any one exposure, and few exposures show as many as two. Hence the Wisconsin sequence as a whole has been established in part on a basis of overlaps, and individual drift sheets have been identified on various sorts of evidence in various districts. The principal kinds of evidence that have been cited include interbedded sheets of loess, interbedded layers of peat and other organic remains, discordances in the trends of two sets of end moraines, distinct differences in provenance of drift based on lithology, differences in degree of erosional dissection of drift sheets, and differences in depth of leaching of drift sheets. Some of these lines of evidence are applicable only to individual exposures; others are applicable to sizeable areas. None, however, has yet been established across the entire Central Lowland region.

DIFFERENTIATION OF DRIFT SHEETS IN SOUTH DAKOTA

In South Dakota the Wisconsin stage is divisible into four units. The subdivisions are based on interbedded loess sheets, intervening soil zones, discordances in the trends of end moraines and borders of drift sheets, differences in degree of erosion, and intervening stone concentrates. The four units are judged to have the value of substages on a basis of evidence which, although not conclusive, is as reliable as the evidence on which the substages were differentiated in the region farther east. Because the number of subdivisions is the same as those recognized as standard farther east, and because they are of the same order of magnitude, namely, of the order of substages, the four Wisconsin drift sheets in South Dakota are believed to be the approximate correlatives of the four standard substages of the Wisconsin stage.

The foregoing statement is qualified by the word approximate for the reason that along the margin of an ice sheet exact synchrony of a general advance throughout a sector hundreds of miles wide is unlikely. Climatic differences from area to area throughout so great a sector may have been reflected in time lags between adjacent zones. Hence a substage in South Dakota may not be of precisely the same age as a substage in Illinois or Ohio, even though the two may occupy the same relative position in the stratigraphic sequence. Yet both may be a response to a single general climatic variation.

Ideally the drift sheets in a newly studied region such as South Dakota should be correlated by direct tracing from an adjacent region in which the sequence is already well established. At the outset of the present study it was believed that correlation could be made with western Iowa and southwestern Minnesota, where two Wisconsin drift sheets, the Iowan and the Mankato, had been recognized (Leverett, 1932; Kay and Graham, 1943). In 1947, however, it became apparent either that certain substages in eastern South Dakota were completely overlapped by younger substages in Minnesota and Iowa or, alternatively, that more substages than the two (Iowan and Mankato) then recognized in the latter States were represented by belts of outcrop within those States. The desirability of restudy was indicated further by the discovery by Smith and Riecken (1947) that much of the drift in northwestern Iowa, formerly considered to be Kansan, is in fact Iowan; in other words, that in that region the Iowan drift sheet is much more extensive than was believed formerly.

As the result of field conferences among the Director of the Iowa Geological Survey, the writer, and other interested persons, the Iowa Geological Survey took up the problem and, with the co-operation of the Minnesota Geological Survey, reexamined and remapped the critical area in northwestern Iowa and southwestern Minnesota during the seasons 1948 and 1949; further studies were made in northeastern Iowa in 1950. In consequence it was established that four substages of the Wisconsin drift, rather than two, are represented by outcrop belts in western Iowa and Minnesota, and that the four substages are the same as the four recognized in South Dakota.[15] The results of the remapping in western Iowa and Minnesota strengthen the correlation of substages in South Dakota with those recognized in Il-

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[13] The term "stage" is used here as a time-rock unit, and the term "age" is used as the time unit corresponding to stage, as proposed by Flint and Moore (1948).

[14] The term "substage" is used here as a major subdivision of a stage, and the corresponding time unit is referred to as a "sub-age" (Flint, 1947, p. 209).

[15] R. V. Ruhe, 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ. unpublished Ph. D. dissertation.

linois and Wisconsin because they partly close the gap, consisting of drift not yet mapped in detail, that separates the two regions.

In South Dakota, then, the Iowan drift is identified by continuous tracing from its type region of occurrence in the State of Iowa, and the Mankato drift is identified by tracing from its type area of occurrence around Mankato, Minn. Correlation of drift sheets in South Dakota with the type areas of the Tazewell and Cary drifts in Illinois is not yet possible by continuous tracing. Thus far it is based solely on the relative positions of these drifts in the Wisconsin sequence, supported by continuous tracing into an identical sequence occurring in southwestern Minnesota and western Iowa.

Before the substages in South Dakota are described individually, it is desirable to evaluate the evidence mentioned above as supporting their differentiation.

An extensive sheet of loess overlies each of the drift sheets except the Mankato, and lies beneath the next succeeding drift sheet. In South Dakota the Mankato drift is exposed overlying Cary loess, and the Cary drift is exposed overlying Iowan (and presumably Tazewell) loess. Although the Tazewell drift has not been seen overlying Iowan loess, this relationship is inferred from indirect evidence, detailed on page 90. The Mankato drift is overlain by loess only locally. The sheets of loess are not individually recognizable on a basis of their internal characters; they are identified mainly on a basis of their positions relative to the tills in the stratigraphic sequence. Lack of a weathering profile, however immature, in a till beneath the succeeding loess, indicates that in each subage loess deposition succeeded till deposition without significant break. The occurrence of loess beneath till proves deglaciation succeeded by renewed glaciation. Proof is furnished also by the common presence of loess incorporated in till, even at places where the base of the till is not exposed. The only basis for inferring a lapse of time between two successive tills is the loess itself, in addition, of course, to the time required for the glacier margin to readvance over the loess-covered surface. There is no satisfactory basis for inferring either the extent of any deglaciation or the northern limit of any of the loess sheets.

In some exposures tills are separated by zones of carbonaceous soil, developed either in the top of the underlying till or, more commonly, in the top of an intervening loess. The soil zones are Chernozem and Chestnut soils, which pedologists believe can be developed, under favorable conditions, during a period of possibly no more than a few hundred years. In view of this opinion, no great lapse of time between substages can be inferred beyond the time inferred from the existence of the intervening loess sheets themselves. The soil zones merely confirm that time intervals occurred between the times of deposition of the tills.

Certain drift borders and certain end-moraine systems have mutual discordances that are explained only on the hypothesis of major retreat and readvance of the James glacial lobe. The trend of the Tazewell drift border indicates that it lies beneath the Cary drift in northern Hamlin County. In the eastern part of Walworth County the border of the Mankato drift successively lies across Cary and nondifferentiated Iowan and Tazewell end moraines. Mankato end moraines transect Cary end moraines at an angle in Roberts County, in southern Hand County, and along Turkey Ridge in Hutchinson, Turner, and Yankton Counties. In each case, clearly the later glacier was thicker and more vigorous than the earlier glacier had been at the time when the overridden moraine was built.

In connection with variations in the thickness of the glacier from time to time, it might seem that the areal pattern of the substages on the coteaus (pl. 1) constitutes additional evidence of differentiation of the substages, for the Iowan drift covers the Coteau des Prairies, whereas the succeeding drift sheets fail to do so, lapping off in successively lower positions on one or both of its flanks. A similar pattern is present, though it is less clearly evident, on the Coteau du Missouri. This arrangement might be taken to mean that at the maximum of each subage, the glacier was thinner than at the maximum of the subage next preceding, thereby implying a lapse of time necessary for regional thinning of the ice. That thinning occurred is indubitable. There is, however, no means of determining what proportion of the thinning to assign to the time of minimum ice extent before each readvance, and what proportion to the shrinkage of the glacier while it was still present in this region, during the latter part of the preceding subage. In consequence the drift pattern on the coteaus does not afford a measure of the intervals of time when deglaciation was in force.

Some light is shed on differentiation of the substages by comparison of the topographic differences shown by each of the drift sheets. The difference in topographic expression between the Iowan and Tazewell drifts on the one hand, and the Cary and Mankato drifts on the other, is striking. An interesting quantitative measure (fig. 24) of this difference in northwestern Iowa has been put forward by Ruhe (1950). Much slighter topographic differences, as between the Iowan and Tazewell drifts and between the Cary and Mankato drifts, respectively, exist.

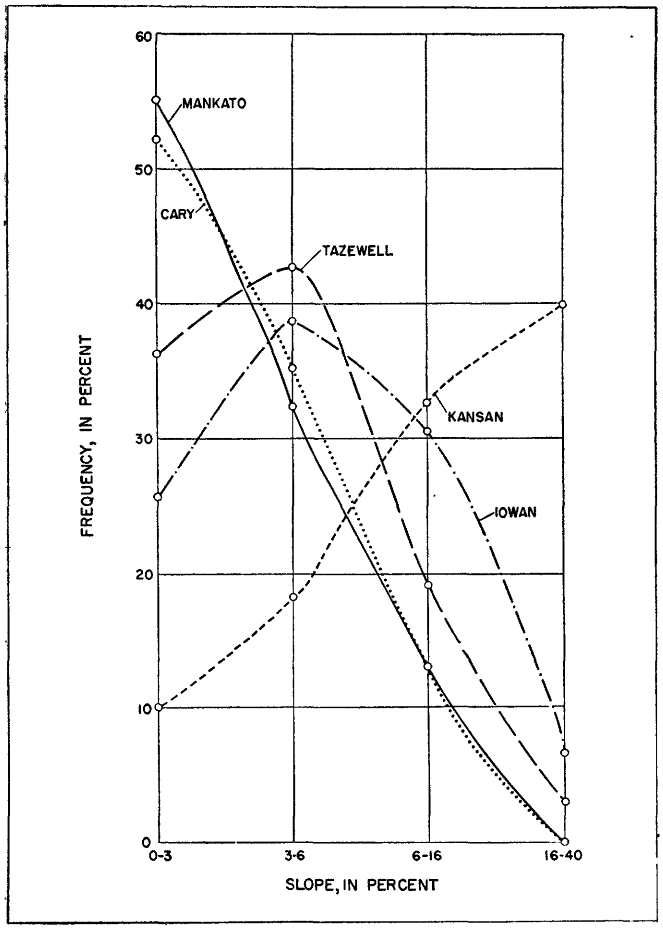

FIGURE 24.—Frequency curves of ground-moraine topography in five drift sheets in northwestern Iowa. (Ruhe, 1950, fig. 2.)

Concentrates of stones are exposed in a few places at the unconformable contact between successive tills. Certainly these features record erosion of the lower till before deposition of the upper, but it is not established that such concentrates could not have been developed by erosion of small thicknesses of till during quite short intervals. Accordingly the presence of the concentrates does little more than confirm the fact of temporary deglaciation, a fact better established on evidence already set forth.

This array of evidence leaves much to be desired, but it is believed to be as reliable as the evidence on which substages of the Wisconsin drift have been differentiated in other States.

Depth of leaching of carbonates in the drift, a line of evidence used in other areas, needs special mention. Percolating water dissolves calcium carbonate from surficial unconsolidated material such as drift and loess and reprecipitates it at slightly greater depth, usually above the water table. The belief has been held that with the passage of time the thickness of the surficial zone leached of calcium carbonate increases and that the thickness of the leached zone hence should be roughly proportional to the elapsed time since the sediment was deposited and should therefore measure the relative ages of two offlapping sheets of such sediment. If time were the only factor to be considered, this might be the case. But other factors, important ones, help to determine depth of leaching at any one place. Chief among them are composition and physical characteristics (especially texture) of the surficial material, climate, and slope of the surface. Together with time, these factors transform depth of leaching into a complex variable. Permeable material containing little primary carbonate beneath a flat surface in a moist climate is likely to become leached to a greater depth in a unit of time than will a relatively impermeable sediment that is rich in primary carbonate, beneath a sloping surface in a dry climate.

Many samplings have borne out these uncertainties. Indeed a single sheet of drift of known age, sampled at many different places, can be expected to yield a wide variety of values on depth of leaching, the extreme range of the values constituting a large percentage of their mean. A review of the literature on depth of leaching, with figures from various areas, is given by Flint (1949a).

In order to check the value of depth-of-leaching data in eastern South Dakota, depth of leaching was tested in two Wisconsin drift sheets, the Cary and the Mankato. Rainfall varies through a maximum of about 15 percent throughout the district tested. The topographic expressions of both drifts seem much the same. All tests were made on broad, flat uplands with negligible surface slope. The chief difference between the drifts is that the older is covered with 2 to 5 feet of loess, whereas the younger has little or no loess cover.

Twenty-five samplings of the Cary drift near its border in Lincoln, Minnehaha, Turner, and Bon Homme Counties gave a mean depth of leaching of 29 inches with an extreme range of 22 inches (18 inches to 40 inches). Fifty-eight samplings of the Mankato drift near its border in Hutchinson, Yankton, and Bon Homme Counties gave a mean depth of 23 inches with an extreme range of 48 inches (0 inches to 48 inches). As frequency-distribution plots made from the two sets of data fail to show a close grouping near the mean, it seems doubtful that the arithmetic means reliably indicate the difference between the ages of the drifts.

Eighty-four samplings of the Cary drift in Charles Mix County, west of the district mentioned above, gave a mean of 15 inches with an extreme range of 36 inches (0 inches to 36 inches). The frequency-distribution curve is irregular; hence the mean figure is believed to have little value. The irregularity is thought to be the result of variable composition of the till, which although generally clayey, contains chalk in amounts that vary sharply from place to place.

The results of the samplings suggest that the Mankato drift cannot be distinguished satisfactorily from the Cary drift, in this region at least, on a basis of depth of leaching of calcium carbonate.

In the drier parts of glaciated South Dakota evaporation draws water and dissolved substances surfaceward by capillarity. In consequence calcium carbonate is deposited as a zone of firm whitish cement (caliche) near the surface. The caliche ranges from discontinuous coatings on pebbles to a continuous firm cement. It is most conspicuous in the drift in Campbell, Walworth, Potter, and Sully Counties, where the precipitation averages about 18 inches, and it diminishes to inconspicuous coatings on pebbles in the district near the mouth of the James River, where the precipitation increases to about 25 inches.

Preliminary samplings in western North Dakota caused Howard (1946) to doubt the value of caliche as a chronologic indicator. From observations in South Dakota, the writer shares this doubt.

TERMINOLOGY OF LOESS SHEETS

The blankets of loess associated with the several Wisconsin drift sheets are closely related in time to the tills they overlie. This is shown by the fact that in no exposure tested is any Wisconsin till leached of its carbonate content beneath the loess overlying it. It is inferred therefore that loess deposition on the till began immediately or soon after the till was exposed by deglaciation. In view of this close relationship it is appropriate to designate the loess by the same name as that of the drift beneath it. This was done first more than 50 years ago (Kay and Graham, 1943, p. 157). For example, loess overlying Iowan drift, and in turn overlain by Tazewell drift, can properly be termed Iowan loess. Where, however, as is more commonly the case, loess over Iowan till extends to the surface without a covering of younger till or a soil of known date, it is probable that it includes sediment of more than one age, inasmuch as post-Iowan loess bodies are present generally in the region. If confusion is to be avoided, the terminology of the loess must take account of this probability.

Because similar relations exist in northwestern Iowa, the problem of terminology was discussed in field conference with the Director of the Iowa Geological Survey. It was agreed to use the following nomenclature in the present report and in current publications of the Iowa Geological Survey:

Name of loess sheet	*Position*	
Mankato	overlies Mankato drift.	
Cary and post-Cary	overlies Cary drift	and extends to the surface.
Cary		and is overlain by Mankato drift.
Tazewell and post-Tazewell	overlies Tazewell drift	and extends to the surface.
Tazewell		and is overlain by Cary drift.
Iowan and post-Iowan	overlies Iowan drift	and extends to the surface.
Iowan		and is overlain by Tazewell drift.

This usage is flexible in that it permits, for example, loess overlying Iowan drift and overlain by Cary drift to be referred to as Iowan-Tazewell loess. As employed in the present paper, as well as currently by the Iowa Geological Survey, it supersedes two former usages. In one, all the loess on the Iowan drift, whether or not overlain by a younger deposit, was termed Iowan loess. In the other, this same loess was termed Peorian loess.

The latter name has a curious history. It was applied by Leverett (1898) to the interval represented by the infantile weathering profile developed in a loess sheet directly underlying Tazewell till and correlated with the loess overlying Iowan drift, in an exposure near Peoria, Ill. Leverett believed, at the time, that the interval (the Peorian interval) was a long and important one; its very short duration was not recognized until later. Meanwhile the view was put forward that the fossils contained in the loess overlying the Iowan drift record a date of accumulation after, rather than during, the Iowan deglaciation, or, in other words, during the Peorian interval of Leverett. For this reason the loess formerly known as Iowan began to be called Peorian. This brought about the circumstance that at Leverett's type locality near Peoria, the name Peorian was shifted from a zone of weathering in the loess, to the body of the loess itself.

Meanwhile geologists returned to the opinion that the loess immediately overlying the Iowan drift dates in fact from the Iowan deglaciation and not from some later time (Kay and Graham, 1943, p. 159), and the existence of post-Tazewell loess was recognized. In Illinois the term Peorian ceased to be used for the loess believed to postdate Iowan till but known to antedate the Tazewell drift, and began to be applied to all the loess outside the border of the Tazewell drift sheet, extending from the present surface down to the base of loess believed to be Iowan. (Kay, G. F. and Leighton, M. M., quoted in Kay and Graham, 1943, p. 156.)

> Within the border of the Tazewell drift [in Illinois] the loess which immediately underlies it may be called Iowan, as originally proposed, and the loess which overlies it, the Tazewell loess.

In Iowa, however, the Peorian loess was differently defined as spanning "the time which in Illinois includes the Iowan loess, Tazewell drift, Tazewell loess and Cary drift." (Kay and Graham, 1943, p. 195). The latter usage has been discarded by the Iowa Geological Survey because it was based on the mistaken belief that the loess referred to lies between the Iowan drift and the Mankato drift Actually a part of the drift in that State, formerly believed to be Iowan, is Tazewell, and a part of that believed to be Mankato is Cary.[16] In Nebraska the usage has been similar to that in Iowa (Condra, Reed, and Gordon, 1950, p. 32). In Kansas a "Peoria silt member" is defined as a loess overlying the Loveland loess and separated from an overlying loess by a recognizable soil (Frye and Fent, 1947, p. 47).

Understandably, this very confused situation developed gradually in consequence of gradually increasing refinement of stratigraphic knowledge. It is sketched here to show why the author's usage adopted in the present report departs from some usages now current, although he believes it to be close to that originally proposed.

WISCONSIN STRATIGRAPHY INFERRED FROM WELL LOGS

Of the 276 drillers' logs (p. 29) examined during the present investigation, those disclosing apparent evidence of two or more drift sheets have been interpreted with the aid of knowledge gained from examination of stratigraphic sections exposed at the surface.

Interpretation of the stratigraphy of the drift from well borings is inaccurate because the till sheets are similar to each other, and the jetting method commonly used in boring through the drift makes difficult the location of contacts and the separation of till from stratified material having a similar range of grain sizes. Accordingly no accuracy is claimed for the interpretations made. They are little more than partly controlled guesses, to be corrected and improved when in the future results of extensive core borings become available.

Instead of being taken verbatim from the drillers' logs, descriptions have been put into terms as uniform as possible. Some drillers used such terms as "yellow till" and "yellow clay" for oxidized till, and "blue till," "blue clay," and "joint clay" for unoxidized till. After checking at various localities, these terms are translated with fair confidence.

Most of the stratigraphic interpretations are made with question marks, because it is not certain whether a considerable thickness of oxidized till is referable to a single substage, or whether it represents two substages oxidized at two different times, bringing about complete oxidation.

Loess is rarely identified in drillers' logs, perhaps owing to the superficial similarity between the particles composing loess and those composing the fines in a till. Also there is little basis in the logs for distinguishing between Wisconsin tills and pre-Wisconsin tills. When disaggregated, and in the absence of boulders, these tills are virtually impossible to distinguish from each other.

Todd (1902, p. 33) remarked long ago that the many borings in the James River lowland reveal no clear evidence of a till older than the Wisconsin. Todd's statement is still true. If, as the writer believes, the lowland has been deepened and notably widened by streams and glaciers since the drainage diversion in Illinoian time, then most or all of the former pre-Wisconsin drift in that district is likely to have been lost through erosion.

The Blunt damsite section (figs. 25, locality 1; 26) is interpreted separately, because it is based on logs that are more detailed and more closely spaced than the logs of most of the single, isolated drill holes known in eastern South Dakota. The section was constructed from 21 holes drilled by the United States Bureau of Reclamation in 1948 in secs. 19, 20, and 29, T. 113 N., R. 75 W., Sully County. The line of holes trends northwestward and is about 2 miles long. It includes the valley occupied by North Medicine Creek and part of the adjacent upland on each side of the creek.

The humified zone found in several of the holes is believed to be the soil formed during the Tazewell-Cary interval. The base of the Cary drift, accordingly, is placed at the top of the humified material. The distinction between Iowan and Tazewell rests on less firm evidence, and is based principally on the presence of two distinct till bodies beneath the humified zone. As the section lies in a topographic position lower than any believed to have existed in this vicinity as early as Illinoian time, the entire Pleistocene section here is referred to the Wisconsin stage.

Logs of 19 additional drill holes penetrating two or more probable Wisconsin drift sheets are shown graphically in plate 6, and their locations are shown in figure 25.

IOWAN SUBSTAGE

AREAL DISTRIBUTION

In extreme eastern South Dakota the Iowan drift sheet covers all the territory not covered by younger drift. In the central part of the State Iowan and Tazewell drift (not differentiated) covers all the territory between the western limit of the Cary drift and the west-

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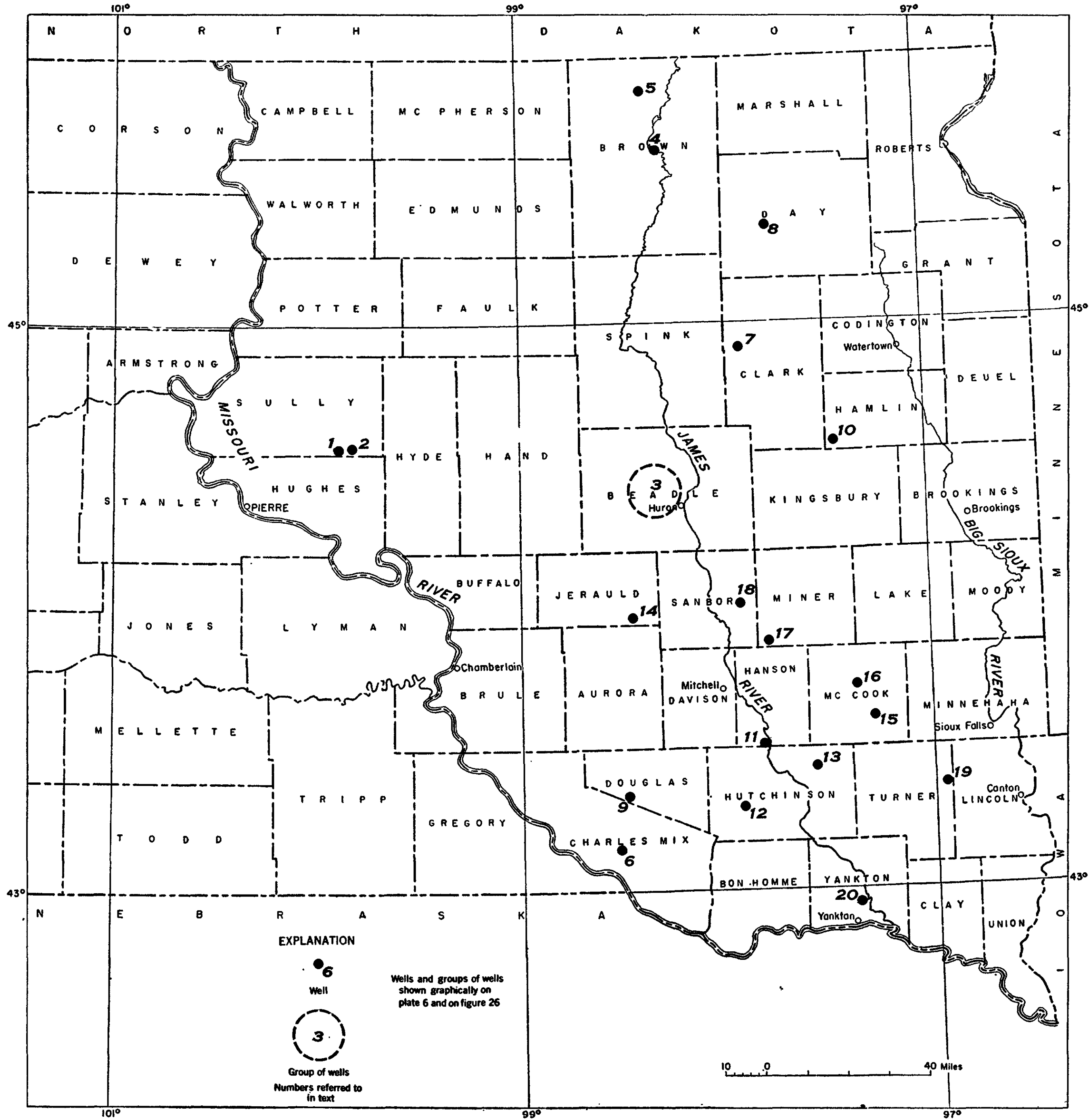
[16] Ruhe, op. cit.



Based on U.S. Geol. Survey map of South Dakota

FIGURE 25.—Sketch map of part of South Dakota showing locations of the wells and groups of wells referred to in text and in figure 26 and plate 6.

ern limit of glaciation. This distribution, shown on plates 1 and 3, implies that probably the entire glaciated region of South Dakota was covered by Iowan ice, despite the fact that the extent of Iowan drift now concealed beneath younger glacial deposits is unknown.

The outer limit of the Iowan drift in northwestern Iowa (pl. 3), as determined by Smith and Riecken (1947) from a complex pattern of borings through overlying loess, is irregular, with reentrants extending north up many valleys and with salients projecting southward on many interfluves. In the writer's opinion the irregularity is largely erosional. If this is the case, the present drift border does not accurately represent the margin of the former glacier, which was less irregular than the drift border and probably extended considerably farther south. Todd (1908, p. 5) thought that

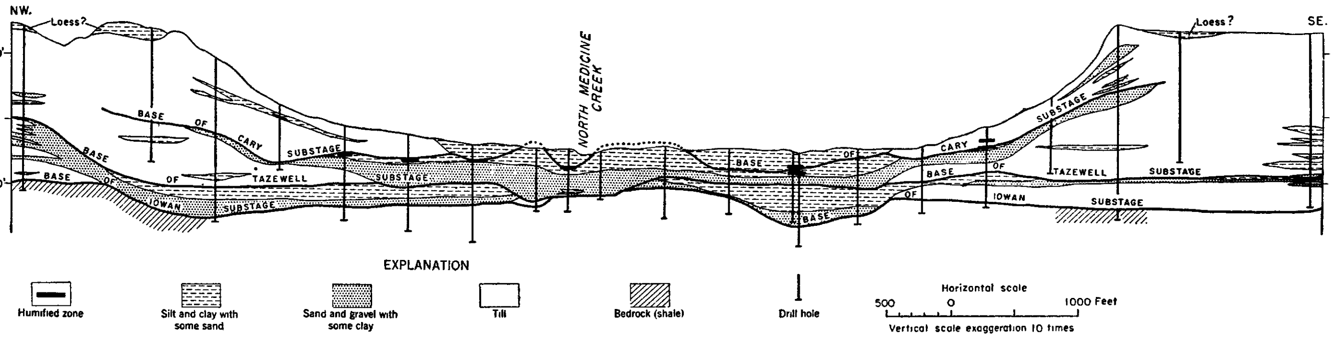


FIGURE 26.—Profile and section constructed from the logs of 21 drill holes at the Blunt damsite (locality 1, fig. 25). Section prepared by U. S. Bureau of Reclamation; interpretation by Bureau of Reclamation in consultation with R. F. Flint.

in the early part of the Wisconsin age the ice must have obstructed, or entirely filled, the Missouri River trench nearly as far southeast as Sioux City. "Otherwise," he wrote, "it is difficult to account for the occurrence of considerable masses of fresh till only 30 to 40 feet above the Missouri a little below the mouth of Big Sioux River on the Iowa side." Presumably the till referred to is Iowan. The writer made an attempt to find the exposures Todd saw, but found only pre-Wisconsin till exposed.

In northeastern Nebraska the Iowan drift is known to be present (Simpson, 1947), but the position of its outer limit is not known in detail because a thick cover of loess masks it. The generalized line shown in plate 3 is little more than conjectural; its lack of irregularity reflects only lack of detailed information. It is drawn tangent to the outermost known exposures of till believed to be Iowan, on information supplied by E. C. Reed of the Nebraska Geological Survey and H. E. Simpson of the U. S. Geological Survey. According to Mr. Simpson some of the till contains, in its basal part, inclusions of dark yellowish-brown to purplish silt similar to the Loveland loess. If the silt is in fact Loveland, it must have acquired its color by Sangamon weathering, and the inclosing till must therefore be Wisconsin. Further field data are needed before the gap in the drift border between northwestern Iowa and northeastern Nebraska can be bridged. It is known, however, that farther east in Iowa the Iowan drift lies beneath the younger drift sheets.

A comparison of the Iowan drift border (on the assumption that the outermost drift west of the Missouri River is Iowan) with the borders of the younger drift sheets shows that in Iowan time the ice sheet lacked the distinct broad lobes, centering along the axes of the James and Des Moines valleys, that characterize the later ice sheets. It follows that the Iowan ice was thick enough to overflow the Coteau des Prairies entirely and to stand, at its maximum extent, with a border free of pronounced lobation across western Iowa, Nebraska, and southern South Dakota. The inconspicuous lobation of the Iowan drift contrasts with the strong lobation of the Cary and Mankato drift sheets. Although it may result from relative thickness of the Iowan ice, it may be also, in part, a consequence of smaller regional relief—particularly smaller depth of the James River lowland—than that of later Wisconsin time.

CORRELATION

Comparison of the Iowan drift border as shown on plate 3, with the border earlier mapped by Leverett (1932, figs. 6, 7) shows that all the drift area in South Dakota classified by Leverett as Kansan is classified here as Iowan. The reclassification, which affects Iowa and Minnesota as well, arose as a result of detailed soil studies in northwestern Iowa by G. D. Smith and F. F. Riecken, followed, in 1947, 1948, and 1949 by field conferences attended by Smith, Riecken, personnel of the Iowa Geological Survey, and the writer. The reclassification is accepted by the Iowa Geological Survey. The historical background of the original classification has been clearly set forth by Ruhe[17] and need not be repeated here.

The evidence on which the drift in Iowa, formerly mapped as Kansan, is now believed to be Iowan is stated succinctly by Smith and Riecken (1947) and consists of three elements:

The till beneath superficial loess on broad, flat, poorly drained uplands is invariably free from surface alteration beyond slight oxidation Kansan till in similar situations is altered to gumbotil.

The area reclassified as Iowan has a distinctive topography, with gentler slopes, smaller relief, and broader interfluves than the Kansan drift area, and the change from one area to the other is abrupt.

Beyond the outer margin of the area reclassified as Iowan the thickness of the mantle of surface loess increases strikingly, and at the margin itself the loess is coarser and less well sorted than elsewhere. These

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[17] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation, p. 3–11.

changes are best explained on the hypothesis that a sheet of loess, unbroken beyond the Iowan margin, is split into two parts, inside the margin, by a wedge of Iowan drift.

Taken together, these lines of evidence establish a strong probability that a Wisconsin drift sheet immediately underlies the surficial loess in the critical area. That this drift is in fact Iowan was established by Smith and Riecken (1947, p. 713).

In South Daokta the last of the three lines of evidence set forth above can not be applied, inasmuch as no continuous area of Kansan drift, not mantled with Iowan drift, is believed to exist there. Kansan drift does crop out in eastern South Dakota, but only in areas of strong dissection where overlying Iowan drift is believed to have been removed by erosion.

The first and second lines of evidence, however, are applicable. On an upland interfluve, nearly 1 mile wide, with a nearly flat top, and outside the Tazewell and Cary drift borders, an auger hole was put down (in the NW¼ sec. 1, T. 95 N., R. 49 W., Union County) by Smith, Riecken, H. G. Hershey, and the writer. The auger penetrated calcareous loess to a thickness of 24.3 feet, and at that depth entered till, penetrating it for 1 foot. The till is very calcareous, contains small fragments of fresh limestone, lacks secondary carbonate, and shows no trace of humification. These characteristics are identical with those found in Iowa, and can not be explained if the drift beneath the loess is considered older than Wisconsin. Augering in another broad, nearly flat interfluve in Minnehaha County yielded similar results. A hole in the NW¼ sec. 20, T. 104 N., R. 47 W. revealed 12 inches of medium sand, probably eolian, and 24 inches of till beneath the sand. The till is slightly oxidized but contains original carbonate even at its upper surface. This implies that the till is Wisconsin.

The topography of the reclassified area in South Dakota is identical with the topography of the area in Iowa that is continuous with it. It is constructional topography, with faint relief, superposed on an older dissected surface. It differs from the topography of the Kansan drift, which is wholly erosional.

Three lines of evidence supporting the Iowan age of the drift in South Dakota can be added:

The till, 30 feet thick in the center of sec. 25, T. 103 N., R. 48 W., Minnehaha County (described in section for locality 21, p. 52), overlies and incorporates in its basal part silt believed to be Loveland loess. If the underlying silt is Loveland, the till must be Wisconsin. The till is calcareous throughout.

The till immediately beneath the surficial loess contains abundant boulders, a fact, as stated earlier, believed to be true only of Wisconsin drift in this region.

In the critical area, particularly in Minnehaha and Moody Counties, the till beneath the upland surface is dotted with ice-contact knolls of sand and gravel. Such features are common in the Iowan drift in Iowa, but are virtually unknown in the Kansan drift. Leverett (1932, p. 24) stated "no knolls of constructional type have been noted on the Kansan drift in Iowa or any of the bordering States," but "knolls [are] preserved within the Iowan drift area." It is curious that in the same publication he (Leverett, 1932, figs. 6, 12) mapped the knoll-bearing drift sheet in South Dakota as Kansan.

In summary, the Iowan drift sheet is traced directly into South Dakota from Iowa and Minnesota, and the basis for dating the drift as Iowan in those States is confirmed by evidence within South Dakota itself.

TILL

As stated on pages 59–60, it does not seem possible to distinguish among the Wisconsin tills on a basis of their physical characteristics. For a description of the Iowan till the reader is therefore referred to the description of Wisconsin till characteristics set forth on that page, and to the measured sections at localities 2 (p. 38), 4 and 8 (p. 34), 17*A* and 17*C* (p. 35), 17*D* (p. 36), 21 (p. 52), 22 and 28 (p. 37), and 29 (p. 53).

The Iowan till is thought to be thinner than the Tazewell till, and it is certainly thinner than the Cary and Mankato tills. In most exposures Iowan till ranges from 3 to 8 feet in thickness. In one exposure (locality 8, p. 34), however, it is less than 1 foot thick, in another (locality 21, p. 52) it is 30 feet, and in still another (locality 1, p. 92) it is 80 feet thick. At one locality (17*A*, p. 35; and 17*D*, p. 36) 14.5 feet of Iowan till was exposed, but a thickness of 25 feet was inferred.

These values compare well with the data from Iowa. There the Iowan till is said to average 1 to 8 feet in thickness, with a maximum observed thickness of 45 feet (Kay and Graham, 1943, p. 155). However, unpublished observations by R. V. Ruhe in northwestern Iowa led him to believe that in that region the Iowan till is thicker than the average mentioned by Kay and Graham, an average derived mainly from observations in eastern Iowa.

An average-thickness value is not very significant because thickness is variable even within short distances. Furthermore, where the base is not exposed it is difficult to determine the true thickness of a nonstratified sediment such as till. For example, at one locality (SE¼ sec. 8, T. 95 N., R. 50 W., Union County) till was exposed in 1947 for 200 feet along a road having a gradient of about 2 degrees. The base of the till was concealed, although the top was visible. Measured vertically, from the lowest point on the road to the highest, the thickness was 28 feet. However, the maximum thickness exposed in any single part of the section was 7 feet. Clearly the till was more than 7 feet thick; it is doubtful, however, that it even approached 28 feet. Its true thickness remains unknown.

The Iowan till is so thin that although commonly calcareous, it is oxidized from top to base in nearly every exposure seen. One exception is the locality where a maximum thickness of 30 feet was measured (locality 21, p. 52). At that place nonoxidized areas of till were exposed in section in the basal 5 feet. Other exceptions are localities 1 and 2, page 92.

As seen in its exposures and as inferred from its topographic expression, the Iowan till mantles a preexisting surface that varies from nearly flat to sharply dissected. The till is so thin that it may be doubted whether it succeeds in masking that surface in any area.

In the breaks of the Missouri River the drift, at least in part Iowan, consists principally of boulders and smaller stones scattered over the dissected surface. The till, thin at best even in the flatter country, did not remain on the steeper slopes because the fine-grained constituents were washed away, not only after deglaciation but also probably during deposition from the basal part of the glacier.

BOULDERS

The drift west of the Missouri River consists mainly of scattered boulders. In this respect it differs markedly from most of the drift east of the breaks; so it is best described separately.

Cobbles, pebbles, and smaller fragments, as well as boulders, are visible in some road cuts. In this grass-covered, dissected cattle-range country, however, they are not easily seen on the surface. Boulders, on the other hand, are observable without difficulty at distances of as much as half a mile, and as many as could be seen on road traverses, supplemented in places by foot traverses, were mapped.

The boulders constitute the same assemblage of igneous and metamorphic rock types, plus Paleozoic limestones and dolomites, that are found in and on the drift east of the river. They have the same range of shapes, including glacially cut facets, and some are striated. Some have been abraded by the wind since they were glaciated.

Vertically the boulders occur in all positions—on the tops of the highest interfluves, on steep slopes, and on the floors of the deepest valleys—through a range of several hundred feet. Areally they are related to the existing topography; they are found farther west in the valleys than on the interfluves. All those seen are on the surface. Inspection of hundreds of cuts in the colluvium, as much as 12 feet thick, on the Pierre shale slopes and in the alluvium of the valley floors revealed no boulders in addition to those visible on the surface. Near the river, however, they do occur on interfluves beneath the surficial loess. Apparently, therefore, they postdate the topography and the colluvium and antedate the loess.

The boulders are very unevenly distributed. In a few areas they are so closely spaced as to form a continuous litter; in others their numbers average several score per square mile. Over the greater part of the region, however, they number no more than one per mile, and, in the outermost, western part of the region, one can travel several miles between boulders. These erratics were recognized by Todd (1899, p. 42–43) early in his pioneer field study, and he traced their general western limit with fair accuracy.

No doubt the boulders are in part a residual concentrate of the coarsest elements in former till, left behind through the removal of the fines by sheet erosion and perhaps by deflation. This origin can be attributed to some of the boulders close to the river and in the areas of steepest slopes. A few patches of till are known. One patch, in the NW¼ sec. 3, T. 15 N., R. 31 E., Dewey County, is in the Missouri River trench itself. Exposures reported by J. C. Mickelson of the South Dakota Geological Survey during geologic quadrangle mapping in 1949 show 4 feet of till overlain by 3 feet of loess. Other patches of till, as much as 2 feet thick, are reported on interfluves in southeastern Lyman County.[18] However, the scarcity of such material makes it unlikely that many boulders were isolated in this way. Furthermore broad, nearly flat-topped interfluves have boulders lying directly on the bedrock, but do not have till.

Most of the boulders are believed to represent a till equivalent: to have been deposited by glacier ice essentially in their present positions, with no inclosing matrix and with little fine-grained drift of any kind.

It follows that the outer limit of the boulders represents the minimum outer limit of the glacier that deposited them. In order to compare this limit with the topography a line was drawn connecting the outermost boulders seen. This zigzag line was compared with the topographic map (pl. 2) and was found to agree with it in that the boulders extend less far west on interfluves than in valleys. By the use of the topographic map the zigzag line was smoothed out, with the result plotted in plate 1. The smoothed curve shows systematic lobation such as would be expected of an ice sheet invading dissected terrain having considerable relief. Whether

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[18] Warren, C. R., 1950, Preliminary report on the geology of part of the Chamberlain, S. Dak., quadrangle: U. S. Geol. Survey, manuscript on open file.

the lobation of the actual glacier margin was somewhat greater or somewhat less than the lobation indicated by the boulders perhaps will never be known. All that can be said at present is that the glacier margin is not likely to have been radically different from the line mapped.

Before the foregoing interpretation of the deposition of the boulders was reached, two alternative interpretations were considered and rejected. The first is that most of the boulders represent the residual concentrate from the erosion of a mantle of pre-Wisconsin till. This is made doubtful by the chemical freshness of the boulders, their relation to the topography, and the inferred extent of pre-Wisconsin glaciation.

If the boulders were pre-Wisconsin they should show at least some chemical decomposition. However, they are as fresh and firm as the boulders in and on the Wisconsin drift east of the river. Indeed, throughout the entire glaciated region the boulders are generally fresh, with the exception of some of the highly micaceous (commonly biotitic) granitic and gneissic rock types. These show little decomposition, for their plagioclase feldspars, hornblendes, and biotites are virtually unaltered, although they do show disaggregation. Apparently the presence of micas facilitates ready disaggregation.

The boulders postdate the present deep dissection, which, in turn, did not come into existence until after the Illinoian ice sheet had reached its maximum extent (fig. 12; p. 55).

No pre-Wisconsin glacier could have reached west of the site of the Missouri River trench, because the glacier-marginal stream channel or channels that would have resulted do not exist west of the trench (p. 144).

Therefore the boulders west of the Missouri River are Wisconsin rather than pre-Wisconsin.

The second alternative interprets the boulders as having been rafted into their present positions by icebergs floating on a vast lake or series of lakes ponded between a Wisconsin ice sheet on the east and the sloping surface of the plateau on the west. A similar explanation has been advanced in other regions (compare Leverett, 1929b, p. 33–47), apparently in the belief that an extensive area cannot have been glaciated without having received deposits of till. Although the writer does not share that belief, there is some evidence of ponding of the valleys that enter the Missouri River from the west, and it seems possible that some of the boulders now at relatively low altitudes may have been rafted by ice on such ponds. A granite boulder on a highway shoulder near the Cheyenne River bridge in sec. 31, T. 7 N., R. 18 E., Ziebach County, was seen by C. R. Warren, of the U. S. Geological Survey, in 1949. If not transported by human agency this boulder may have reached its extreme western position by rafting. However, since the total absence of strand lines and spillway outlets on the interfluves themselves precludes the possibility of a lake that submerged the uplands as well as the valleys, the numerous upland boulders remain unexplained by the lake hypothesis.

The boulders, therefore, are considered to have been mostly or wholly deposited by glacier ice. And whereas it has not been established firmly that they are not of somewhat different dates in different places, it is probable that all are of Iowan age.

A reasonable explanation, although perhaps not the sole cause, of the contrast between the boulders west of the Missouri River breaks and the till east of the breaks is the relation of topography to the direction of flow of the glacier that made the deposits. The Missouri River trench, with its accompanying breaks, may have acted as a complex baffle or cleat. As the glacier entered this zone the basal ice, containing the bulk of the drift, was trapped in the maze of topographic pockets. Basal drift easily lodged among the pockets from the slowly flowing or stagnant lower ice, while the upper part of the ice mass, unimpeded by the baffle, flowed easily westward. The upper part of an ice sheet, however, contains very little drift, and that little is likely to be of distant origin. Relatively little drift of distant origin is exactly what is found west of the Missouri River. A broadly analogous case has been argued for the origin of the scattered boulders over the Gaspe highland in southeastern Quebec (Flint, 1947, p. 82–83).

This reconstruction is supported by the peculiar distribution of pre-Cary drift east of the Missouri. No continuous drift cover exists, of course, anywhere in the breaks. East of the breaks, however, the continuity of the drift cover depends on the topography northeast of it. Where the land immediately northeast is smooth and of moderate altitude, as for example in southern Potter County, Sully County, Hughes County, and southern Brule County, the pre-Cary drift consists of a fairly continuous sheet of till. In contrast, in the lee of high areas of notable dissection, as in western Campbell, southwestern Walworth, southern Hyde, and northwestern Buffalo Counties, the drift is thin and patchy and in some areas consists of little more than scattered boulders. The extreme case is in Buffalo County, which lies in the lee of the high, dissected Ree Hills, as well as in the lee of four valleys (Elm Creek, Little Elm Creek, an unnamed creek, and Campbell Creek), all trending southeast at right angles to the direction of glacier flow. An area nearly equal to three townships is entirely free of drift; yet its altitude is no higher than that of adjacent areas possessing a drift cover.

The combination of baffles upstream from this driftless area apparently succeeded in removing all the rock fragments from the overriding ice.

Three other driftless areas, of small size, occur in southwestern Charles Mix County, but they do not lie in the lee of a highland. Each is in itself an isolated minor highland. None of these areas was overrun by ice in Cary time, and the highest, at least, seems to have been ice free even in Iowan time.

The Iowan drift in northeastern Nebraska contrasts with the drift west of the Missouri trench in that it consists of clay-rich till ordinarily several feet thick. At first thought the contrast seems anomalous, in that the Iowan ice had to flow across the Missouri trench in order to reach northeastern Nebraska. However, the trench in the latter district is much wider and shallower than it is farther upstream, and is not fringed on its northeastern side by a belt of deeply dissected country. These differences probably explain the ability of the Iowan glacier to transport into Nebraska drift thick enough to be deposited as normal till.

Certain concentrations of boulders, occurring mainly in Corson County, may be of special significance. The most remarkable concentration occupies an area of about 5 square miles, elongate northward, extending from sec. 15, T. 22 N., R. 27 E., to the North Dakota State line. Its western limit is sharply marked; its eastern limit is gradational. Road cuts within the area expose glacially shaped foreign boulders, cobbles, and pebbles in a matrix of sand derived from the Fox Hills standstone, the local bedrock. The orientation of the concentrate and the distribution of boulders within it strongly suggest that it is the equivalent of an end moraine, built at the outer margin of the ice sheet during an episode of balanced regimen.

Three other concentrates, similar though less strikingly developed, occur 2 miles west of the one just described, in the southwestern part of T. 18 N., R. 26 E., and in the northeastern part of T. 18 N., R. 25 E. A similar concentration, only 1 mile long but oriented parallel with the inferred border of the drift, was noted by Crandell[19] in the S½ sec. 10, T. 4 N., R. 29 E., Stanley County.

In Corson County, also, there are at least two bodies of thin lacustrine silt that fill shallow upland reentrants made by stream dissection. The lakes were temporary, having existed only while the glacier margin acted as a dam. One, more than 2 square miles in area, centers in the SW¼ sec. 14, T. 22 N., R. 27 E. The other, much smaller, is in secs. 6 and 7, T. 22 N., R. 28 E. The presence of these nondissected bodies of fine sediments constitutes further evidence that most of the boulders in this region are not a residue left by the erosion of till.

ICE-CONTACT STRATIFIED DEPOSITS

Throughout a large area east of the Big Sioux River in Minnehaha and Moody Counties the Iowan stage is marked by ice-contact drift in the form of knolls of sand and gravel in random positions on upland interfluves. Poorly rounded pebbles and cobbles, irregular stratification, and local structures indicating disturbance characterize these deposits. Ice-contact origin must be inferred from these internal characteristics alone, inasmuch as the knolls have gentle slopes (rarely exceeding 8 degrees), are mantled with loess, and do not now show ice-contact topographic forms. Their positions, however, preclude their being erosion remnants. They are best explained as kames, as was recognized by Rothrock (Rothrock and Newcomb, 1926, p. 16–21) many years ago.

The Iowan drift includes, in addition to the abundant upland knolls, a great mass of sand with subordinate pebble gravel, banked against the south side of the trench of the Big Sioux River downstream from Sioux Falls. Most of it lies within secs. 1, 11, and 12, T. 101 N., R. 49 W., Minnehaha County. Single exposures in gravel pits show this body to be at least 60 feet thick; its maximum thickness is probably much greater. Its internal characteristics resemble those in the kames and distinguish it from outwash, which is exposed in the immediate vicinity. This mass is believed to be a kame terrace, accumulated through deposits by a melt-water stream that flowed northeastward along the margin of a valley that contained a large residual mass or tongue of glacier ice.

These ice-contact features, coupled with the fact that the Iowan drift lacks end moraines, set off the Iowan drift from the three younger Wisconsin drifts and suggest that a distinctive glacial regimen prevailed in this region during the Iowan deglaciation. Similar knolls and a similar absence of end moraines characterize the Iowan drift in Iowa (Leverett, 1932, p. 28). The building of end moraines requires actively flowing ice, and as the accumulation of kames on the upland and kame terraces in valleys requires that the glacier be flowing very slowly or be entirely stagnant, it seems likely that the marginal part of the Iowan glacier ceased to flow actively when it reached its extreme position. It is best pictured as thinning down, losing the well-defined terminus it possessed during its expansion, and, lacking the energy necessary to build end moraines, quickly wasting away. This interpretation was foreshadowed by Leverett (1932, p. 28) as a result of observations in Iowa.

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[19] Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, 298 p.

OUTWASH

In South Dakota, as in many other parts of the country, outwash from the Iowan ice constituted valley trains. These have been trenched, so that they now remain only as discontinuous terraces well above present stream profiles. In a reconnaissance study outwash is mapped through recognition of the terraces as topographic forms, supported by evidence from exposures of outwash sediments in terraces. Although Iowan outwash bodies were identified during the present reconnaissance, they were not mapped in detail because the terrace forms have lost their distinctness through mass wasting and, more important, through burial beneath a blanket of loess. Systematic borings would be required for the accurate mapping of Iowan outwash; undoubtedly more bodies exist than have been recognized. No doubt still other outwash bodies existed in Iowan time, but as the same streamways were used by proglacial streams during one or more post-Iowan glaciations, the later streams, planing laterally, cut away many remnants of Iowan outwash spared by late-Iowan stream incision.

A terrace, possibly cut by Iowan melt water, is represented by a remnant on the west side of Skunk Creek, Minnehaha County, in secs. 11 and 14, T. 102 N., R. 51 W. It stands 60 feet above the creek and 30 feet above a terrace of Cary outwash. Iowan outwash may also underlie the flat along West Pipestone Creek in secs. 15, 22, 27, and 35, T. 104 N., R. 48 W., Minnehaha County. Sand and gravel, underlying thick Iowan and post-Iowan loess on the slope east of Brule Creek, in sec. 5, T. 93 N., R. 50 W., Union County, is also probably Iowan outwash. In the SW¼ sec. 18, T.106 N., R. 48 W., in the southeast wall of the Big Sioux River trench, are parallel-bedded fine-grained sediments, apparently lacustrine, overlain by 4 feet of Iowan till. Similar sediments are exposed nearby, and in one section the till contains small coherent blocks of the stratified material. Probably the lacustrine sediments record ponding in the Big Sioux River valley by Iowan ice or drift, followed by glacial advance and overriding.

LOESS

The close relationship of the Iowan and post-Iowan loess to the Iowan till underlying it is shown by the fact that no part of the till beneath the loess has been found leached of its carbonate content. It is inferred, therefore, that this loess began to accumulate as soon as the till was exposed by the melting ice sheet.

Iowan loess—that is, loess lying between Iowan till and Tazewell till—has not been found exposed in South Dakota nor has it been recognized in the few borings put down through the Tazewell till. It is, however, exposed in northwestern Iowa.[20] There, too, the thickness of the superficial loess abruptly diminishes at the margin of the Tazewell drift sheet. This implies that there is a split in the loess, some of it lying underneath the Tazewell drift as Iowan loess.[21]

Attempts to differentiate Iowan loess from post-Iowan loess in South Dakota, through discontinuities in grain size and through zones of leaching, have proved fruitless thus far, though it is likely that detailed study could succeed where reconnaissance has failed.

Iowan and post-Iowan loess (not differentiated) covers the entire area of outcrop of Iowan drift. If well-log data are accepted, this loess is at least 90 feet thick in parts of Union County, in the extreme south, and thins northward very irregularly to only 3 or 4 feet in Brookings County. In some exposures this loess grades into fine sand which immediately overlies the Iowan till. In the south the chief sources of sediment are believed to have been outwash in the Missouri valley and possibly in the valley of an ancestral Vermillion River. In the north the chief source was probably outwash in the Big Sioux River valley. Other, local sources, however, are believed to have contributed to this loess sheet.

In the central part of the State Iowan and post-Iowan loess mantles terraces in the Missouri River trench and covers the eastern brink of the trench in areas of little dissection to a thickness of 10 to 15 feet and exceptionally 30 feet. West of the trench it is patchy and thins to the vanishing point within a distance of 5 to 30 miles. East of the trench it thins to 3 or 4 feet where it passes beneath the Cary drift. In and close to the trench this loess includes conspicuous amounts of fine sand; away from the trench in both directions the average grain size diminishes rapidly.

According to Todd (1899, p. 85), loess at Sioux Falls, dated by the writer as probably Iowan and post-Iowan, yielded tusks, teeth and bones of a mammoth, and in or immediately beneath the loess were found mastodon bones and the skull of a musk ox.

STONE CONCENTRATE

In many exposures the surface of the Iowan drift beneath the overlying loess is marked by a concentrate of stones, mostly of pebble size. The stones are similar in size range and lithology to those within the till, and differ from them only in that a considerable proportion of them have been secondarily cut by windborne sand and silt.

Wind cutting is evidenced variously by polishing, pitting, fluting, differential etching according to mineral

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[20] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation, p. 59–73.

[21] Idem, p. 57.

hardness, and faceting with one or more margins of a facet forming sharp "keels." Most of the stones were wind cut on one side only, but some are modified on two or even three sides. So many of the stones appear to be displaced from the exact positions they occupied at the time of cutting that attempts to judge wind direction from their orientation have not met with success.

The fact of surface concentration of the stones implies removal of the fine-grained matrix of the till that once inclosed them. Comparison of the concentrate with the frequency of stones in the till beneath indicates that in most places reworking of from less than 1 foot to about 2 feet of till would have produced the concentrate.

The fact of wind cutting, coupled with the occurrence of the concentrate on flat surfaces as well as on gentle slopes, suggests that the till was reworked by the wind. Whether the concentrate is in fact a deflation armor, or whether it was concentrated in considerable part by sheet runoff, is not apparent. That concentration occurred rapidly is established by the fact that the till was not leached appreciably before the mantle of loess now covering the concentrate began to accumulate. No change in the concentrate with latitude was observed. Probably the stormy conditions at and immediately beyond the margin of the ice sheet favored exceptional rainfall and high winds. These may have been supplemented by strong katabatic air currents descending the marginal slope of the glacier. The combination of these forces may have concentrated the stones in the zone peripheral to the glacier. As the ice margin retreated, winds gradually diminished in strength, so that areas of former deflation may have become areas of accumulation of loess, which buried the stone concentrate.

The stone concentrate is less distinct and evidence of wind cutting of stones is less conspicuous in the central part of the State than in the eastern part. The difference implies that during the Iowan deglaciation wind abrasion and deflation of the surface drift were more effective in the east than they were farther west. The cause lies in meteorologic differences that have not been explained.

A similar concentrate is widely present on the Iowan drift in Iowa.[22] In South Dakota a surface concentrate is not confined to the Iowan drift. A similar one is conspicuous on the Tazewell drift, and in certain areas in the western part of the glaciated region concentrates and scattered ventifacts are seen on still younger drift sheets.

TOPOGRAPHIC EXPRESSION

As all the Iowan drift, differentiated from the Tazewell drift, lies in the vicinity of the Big Sioux River, much of it is affected by stream dissection. A part of the dissection postdates the drift but a great deal of it—just what proportion will probably never be known—existed before the Iowan drift was deposited. This is inferred from the land forms common in the district. They indicate a general pattern of dissection with relief of more than 200 feet, but within this pattern is a local relief of swells and swales that can be interpreted as a constructional surface superposed on the earlier, erosional relief. The topography is complicated further by the ubiquitous Iowan and post-Iowan loess. Where thick, the loess appears to have augmented the relief of the drift on nearly flat surfaces by accumulating unevenly; where thin, it has diminished relief by filling depressions more than it has heightened the hills.

Where dissection is least apparent, as in the southeastern part of Moody County, the Iowan drift, with its loess mantle, has a local relief rarely exceeding 20 feet, with slopes of less than 3 degrees. The topography consists of low swells and broad, gentle depressions, merging in some areas into extensive flat surfaces. The depressions are not closed; on the contrary they form an integrated system draining into the Big Sioux River and neighboring streams. Evidently whatever closed depressions existed have been destroyed by drainage or are masked beneath loess. The prevailing thinness of the Iowan drift, however, makes it seem unlikely that basins were as common in it initially as they now are in the Cary and Mankato drift sheets. The Iowan till sheet is more accurately viewed as a thin though somewhat variable veneer over a previously dissected surface. In most places it should be classed as ground moraine; in others, however, it is no more than a thin sheet of till that reflects the relief of an underlying terrain which it has modified little if at all.

A minor though locally conspicuous element in the topography of the Iowan drift consists of the gravel knolls on upland interfluves.

The Iowan drift in South Dakota lacks end moraines. As noted earlier, this fact differentiates it from the younger drifts, and implies deglaciation uninterrupted by change in the glacial regimen.

BREAK BETWEEN IOWAN AND TAZEWELL SUBSTAGES

The Iowan-Tazewell break represents only a moderate shrinkage of the glacier in eastern South Dakota. The evidence is threefold.

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[22] Ruhe, op. cit., p. 29–30; a summary of Iowa literature is given in Wilson, 1945.

The Iowan loess beneath the Tazewell drift in western Iowa, is, by inference, only 1 to 2 feet thick;[23] this is much thinner than the Tazewell and post-Tazewell loess. The calculation is based on so many borings that the thinness of the Iowan loess can hardly be the result of erosion by the Tazewell glacier; its uniform thinness must be initial. Furthermore, where exposed, the Iowan loess is calcareous beneath the Tazewell till, indicating a lapse of time between loess and till insufficient for leaching of the loess.

No weathering profile or soil zone in the stratigraphic position of the Iowan-Tazewell break has been noted either in Iowa[23a] or in South Dakota. Indeed there appears to be no discontinuity in the Iowan and Tazewell loess sheets; outside the area of Tazewell drift the sheets are indistinguishable; hence loess deposition seems to have been continuous through the two subages. This implies only a moderate shrinkage of the glacier between the two expansions, with fine-grained outwash continuing to be deposited in this region, as a source of loess, throughout the whole time.

The topographic expressions of the Iowan and Tazewell drift sheets are similar, although they differ markedly from those of the Cary and Mankato drift sheets (fig. 24). These topographic comparisons are clearly evident in South Dakota. In Iowa analogous comparisons, shown quantitatively (Ruhe, 1950)[24] are convincing. As this similarity is attributed mainly to similarity in glacier regimens, it is inferred that during the Iowan-Tazewell break changes in the regimen of the ice sheet were slight in comparison with the changes that occurred during the Tazewell-Cary interval.

It is believed, therefore, that the ice-sheet margin withdrew only moderately between Iowan time and Tazewell time, and that loess was deposited without interruption during the interval.

This conclusion supports the view that the Peorian interval named by Leverett in 1898 is a very minor affair in the Wisconsin sequence as a whole. This was recognized by Leverett himself, who, referring to similarities between the Iowan and Tazewell drifts, wrote in 1942: "There is thus a possibility, if not a probability, that the Tazewell substage includes the Iowan" (Leverett, 1942, p. 1002).

It is of further interest to note that soil scientists have found thus far only very minor differences between the soils developed on the Tazewell drift and those developed on the Iowan drift, although they have found some soil differences between these drifts and the younger drifts (p. 20).

Furthermore, Leonard (1951, p. 327) has demonstrated, in the Wisconsin loess sequence in Kansas, a transition from an Iowan zone to a Tazewell zone without unconformity or even change in rate of accumulation. This contrasts sharply with the hiatus and weathering zone that separate the Tazewell zone from the overlying Cary and (or) Mankato zone. The Kansas relations therefore support the inference that shrinkage of the ice sheet following the Iowan maximum was only moderate.

TAZEWELL SUBSTAGE

DIFFERENTIATION FROM THE IOWAN SUBSTAGE

NORTHEASTERN SOUTH DAKOTA

The drift sheet here classified as Tazewell was mapped as Iowan in rapid reconnaissance by Leverett (1932, fig. 5), who recognized this drift as a distinct body, but dated it incorrectly. Reclassification is made necessary by the reclassification of a part of the Kansan drift of Leverett, as Iowan, as already set forth.

The Tazewell drift in South Dakota is so identified mainly on a basis of its position in the Wisconsin stratigraphic sequence. It is correlated by continuous tracing outside the State only with the drift sheet mapped by Ruhe[25] as Tazewell in southwestern Minnesota and northwestern Iowa, and is not therefore proved to be equivalent to the Tazewell drift of the type area in Illinois.

Discrimination between Iowan drift and Tazewell drift in western Iowa is difficult at best, because both drifts are thin, because both are buried beneath a thick blanket of loess, and because, as stated in the preceding section, the related glaciations are believed to have been separated by only a brief interval, marked by the deposition of 1 to 2 feet of loess.

The evidence on which the Tazewell drift has been distinguished from the Iowan drift in western Iowa is fourfold: Presence of sections exposing two Wisconsin tills with intervening loess, outside the limit of the Cary drift, faint but persistent differences in topography and drainage, presence of end moraines, abrupt thinning of the surficial loess along the line of topographic change.

The presence of Tazewell drift in northeastern South Dakota is believed to be established, because the border of that drift has relief and greater irregularity of individual swells and swales than are found in the Iowan drift. The border itself is characterized by a discontinuous end moraine, a feature not known to occur in the Iowan drift in central United States. The moraine occurs through a sector 10 miles long in Hamlin and Deuel Counties. In Brookings County the outer limit of the

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[23] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation. P. 57.

[23a] Idem, p. 115.

[24] Idem, p. 40.

[25] Idem.

Tazewell drift is marked by a broad swell whose outer slope is much steeper than the general slope of the Iowan drift surface beyond it. The swell is diversified by faint knolls. Probably it is a loess-mantled end moraine, but, as this interpretation is not certain, the feature is not so mapped. A road traverse of the entire area of Tazewell outcrop was made in an attempt to obtain stratigraphic confirmation of the validity of the topographic differences, but without success. In consultation with the writer, Mr. F. C. Westin of the South Dakota State College made three deep auger borings on broad, nearly flat upland interfluves in the area of Tazewell drift in Brookings County, in the hope of discovering Iowan loess and Iowan till beneath the uppermost till. The results were as follows:

Location	*Feet*
0.1 mile east of the north quarter corner sec. 13, T. 112 N., R. 49 W.:	
Loess	2.5
Till, with silt-rich matrix, dusky-yellow when dry, calcareous	19.0
Till, with clay-rich matrix, olive-gray when dry, calcareous, at least	3.0
North quarter corner sec. 8, T. 112 N., R. 48 W.:	
Loess	3.0
Till, with silt-rich matrix, dusky-yellow when dry, calcareous	19.0
Till, with clay-rich matrix, olive-gray when dry, calcareous, at least	11.0
S½SE¼ sec. 21, T. 112 N., R. 48 W.:	
Loess	3.0
Till, with silt-rich matrix, dusky-yellow when dry, calcareous, at least	17.0

They afford no stratigraphic proof of the separate identity of the Tazewell drift. They do, however, suggest the possible presence of a normal, clay-rich till, overlain by a younger till in which loesslike silt has been incorporated through overriding and plowing up of an intervening loess sheet.

On the Coteau des Prairies the Tazewell drift has a belt of outcrop 5 to 10 miles wide between the Iowan drift belt and the Cary drift belt, or, in the extreme north, between two lobes of the Cary drift. West of the Big Sioux River valley the Tazewell drift has not been identified with certainty. At one place this section is exposed in a road cut and ditch:

Section 0.2 mile north of the southeast corner of sec. 12, T. 105 N., R. 50 W., Moody County

	Feet
5. Loess, sandy	1.5
4. Till, sandy, includes a 15-inch quartzite boulder, the upper part of which is wind etched	1.0
3. Sand, with pebble gravel, crossbedded	5.0
2. Loess, sandy, oxidized at top; mottled near base; calcareous	3.2
1. Till, moderate olive brown when moist; slightly fissile; calcareous	1.5
Base concealed.	

In the section, units 1 and 2 appear to constitute one glaciation, whereas 3, 4, and 5 constitute another glaciation. These two glaciations may be, respectively, Iowan and Tazewell, Iowan and Cary, or Tazewell and Cary. The presence of the wind-etched boulder in the upper till is suggestive of Iowan or Tazewell rather than Cary drift. However, as wind-etched stones are not diagnostic of pre-Cary drifts, and as Cary end moraine is present less than 2 miles west of this point, the possibility that the upper till is Cary can not be excluded.

Hence all that can be said is that Tazewell drift may be present at the locality mentioned, but that otherwise no evidence has been found that, west of the Big Sioux River, the Tazewell drift border does not lie beneath the Cary drift in Hamlin County. That it should do so on the eastern flank of the James glacial lobe is not surprising, for on the western flank of the Des Moines lobe in western Iowa, the Tazewell drift border is overlapped by the more narrowly lobate Cary drift sheet. A detailed survey of southern Yankton County failed to yield evidence of more than one pre-Cary Wisconsin drift.[26] Hence it can be inferred, at least for the present, that in southern South Dakota Tazewell ice reached less far south than did Cary ice.

CENTRAL SOUTH DAKOTA

Satisfactory discrimination of the Tazewell drift in central South Dakota on the western side of the James lobe is even more difficult because there the drift sheets are still thinner and the pre-Wisconsin surface is far more dissected than in the Coteau des Prairies.

It is believed that in central South Dakota the Tazewell drift is the surface drift in a belt lying between the Iowan drift and the Cary drift. Supporting this belief are the presence, in seven exposures, of two bodies of drift, both dating from pre-Cary Wisconsin time, and separated locally by thin loess; the presence, in the Pierre district, of valley fills logically assignable to the Iowan and Tazewell substages; the presence of end moraines east of the Missouri River and the absence of such features west of the river.

Admittedly these facts are not compelling. It could be argued that both belts of drift are Iowan, that end moraines characterize the Iowan drift here although they are absent farther east, and that the two Wisconsin tills exposed in several sections outside the Cary drift border record mere oscillations of the Iowan glacier margin. It must be conceded that the facts at hand do not disprove this point of view.

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[26] Simpson, H. E., 1952, Geology of an area about Yankton, S. Dak.: Yale Univ., unpublished Ph. D. dissertation.

Nevertheless the facts are consistent both areally and stratigraphically with the interpretation that the drift sheets present, indubitably two in number, are the same sheets identified as Iowan and Tazewell on the Coteau des Prairies. The latter constitute little more than two advances of the margin of the ice sheet, separated by the time required for the continuous deposition of 1 to 2 feet of loess; the glacial regimen during the first (Iowan) maximum and the deglaciation following it was such as to inhibit the building of end moraines, whereas such moraines were built during the second (Tazewell) maximum and during the subsequent glacial retreat. Viewed in this light the two interpretations differ very little. Hence, in the absence of proof, the similarity of the sequences in the central and eastern parts of the State is believed to lend probability to the interpretation that in central South Dakota the belt of drift lying between the Iowan drift and the Cary drift is Tazewell. Indeed, it seems improbable that the inferred differences in glacial regimen on the western flank of the Des Moines lobe would not have left evidence also on the western flank of the James lobe.

Supporting the concept that Tazewell drift is present at the surface in the western part of the James lobe are three groups of data: sections exposing two drifts, alluvial fills in the Missouri River trench, and the distribution of end moraines.

SECTIONS EXPOSING TWO DRIFTS

The seven exposed sections described below record two Wisconsin drift sheets occurring outside the limit of the Cary drift. The thinness of these drifts is noteworthy, but inasmuch as the drift on the Coteau du Missouri generally is remarkably thin, this fact is not believed to weigh against the interpretation of the two pre-Cary drifts as two substages.

Cut made by U. S. Army Engineers in northeast bluff of Missouri River trench near northeast abutment of Oahe dam, NW¼ sec. 6, T. 111 N., R. 79 W., Hughes County, S. Dak.

[Section, exposed in June 1950. Measured by D. R. Crandell]

	Feet
6. Loess, dusky-yellow when dry. (Cary and post-Cary.)	3.0
5. Loess, humified, olive-gray to medium dark-gray when dry. (Tazewell?)	1.3
4. Loess, dusky-yellow when dry, with light olive-gray mottling (Tazewell?)	5.0
3. Till, clay-rich, moderate yellowish-brown to moderate-brown when dry; contains boulders as much as 6 feet in diameter, of nonweathered igneous and metamorphic rocks. (Tazewell?)	35.0
2. Sand, very fine to medium; included silt and clay; locally contains coarse and very coarse sand; locally laminated; moderate yellowish-brown when moist. (Iowan)	12.0
1. Glacial drift, predominantly rubbly till with inclusions of stratified drift; size fraction larger than 10 inches consists of boulders, commonly spheroidal, of Pierre shale, unoxidized clayey till, and fresh igneous, metamorphic, and well-consolidated sedimentary rocks as much as 3 feet in diameter. Size-fraction smaller than 10 inches, mainly pebbles, contains relatively little clay. Inclusions of stratified drift are sand and pebble gravel. A persistent layer of sand up to about 6 feet thick, about 50 feet below top of the unit pinches and swells and appears to have been deformed after deposition. (Iowan drift, chiefly till.)	80.0
Pierre shale (seen by R. F. Flint in 1946 but covered with colluvium in 1949 and 1950).	
	136.3

Gully southeast of Pierre Municipal Airport, SW¼ sec. 35, T. 111 N., R. 79 W., Hughes County, S. Dak.

[Section measured by D. R. Crandell]

	Feet
6. Loess, moderate yellowish-brown when moist; lower 4 feet mottled	8.0
5. Sand, medium, and silt	>2.0
4. Till, pebbly, clay-rich, oxidized, calcareous; joints in lowest 4 feet filled with gypsum and stained grayish brown when moist; contains unweathered boulders of igneous rock as much as 4 feet in diameter, chips and flakes of Pierre shale, and iron-oxide concretions from Pierre shale; moderate-brown to dark yellowish-orange when dry. (Tazewell?)	23.0
3. Sand, coarse to very fine, alternating cross-bedded and horizontally stratified in lowest 6 feet; horizontally bedded in uppermost 20 feet; contains lenticular bodies of till and upward-projecting parts of till of unit 2. (Iowan?)	26.0
2. Till, clay-rich, calcareous, unoxidized except along joints. Joints are stained dusky red. Till contains unweathered boulders of igneous rocks up to 3 feet diameter. Color of unoxidized till medium light-gray when dry; of oxidized till, moderate yellowish-brown when dry. (Iowan?)	15.0
1. Pierre shale.	
	74.0

Crandell[27] stated that the lithology of the lower tills exposed in measured sections 1 and 2 is not duplicated in exposures of the surficial drift in the Pierre area. This fact is consistent with the concept that the correlation of the lower tills is not the same as that of the upper tills.

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[27] Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, p. 156–157.

Road cut 0.25 mile south of the northeast corner of sec. 36, T. 119 N., R. 77 W., Potter County, S. Dak.

[Exposed in July 1949]

	Feet
4. Loess, dark yellowish-brown when dry, dusky yellowish-brown when moist, somewhat sandy. (Tazewell and post Tazewell?)	1.0
3. Till, moderately stony, clay-rich and light olive-gray when dry in upper part, grading down into silt-rich and light olive-brown when dry in basal part. (Tazewell?)	1.4
2. Loess, grayish-yellow when dry, dusky-yellow when moist, with brown mottling, extremely compact; strong fissility parallel with upper surface. (Iowan?)	1.0
1. Till, light olive-gray when dry, moderate olive-brown when moist, with clay-rich matrix inclosing abundant small pebbles and masses of olive-gray Pierre shale. Base concealed in floor of ditch. (Iowan?)	2.0
	5.4

The section measured is near the center of an exposure 150 feet long, trending from north to south. Toward the north end the upper loess (4) pinches out, exposing the upper till (3) at the surface. Toward the south end the upper till (3) pinches out, so that the loess sheets (2) and (4) are in contact, but without apparent unconformity. A strong accumulation of calcium carbonate, the *B* horizon of the soil profile, has developed in them in relation to the existing surface. The opposite road cut, east of the section measured, exposes (4) and (3) only.

This section is interpreted as follows: (4) Tazewell and post-Tazewell loess, (3) Tazewell till, (2) Iowan loess, (1) Iowan till.

The slope, in the immediate vicinity of the cut, is gently westward. In terms of the direction of glacier flow this is a lee slope, on which conditions should have been favorable for the preservation of loess beneath overriding ice. The fissility in the lower loess (2), never seen in sections free of a till capping, is believed to be secondary, having been induced by the pressure of the Tazewell ice. The color and texture of the base of the upper till (3) are loesslike, and are thought to have resulted from incorporation into it of loess from the ground over which the ice was flowing. Probably only the basal part of what was originally a much thicker body of Iowan loess now remains.

The fourth section, road cuts in NE¼ sec. 20, T. 110 N., R. 75 W., Hughes County expose 5 to 8 feet of poorly rounded sand-gravel outwash overlying, with sharp contact, 4 to 6 feet of sandy loess, beneath which is clay-rich till at least 8 feet thick. The outwash is part of an extensive body that forms a broad apron on the distal slope of an end moraine and funnels westward into the valley of Chapelle Creek. The moraine, with its outwash, lies outside the Cary drift border and is believed to be Tazewell. As the till physically resembles the Wisconsin tills, and is separated from the outwash by a body of loess, it is interpreted as Iowan. The loess is considered to be Iowan loess. The evidence is indirect and therefore not compelling, but the correlation suggested seems probable.

The fifth section, one part of a road cut 0.4 mile west of the northeast corner sec. 26, T. 124 N., R. 78 W., Walworth County, exposes clay-rich till 1 foot thick, overlying grayish-yellow loess at least 4.5 feet thick. The contact parallels the local surface, suggesting that the till-depositing ice flowed over a topography like the present topography. Another part of the cut exposes pebble gravel, apparently of ice-contact character, overlying the same loess, and in turn overlain by one foot of yellowish-gray loess.

In these exposures the till and upper loess are considered to be Tazewell; the lower loess Iowan.

In a road cut, 0.2 mile south of the north quarter corner sec. 21, T. 124 N., R. 78 W., Walworth County, till, with an exposed thickness of at least 3 feet, has a conspicuously loesslike matrix and includes masses of mottled, fissile loess, some with stones worked into them. The till is interpreted as Tazewell, and the reworked loess, Iowan.

Near the north quarter corner sec. 10, T. 125 N., R. 77 W., Campbell County, a section in a road cut was measured. Here, in the proximal part of a narrow end moraine, yellowish-gray loess (2) 4 feet thick, overlies clay-rich till (1) of Wisconsin aspect. Resting on the loess is a scattering (3) of pebbles and cobbles having glaciated shapes. No source from which the stones could have been derived by creep is apparent. The stones are interpreted as a till equivalent, deposited by glacier ice without an inclosing matrix. Till equivalent similar to this occurs in many places on the Tazewell and Cary loess sheets and are not exceptional. The section exposed here is interpreted as: (3) Tazewell till equivalent, (2) Iowan loess, (1) Iowan till.

None of the exposures described above is convincing by itself. Taken alone, each might represent a glacial readvance of local and minor importance. However, no stratigraphic evidence of minor readvance has been seen in the Iowan or Tazewell drift elsewhere in South Dakota, nor has it been reported from western Iowa or northeastern Nebraska.

Taken together, and added to the evidence from alluvial fills and end moraines, these sections suggest strongly that on the western side of the James lobe, outside the Cary drift border, both Iowan drift and Tazewell drift are present.

ALLUVIAL FILLS IN THE MISSOURI RIVER TRENCH

Remnants of two bodies of Wisconsin stratified drift, apparently older than the Cary drift, occur in the Missouri River trench in the Pierre district. These bodies were considered by Crandell[28] as alluvial fills, and were tentatively assigned by him to the Iowan and Tazewell substages respectively. Detailed examination of the Missouri River trench both upstream and downstream from Pierre would doubtless throw light on the strength of this evidence.

DISTRIBUTION OF END MORAINES

The belt of country lying between the Cary drift border and the Missouri River breaks in Hughes, Sully, Potter, Walworth, and Campbell Counties is marked by discontinuous but distinct end moraines, whereas west of this belt (apart from the boulder concentrations in Corson County) the drift lacks end moraines. This relationship is identical with that on the western flank of the Des Moines lobe, where the moraine-marked Tazewell drift has been differentiated from the moraine-free Iowan drift, and hence is consistent with the view that the Tazewell drift is present in the western part of the James lobe.

DRIFT BORDER

All the end moraines and all the sections exposing two pre-Cary Wisconsin drift sheets occur east of the Missouri River trench. Therefore it is inferred that in Tazewell time the James glacial lobe reached the vicinity of the trench but did not cross it. Detailed study of the Pierre district led Crandell[29] to a similar tentative opinion.

However, the data at hand are inadequate to permit delineation of the Tazewell drift border on a map. For this reason the Iowan and Tazewell drift sheets on the western side of the James drift lobe are grouped together on the map, plate 1. Indeed it is unlikely that the exact outer limit of the Tazewell drift in this zone will ever be known. From various indications the writer would guess that the Tazewell drift border emerges from beneath the Cary drift in the northern part of Buffalo County, traverses the southeastern part of Hughes County, and follows the Missouri River trench northward at least as far as the northern line of Potter County. If the end-moraine equivalents in Corson County are assumed to be of Tazewell age, then the Tazewell drift border can be thought of as crossing the trench and as trending northwestward across that county.

If the Tazewell drift border has a position somewhat like the one suggested, and if all the drift lying west of it is Iowan, then the Iowan and Tazewell borders bear essentially the same areal relationship to the Cary and Mankato drift sheets on the west side of the James lobe in South Dakota, as they do on the west side of the Des Moines lobe in Iowa. (See fig. 27.) The relationship implies that both lobes were broader during the Iowan and Tazewell subages than during the Cary and Mankato subages.

TILL AND END MORAINES

The physical characteristics of the Tazewell till do not differ recognizably from those of the Iowan till. Most cuts expose only a few feet of this till, although the heights of some end moraines imply that it is locally thick. A maximum of 30 feet of stony till with a clay-rich matrix, moderate yellowish brown when dry and dark yellowish brown when moist was exposed in 1949 in a ditch in the NW¼SW¼ sec. 33, T 111 N., R. 47 W., Brookings County.

A surface concentrate of wind-cut stones is evident on the Tazewell till as commonly as on the Iowan, suggesting nearly identical physical conditions, at the outset of deglaciation, in both subages.

An exposure 34 feet thick, in sec. 17, T. 121 N., R. 76 W., Walworth County, on the south slope of the prediversion valley of the Moreau River, shows six tongues of clay-rich till interbedded with parallel-bedded silt, clay, and fine sand, evidently lacustrine. The section indicates the repeated encroachment of glacier ice into a temporary glacial lake. A more typical exposure, showing 11 feet of till overlying ice-contact sand and gravel, is seen in a pit in the SE¼ sec. 22, T. 118 N., R. 78 W., Potter County.

A broad, swell-like end moraine marks the outer limit of the Tazewell drift sheet on the Coteau des Prairies. On the Coteau du Missouri, end moraines believed to be Tazewell interrupt the monotonous surface of the ground moraine. The end moraines stand 20 to 60 feet above the general surface and have a local relief of only 5 to 10 feet.

Discontinuous end moraines occur from central Hughes County westward and northward through Hughes, Sully, Potter, Walworth, and Campbell Counties. Bends and loops in these moraines are related to irregularities in the premoraine surface. The moraine ridges extend westward into premoraine valleys and swing eastward across major premoraine interfluves. Local relief on the ridges amounts to only a few feet—not much more than that of the ground moraine. However, the slopes are steeper and the individual knolls and sags have a much smaller average diameter than those in the ground moraine.

In thoroughly dissected areas end moraines grade into litters of boulders without topographic expression. Ex-

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[28] Crandell, op. cit., p. 170–188.

[29] Crandell, idem, fig. 19, p. 191.

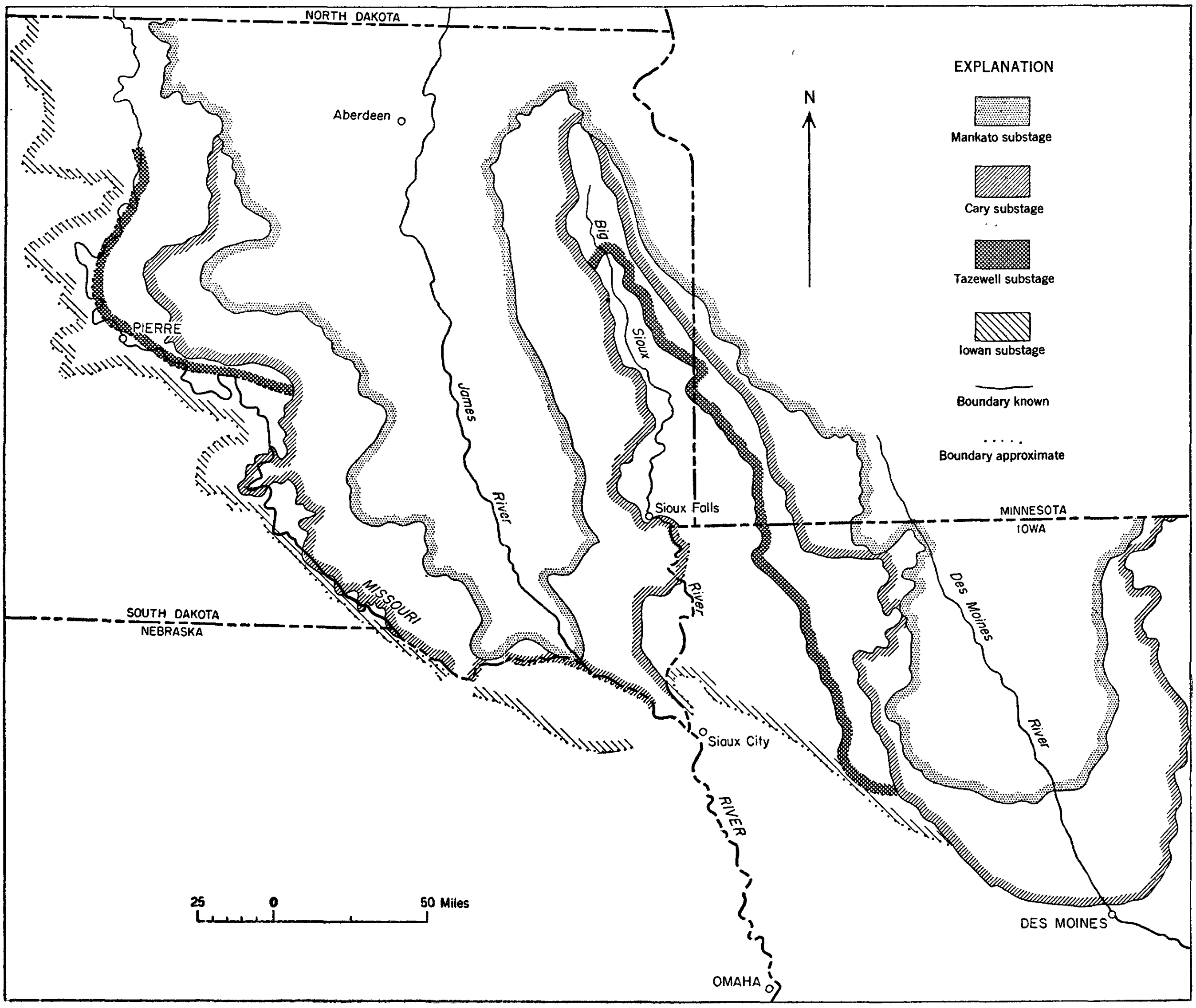

FIGURE 27.—Sketch map showing relations of borders of Wisconsin drift sheets in the James and Des Moines glacial lobes. Iowan border in Iowa after Smith and Riecken (1947), with irregularities smoothed out. Other borders in Iowa and Minnesota after R. V. Ruhe (unpublished). Tazewell border in western part of the James lobe conjectural.

amples are the N½ sec. 22, T. 118 N., R. 78 W., Potter County, the valley of Swan Creek in the vicinity of Akaska, Walworth County, and sec. 18, T. 112 N., R. 8 W., Hughes County. In various places within the Missouri River trench striking concentrations of surface boulders may be in part the equivalents of the end moraines; some, however, may represent no more than that fraction of drift which is of boulder size, deposited on very steep slopes and isolated by the flushing away of finer fractions during and since deposition.

STRATIFIED DRIFT

Gravel knolls are present locally on the Tazewell drift, though they are far less numerous than on the Iowan drift. The best-exposed example is in the southwest corner sec. 5, T. 111 N., R. 48 W., Brookings County. A pit in the knoll exposes 4 feet of irregularly bedded sand and gravel, poorly sorted as to size, overlain by 4 feet of till, suggesting renewed glacial flow and overriding after the accumulation of a kame.

Tazewell outwash bodies resemble Iowan bodies in that they are rarely distinct topographically; mass wasting and a blanket of loess have obscured their outer limits. However, Tazewell outwash has been identified at many more places than has Iowan, and the observer is left with the impression that it is actually more abundant than Iowan outwash. If this impression is valid, then abundance of outwash combines with the presence of end moraines in the Tazewell substage to suggest that in this region Tazewell deglaciation was a longer and more complicated process than the inferred rapid shrinkage of the Iowan ice.

Tazewell outwash covers a terrace cut into till and sloping steeply down Hidewood Creek, where the creek crosses a Tazewell end moraine at the Hamlin-Deuel County line. The terrace was cut by a melt-water stream and was veneered with gravel and sand at or shortly after the time when the moraine was built. Lower terraces, sloping much more gently, are traceable upstream into the area of Mankato drift, and probably date from Mankato time.

Several bodies of outwash lead away from the Tazewell drift area, southwestward toward the Big Sioux River. The most extensive occupies a reentrant in the Tazewell drift border in the vicinity of Elkton, Brookings County, and is traceable, in many exposures, down Spring Creek. The material is chiefly sand and granule gravel, current-bedded predominantly toward the southwest, and containing no fragments with diameters greater than 4 inches. Most of the pebble-size fragments are poorly rounded. The outwash body is overlain by 2 to 4 feet of eolian sand and silt.

Another body of outwash believed to be Tazewell underlies a pair of broad terraces along Pipestone Creek in Moody and Minnehaha Counties. It consists of sand, granules, and pebble-gravel and is overlain by as much as 6 feet of eolian silty fine sand.

Most of the outwash identified as Tazewell occurs along streams that head in the Tazewell drift area. Streams that head farther northeast, in areas of Cary or Mankato drift, have widened their valleys notably during post-Tazewell time, thereby removing most of the Tazewell outwash they may have deposited earlier.

On the west flank of the James lobe, outwash occurs on the distal flanks of some of the larger end moraines, merging into valley trains along streams leading westward to the Missouri River. The most conspicuous valley-train remnants are along Swan Creek and Blue Blanket Creek in Walworth County. High-level outwash occurs in places on the plateau surface, as in sec. 12, T. 120 N., R. 77 W., Potter County.

In contrast with the relatively coarse outwash sediments is a body of laminated silt and clay, occupying an area of about 4 square miles with its center in sec. 5, T. 120 N., R. 76 W., Potter County. The surface of the silt and clay forms an almost nondissected plain that slopes gently down toward the southwest. The sediments were deposited in a temporary lake, dammed on its northeast flank by ice during the Tazewell (or possibly the Iowan) deglaciation.

LOESS

It has not been found possible thus far to distinguish the loess overlying the Tazewell drift from that which overlies the Iowan drift. The physical characters known at present are the same in both bodies of loess. In both, the base of the loess grades down, in many exposures, into fine sand, evidently eolian, as much as 1 foot or more in thickness, and on Tazewell outwash most of the overlying material is eolian sand rather than silt.

In Brookings and Deuel Counties, where areas of both Iowan and Tazewell drift are present, the loess is patchy on both drifts, and rarely exceeds 3 to 4 feet in thickness. No discontinuity in loess thickness at the Tazewell drift border, similar to the discontinuity in northwestern Iowa, has been observed. The most likely explanation of this fact is that most of the loess on these drifts is Tazewell and post-Tazewell, rather than Iowan. Indeed this seems to be the case in Iowa as well, where the Tazewell and post-Tazewell loess is far thicker than the Iowan loess.[30]

The loess-covered Tazewell drift surface in Brookings County is marked by a number of small, very shallow undrained basins, having closures of 1 to 3 feet. Probably the basins are confined to the loess and were excavated by deflation, but it has not been proved that they are not basins in the underlying till, incompletely masked by the overlying loess.

BREAK BETWEEN TAZEWELL AND CARY SUBSTAGES

The interval that separated the Cary subage from the Tazewell subage is the most conspicuous of the three Wisconsin nonglacial intervals in that it embodied a more extreme change in conditions than did the breaks that preceded and followed it. The evidence is both morphologic and stratigraphic.

MORPHOLOGIC EVIDENCE

The morphologic evidence lies in the obvious difference between the surface of the Cary drift and the surface of the Tazewell drift. The Tazewell surface is almost devoid of nondrained basins and has a well-integrated drainage pattern. The Cary surface, away from the immediate vicinity of large streams, is poorly drained and is characterized by large numbers of closed depressions. The difference is observable in the district east of the Big Sioux River and is evident also on the Coteau du Missouri. A traverse along United States Highway 212 in Potter County shows an abrupt change, at Lebanon, between an Iowan and Tazewell (presumably Tazewell) drift surface on the west and a Cary surface on the east. The contrast in slope characteristics in Iowa is shown graphically (fig. 24) by the curves constructed by Ruhe (1950).

The difference between the surface of the Cary drift and the smoother, better-drained surface of the Taze-

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[30] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation, p. 57.

well drift can be attributed to three causes: differences in thickness of overlying loess, differences in glacier regimens during drift deposition, and differences in erosion of the drift sheets. The fact that the average thickness of the loess overlying the Tazewell drift is greater than that overlying the Cary drift implies greater reduction of relief and elimination of more minor irregularities on the Tazewell drift than on the Cary. That the loess blankets have created a difference of this kind is not doubted, but the difference is not great enough to explain the topographic contrast observed. This is evident in that the Tazewell topographic characteristics exist even in places where the overlying loess is thin.

The relative importance of the other causes can not be evaluated from the data available. The parts played by change in the regimen of the glacier between Tazewell time and Cary time (perhaps owing to marked thinning of the ice during the interval between these expansions), and by erosion (including mass-wasting processes) during this interval must await additional facts. In the meantime, it is certain that morphologically the Tazewell-Cary interval represents a conspicuous change in conditions.

STRATIGRAPHIC EVIDENCE

Stratigraphic data suggesting a conspicuous Tazewell-Cary break consist of dark, humified soil zones, in two places accompanied by weathering profiles, developed in loess and overlain by loess, leached eolian sand, and peat. Unfortunately the loess units are not closely dated stratigraphically, so that in no case can the features listed above be attributed to the Tazewell-Cary interval with certainty. Although the weight of evidence favors the interpretation suggested here, such interpretation is made tentatively until better correlation has become possible. The sections are as follows:

Road cut in the Missouri River trench near the south quarter corner of sec. 18, T. 103 N., R. 71 W., Brule County, S. Dak.

[Exposed in 1946; reexamined by C. R. Warren in 1948]

	Feet
6. Granitic boulders (Cary till equivalent)	
5. Loess, yellowish-gray; coarse; calcareous, (pro-Cary), maximum	12.0
4. Soil zone, brownish-black, developed in uppermost 1.5 feet of unit 3, (Tazewell-Cary interval).	
3. Loess, light-gray; compact; with vertical tubular ferruginous concretions. (Iowan and Tazewell)	5.0
2. Till, consisting of till (1) brecciated, with a yellow sandy matrix. (Iowan) Minimum	5.0
1. Till[1] (Illinoian?)	115.0
	137.0

Pierre shale.

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[1] Described in section 2, page 38.

On the basis of the foregoing interpretation two loess bodies, separated by a soil zone, occur between Iowan till and Cary till. The lower loess is best interpreted as Iowan and Tazewell; the upper loess, on the evidence at the locality, could be either Tazewell or pro-Cary—that is, deposited immediately beyond the margin of the advancing Cary glacier, just before that glacier reached its maximum extent. An adequate source, in the form of Cary outwash, was present at that time less than half a mile to the west. The second interpretation is preferred because a soil zone of comparable thickness has not been observed elsewhere between Iowan and Tazewell loess.

Road cut in high terrace in Missouri River trench near the south quarter corner sec. 31, T. 104 N., R. 71 W., Brule County, S. Dak.

[Exposed in 1946; reexamined by C. R. Warren in 1948]

Surface of terrace, dissected.	*Feet*
4. Pebble gravel, pebbles of northeastern glacial provenance, fairly well rounded; forms a very thin discontinuous veneer. (Cary outwash.) Maximum	1.0
3. Silt, loesslike, dusky-yellow when dry; no stratification; calcareous. (Pro-Cary? loess.)	4.0
2. Soil, brownish-black, developed in uppermost 1 foot of unit 1. (Tazewell-Cary interval?)	
1. Silt, loesslike, yellowish-gray when dry; faintly laminated in lower part, possibly aqueous; calcareous. (Iowan and[or] Tazewell.)	5.0
	10.0

Base concealed.

The date tentatively assigned to unit 2 hinges on the date of unit 3. If unit 3 is Tazewell loess, then unit 2 must represent the Iowan-Tazewell interval.

According to C. R. Warren (written communication), at more than 10 localities in northwestern Brule County, Cary till equivalent overlies a well developed humified soil zone at the top of loess. Underlying the loess in turn is Wisconsin till, probably Iowan. Although the stratigraphic position of the soil zone has not been fixed more closely, it is believed to represent the Tazewell-Cary interval.

Section from borrow pit near the north quarter corner sec. 36, T. 106 N., R. 71 W., Buffalo County, S. Dak.

[Exposed in 1946; revisited in 1948]

	Feet
2. Loess, pale yellowish-brown when dry; humified soil zone in uppermost 1 foot; uppermost 8–14 inches noncalcareous; nodular secondary carbonate in basal part	2.5
1. Loess, increasingly sandy toward base; faint horizontal lamination; humified soil zone in uppermost 1 foot; oxidized pale yellowish-orange beneath soil, oxidation diminishing downward; calcareous	8.0
Base concealed.	10.5

Interpretation of the above section:

2. Cary and post-Cary(?) loess with Recent soil.
1. Iowan and Tazewell loess, with oxidation and soil zone developed during Tazewell-Cary interval.

The latest glaciation of this area is ascribed to the Iowan and Tazewell (not differentiated) but was probably Iowan. The calcareous character of the upper part of unit 1 does not disprove that weathering occurred before the deposition of unit 2 because it contains secondary carbonate that is apparently a part of the *B* horizon of the weathering zone developed in unit 2.

According to Todd (1899, p. 121) in a well dug in Douglas County (SE¼ sec. 23, T. 100 N., R. 64 W.) in the town of Corsica, a layer of muck was found at a depth of 20 feet, from which were recovered 12 species of freshwater mollusks, pieces of wood including "the stem of a hemlock or tamarack" 10 inches in diameter, and numerous cones of the same kind of tree. Similar finds were reported by Todd from wells located several miles west.

The material now exposed at the surface at the Corsica locality is Cary till. From this fact it seems probable that the peat dates from the time immediately preceding the Cary subage, namely, the Tazewell-Cary interval, although it is not established that the peat is not older.

Pit near center of sec. 32, T. 111 N., R. 79 W., in city of Pierre, Hughes County, S. Dak.

[Exposed in 1946 and 1947]

	Feet
5. Loess, yellowish-gray, sandy, medium-gray humified soil zone at upper surface, calcareous	8.5
4. Loess, yellowish-gray, sandy, humified soil zone at upper surface, calcareous	3.5
3. Loess, dusky-yellow, very sandy, humified soil zone at upper surface, contains fossil rodent and anurin	3.0
Contact apparently conformable.	
2. Sand, clay, and silt, parallel laminated horizontally	2.0
Contact apparently conformable.	
1. Gravel, consisting of granules, pebbles, and a few cobbles, northeastern (glacial) provenance	12.0
Base concealed.	
	29.0

Interpretation by D. R. Crandell:

5. Mankato(?) loess with modern soil.
4. Cary(?) loess with Cary-Mankato soil.
3. Tazewell(?) loess with Tazewell-Cary soil.
1 and 2. Tazewell(?) stratified drift.

Two other pits in the northwest quarter of the same section, exposed essentially similar sections.

The fossil rodent in unit 3 was identified by Dr. J. T. Gregory of the Yale Peabody Museum as the pocket mouse *Perognathus hispidus* (cf. P. h. *paradoxus* Merriam). This dry-climate dweller now lives in the plains region from Mexico to South Dakota. As the Pierre locality is at the northern limit of this range, the climate, when unit 3 accumulated, or was humified, is inferred to have been as now or possibly warmer, but not colder.

Dr. Gregory was unable to identify the anurin generically. He stated his opinion that the fossil probably has little ecologic significance.

Crandell[31] listed 12 additional sections in the Pierre district, in which a buried soil zone occurs in loess overlying Tazewell(?) drift. That the soil zone or zones belong to the Tazewell-Cary interval is presumed, although it is by no means certain.

Road cut in the NE¼NW¼ sec. 9, T. 103 N., R. 72 W., Lyman County, S. Dak.

[Exposed in 1947 and 1948. Section measured and interpreted by C. R. Warren]

	Feet
6. Loess, upper 2 feet leached; lower part contains secondary carbonate	4.0
5. Stones of far northeastern provenance (till equivalent).	
4. Soil zone, black, humified; developed in the uppermost 1.5 feet of unit 3.	
3. Sand, medium-grained, faintly laminated horizontally	6.5
2. Stones of far northeastern provenance (boulder concentrate).	
1. Till, clay-rich; contains few stones; calcareous; minimum	7.0
Base concealed.	

Interpretation by C. R. Warren:

6. Cary and post-Cary loess.
5. Cary till equivalent.
4. Soil developed during Tazewell-Cary interval.
3. Iowan and (or) Tazewell eolian sand.
1 and 2. Iowan and (or) Tazewell till.

Road cut near east bluff of Big Sioux River trench in the SW¼NE¼ sec. 11, T. 104 N., R. 49 W., Minnehaha County, S. Dak.

[Exposed in 1947]

	Feet
3. Sand, medium-grained, yellowish-gray; with a weakly calcareous *A* horizon underlain by a horizon of nodules of secondary carbonate	12.5
Sharp contact.	
2. Sand, fine, grayish-yellow, noncalcareous	4.5
1. Till, dusky-yellow, clay-rich; overlain by stone concentrate including ventifacts; calcareous	4.0
Base concealed.	

Both sands are believed to be eolian, and are best interpreted as contemporary with the formation of outwash bodies in the valley of the Big Sioux. The relations imply that a weathering profile marked by com-

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[31] Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, p. 220–225.

plete leaching developed in sand (2) before sand (3) was deposited, and that no leaching of the till occurred before the deposition of sand (2). The till is Iowan, and as Mankato outwash is insignificant here, no Mankato eolian sand is expectable. Hence the sands might be either Iowan and Tazewell, or Iowan-Tazewell and Cary, respectively. The former interpretation seems unlikely for two reasons. It implies a weathering interval between the Iowan and Tazewell subages; an interval not recorded in any other exposure seen. Also it implies that the massive Cary outwash body in the Big Sioux valley had no eolian equivalent here, for there is no evidence of post-sand erosion. Hence the interpretation is adopted that sand (2) was wind deposited during Iowan and Tazewell outwash deposition, was leached during the subsequent interval, and was blanketed by a new accumulation of windblown sand as Cary outwash covered the Big Sioux valley floor.

In Woodbury County, Iowa, in the northwest corner of sec. 31, T. 89 N., R. 47 W. (detailed in section 16, p. 35), loess 9 feet thick, referred to the Cary and Mankato, is separated from underlying loess, 35 feet thick, referred to the Iowan and Tazewell, by a 2-foot humified soil horizon, referred to the Tazewell-Cary interval. The loesses and soil are Wisconsin, for the lower loess rests on a weathering profile developed on Loveland(?) loess. The exposure yields no evidence that this place was invaded by any Wisconsin glacier, although it is likely that Iowan glacier ice approached the vicinity. No evidence of an erosion interval, in the form of an unconformity, is exposed. The section appears to be a complete record of Wisconsin events at this place.

A section exposed at SW¼ sec. 8, T. 81 N., R. 44 W., Harrison County, Iowa, and described by Ruhe[32], resembles the Sioux City section immediately preceding in that it exposes a soil zone between two Wisconsin loess sheets. Ruhe referred the soil zone to the Tazewell-Cary interval.

CORRELATION WITH THE REGION OUTSIDE THE WISCONSIN DRIFT

The general occurrence of a humified soil, accompanied in some places by a weathering profile, between two Wisconsin loess sheets in Nebraska was recognized in 1939 by Lugn (1939, p. 878), and by the Nebraska Geological Survey some years later (Condra, Reed, and Gordon, 1950, p. 12, 54). In 1945 Schultz and Stout (1945, p. 241; fig. 3, *A*) applied the name Bignell loess to the loess overlying the soil zone, referred to by them as Soil X. The underlying loess they referred to as Peorian. Three years later they (Schultz and Stout, 1948, p. 570) described the humified zone as having an average thickness of 1.5 feet and proposed to call it the Brady soil.

In 1949 Frye and Leonard (1949, p. 887, 897; see also Frye, 1949, p. 481) correlated a weathering profile widespread in northern Kansas with the Brady soil. In 1950 Ruhe[33] correlated the soil exposed between loess sheets in Harrison and Woodbury Counties, Iowa (see sections above) with the Brady soil, and suggested that the soil dates from the Tazewell-Cary interval. The Brady soil is the only soil zone or weathering profile that has been surely identified in the region outside the limit of the Wisconsin drift; it occupies a middle position in the Wisconsin stratigraphic section.

The repeated occurrence in South Dakota of a buried soil (and weathering profile) in, or apparently in, a mid-Wisconsin stratigraphic position suggests that this soil is the probable correlative of the Brady soil of Schultz and Stout. The two localities at which more than one buried soil is exposed are situated within the Missouri River trench, immediately at the source of supply of loess such as separates the buried soils. These localities therefore are ideally situated to receive considerable deposits of loess within short intervals of time. Hence it is reasoned that one or more of the buried soils exposed at such localities may represent short intervals, and do not necessarily demand correlation with the Brady soil.

CARY SUBSTAGE

CORRELATION

Overlying the Iowan and Tazewell deposits is a third drift sheet, constituting, with the loess overlying it, the Cary substage. It occupies all of the James River lowland and extends laterally on to both coteaus. Its well-marked lobate form shows that it was deposited by a lobe of the ice sheet that flowed down the lowland but could not entirely override the coteaus. This was the James lobe. It was called James River lobe by Leverett (1932, p. 56) and had earlier been termed Dakota lobe. The latter term is ambiguous, a fact that may have led Leverett to avoid it. The former term is shortened here to bring it into parallelism with the well-established term Des Moines lobe applied to the lobe centering in the valley of the Des Moines River in Iowa. Only the northwestern flank of the Des Moines lobe of Cary drift lies within South Dakota.

In most sectors the Cary substage is readily differentiated from the Iowan and Tazewell substages because of its topography. The differentiation is confirmed by the existence of numerous exposures in which

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[32] Ruhe, R. V., Reclassificaton and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation, p. 112–114.

[33] Idem, p. 117.

Cary drift overlies Iowan or Tazewell loess or till. Clearly the glacier invaded this region following an interval of deglaciation and deposition of loess.

The Cary substage has not been traced continuously into South Dakota from Illinois, the region that includes the type locality. Drift in South Dakota is identified as Cary because it is the third of four substages of the Wisconsin stage in this region, thus occupying the same position as the Cary drift in the Illinois-eastern Iowa region. On a similar basis drift on the west flank of the Des Moines lobe in Iowa and Minnesota, formerly classified as Mankato, is now recognized as Cary.[34]

DRIFT BORDER

The border of the Cary drift sheet, topographically distinct from the Iowan and Tazewell drifts, enters South Dakota in northeastern Brookings County and trends northwestward, along the eastern flank of the Coteau des Prairies, through Deuel, Codington, Grant, and Roberts Counties. In this sector the border is marked by a conspicuous end moraine, named by Leverett (1932, p. 57) the Bemis moraine. In the northeastern part of Day County the Cary drift border forms a hairpin curve and trends south-southeastward for nearly 200 miles, facing the border of the Des Moines lobe of Cary drift across a narrow belt of Iowan and Tazewell drift. This trend was induced in the Cary glacier by the coteau, which split the ice into two parallel lobes, the Des Moines lobe on the east and the James lobe on the west.

The Cary drift border along the eastern edge of the James lobe is marked in part by end moraine and in part by ground moraine. In the Sioux Falls district it bends eastward into a broad depression representing a large prediversion valley, and extends beyond the Big Sioux River into Iowa on a 20-mile sector. In this vicinity the drift now classified as Cary was fully described by Carman (1913).

Bending back into South Dakota, the Cary border follows the northern and western flanks of a highland in Lincoln and Union Counties, and is abruptly cut off by the bluffs and alluvial plain of the Missouri River. Southwest across the Missouri River the dissected bluffs on the Nebraska side yield neither stratigraphic nor morphologic evidence of Cary glaciation. Yet with few exceptions, from Union County to the northwest corner of Charles Mix County the northern bluffs display direct or indirect evidence of the former presence of Cary ice. These facts can only mean that throughout this 120-mile sector the Missouri River trench constituted the approximate southern limit of the James lobe during Cary time.

The presence of Cary outwash on the upland in Cedar County, Nebr., opposite the Yankton district, indicates that in the Yankton sector the Cary glacier blocked the Missouri River for a time, at least, detouring it south of its present course.[35] No doubt Cary drift was present on the Nebraska bluffs for a time, but the meandering river has since destroyed whatever evidence may have been there.

Swinging eastward around the highland of the Bijou Hills, the drift border leaves the Missouri trench, returning to it in Brule County. Here, in the vicinity of Chamberlain, the Cary drift forms a minor lobate projection in a prediversion valley similar to the one near Sioux Falls. North of Chamberlain the Cary drift border has a still smaller lobate projection down the valley formed by the junction of Smith and Crow Creeks, where it fails by 5 miles to reach the Missouri River.

Continuing northwestward across Buffalo and Hyde Counties, the Cary border loops far west into Hughes and Sully Counties, making lobes in the drainage basins of Chapelle and Medicine Creeks and in a prediversion valley that passes through Onida. In places the position of the border is doubtful because overlying loess obscures the details. Trending northward across Potter County, the border of the Cary drift lies beneath the overlapping edge of the Mankato drift in the southwest corner of Walworth County. North of this point the Cary drift has not been identified.

Because the loess cover obscures the relations, it is possible that some of the drift in Potter and Walworth Counties mapped as Iowan and Tazewell (not differentiated) may be Cary.

TILL

It has not been found possible to differentiate the Cary till from the other Wisconsin tills on a basis of appearance or mechanical composition. Like the others the Cary till, as seen in exposures, is thin. In most exposures it is only a few feet thick, and in no exposure seen does its thickness exceed 30 feet. No doubt its actual thickness exceeds the thicknesses exposed. At a few places on the western margin of the James lobe ventifacts were seen on the Cary drift, but they are poorly formed, and concentrates of stones comparable with those present on the Iowan and Tazewell drifts are rarely seen.

STRATIGRAPHIC RELATION TO PRE-CARY DEPOSITS

Stratigraphically the Cary substage is set off distinctly from the Wisconsin substages that underlie it. Twenty exposures show Cary drift overlying loess, five

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[34] Ruhe, op. cit., p. 75–77.

[35] Simpson, H. E., 1952, Geology of an area about Yankton, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, p. 265–271.

more indicate indirectly that the Cary ice overrode loess, and three others show Cary till overlying a different till believed to be Wisconsin. It is significant that all these exposures occur within a few miles of the outer limit of the Cary drift. Nearer the center of the James lobe of Cary drift no pre-Cary material has been seen; presumably in that area the Cary ice, eroding more effectively, removed a much greater thickness of the drift over which it flowed.

In the critical sections cited below, the loess beneath the Cary till may be either pre-Cary or pro-Cary (that is, deposited in front of the advancing Cary ice). In either case the sections record the glacial invasion of territory over which loess had been deposited earlier.

The following list contains localities where Cary drift is exposed overlying loess. The sections are shown graphically in figure 28, and their locations are indicated on the map, figure 29.

Sections exposing Cary drift overlying loess.

Localities	*Remarks*
Brule County:	
1. NW¼ sec. 11, T. 104 N., R. 71 W.	Lower till=Iowan(?).
Buffalo County:	
2. W½NW¼ sec. 15, T. 108 N., R. 68 W.	Lower till=Iowan or Tazewell.
3. SW¼NW¼ sec. 27, T. 107 N., R. 68 W.	Road cut.
Clay County:	
4. 0.1 to 0.3 mile south of the east quarter corner sec. 6, T. 93 N., R. 52 W.	Do.
5. Near the center of SW¼ sec. 9, T. 93 N., R. 52 W.	Do.
6. 0.1 mile west of the north quarter corner sec. 6, T. 93 N., R. 52 W.	Do.
7. North quarter corner sec. 27, T. 93 N., R. 51 W.	Do.
Hand County:	
8. Near the south quarter corner sec. 16, T. 109 N., R. 70 W.	Do.
Lake County:	
9. 0.3 mile west of the northeast corner sec. 16, T. 108 N., R. 52 W.	Do.
10. 300 feet west of the north quarter corner sec. 35, T. 105 N., R. 51 W.	Silt beneath till may be aqueous.
Lincoln County:	
11. Southwest corner sec. 16, T. 97 N., R. 49 W.	Dug hole.
Minnehaha County:	
12. 0.1 mile north of the southwest corner sec. 10, T. 103 N., R. 52 W.	Lower till=Iowan or Tazewell.
13. Near the south quarter corner sec. 7, T. 103 N., R. 51 W.	
14. SE¼ sec. 8, T. 102 N., R. 52 W. (south side of highway).	Lower till=Iowan or Tazewell.
15. Near center sec. 13, T. 102 N., R. 52 W. (Between highway and railroad).	Road cut.
Union County:	
16. 0.2 mile west of the southeast corner sec. 19, T. 94 N., R. 50 W.	Road cut.
17. SW¼NW¼ sec. 32, T. 94 N., R. 50 W.	Pit.
18. SE¼ sec. 8, T. 95 N., R. 50 W.	Lower till=Iowan or Tazewell.
Yankton County:	
19. Northwest corner of NE¼ sec. 2, T. 93 N., R. 57 W.	Gully. Middle till=Iowan(?); lower till=Illinoian(?).

Sections in road cuts exposing Cary till with inclusions of loess or with a loess-like matrix, implying the presence or former presence of an underlying loess:

NW¼NE¼ sec. 23, T. 95 N., R. 60 W., Bon Homme County.

Near southwest corner sec. 23, T. 114 N., R. 53 W., Hamlin County. (The till includes several ventifacts, evidently derived from an older stone concentrate.)

North side of highway, in the NE¼NW¼ sec. 14, T. 102 N., R. 52 W., Minnehaha County.

Near southwest corner of sec. 17, T. 122 N., R. 51 W., Roberts County. (The till incorporates ventifacts from an older stone concentrate.)

Northwest corner sec. 31, T. 94 N., R. 50 W., Union County.

Sections exposing Cary till overlying a different till, presumably pre-Cary Wisconsin:

SE¼ sec. 27, T. 115 N., R. 49 W., Deuel County. Here a sandy, mealy, very stony till five feet thick overlies, with sharp contact, a clay-rich till containing few stones. The lower till shows no alteration.

Northwest corner sec. 15, T. 99 N., R. 68 W., Charles Mix County. Here a bouldery drift, very rich in chalk, overlies with sharp contact an olive-gray clay-rich till, fissile, and containing only a moderate amount of chalk.

SE¼ sec. 10, and NE¼NW¼ sec. 14, T. 102 N., R. 52 W., Minnehaha County. Both cuts expose two tills in superposed sequence. In the second exposure the upper till contains inclusions of loess.

The preservation of loess beneath the sole of an overriding glacier is neither as uncommon nor as remarkable as it might at first seem. Loess overridden by ice with little disruption has been reported in Iowa by Kay and Graham (1943, p. 211–217), who mentioned or described 10 such exposures, and by Ruhe.[36] The overlying till was classified by Kay and Graham as Mankato; however, more recent studies in Iowa have suggested that in some or all of these sections the overlying till is Cary. It seems likely that loess is eroded beneath a glacier by the rasping effect of large-sized rock fragments held in the base of the moving ice. A glacier flowing across a surface mantled with loess may erode the loess in this way; at the same time some of the large rock fragments are lodged in its upper part. With continued advance the supply of stones decreases, and

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[36] Op. cit., p. 60–72.

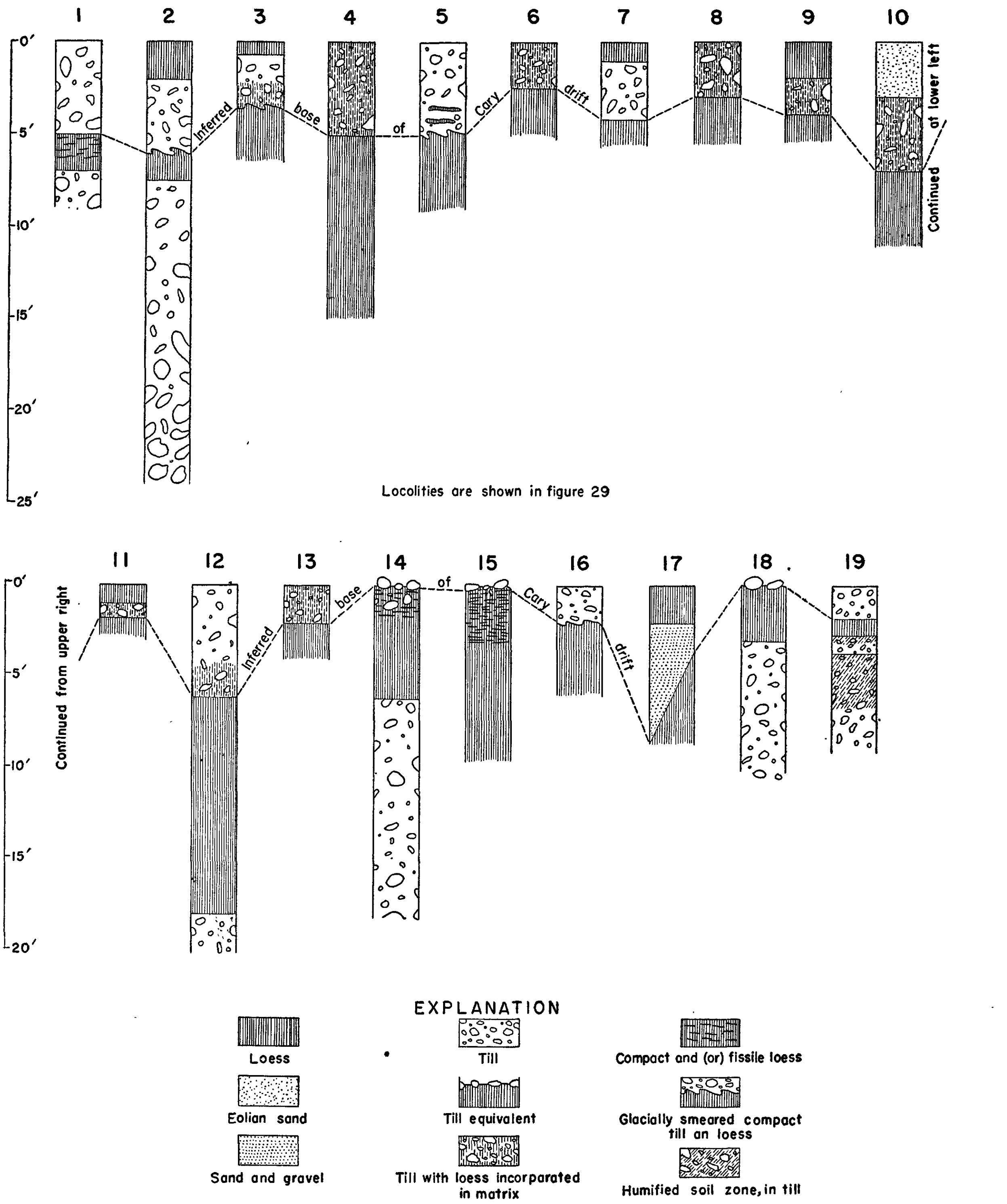
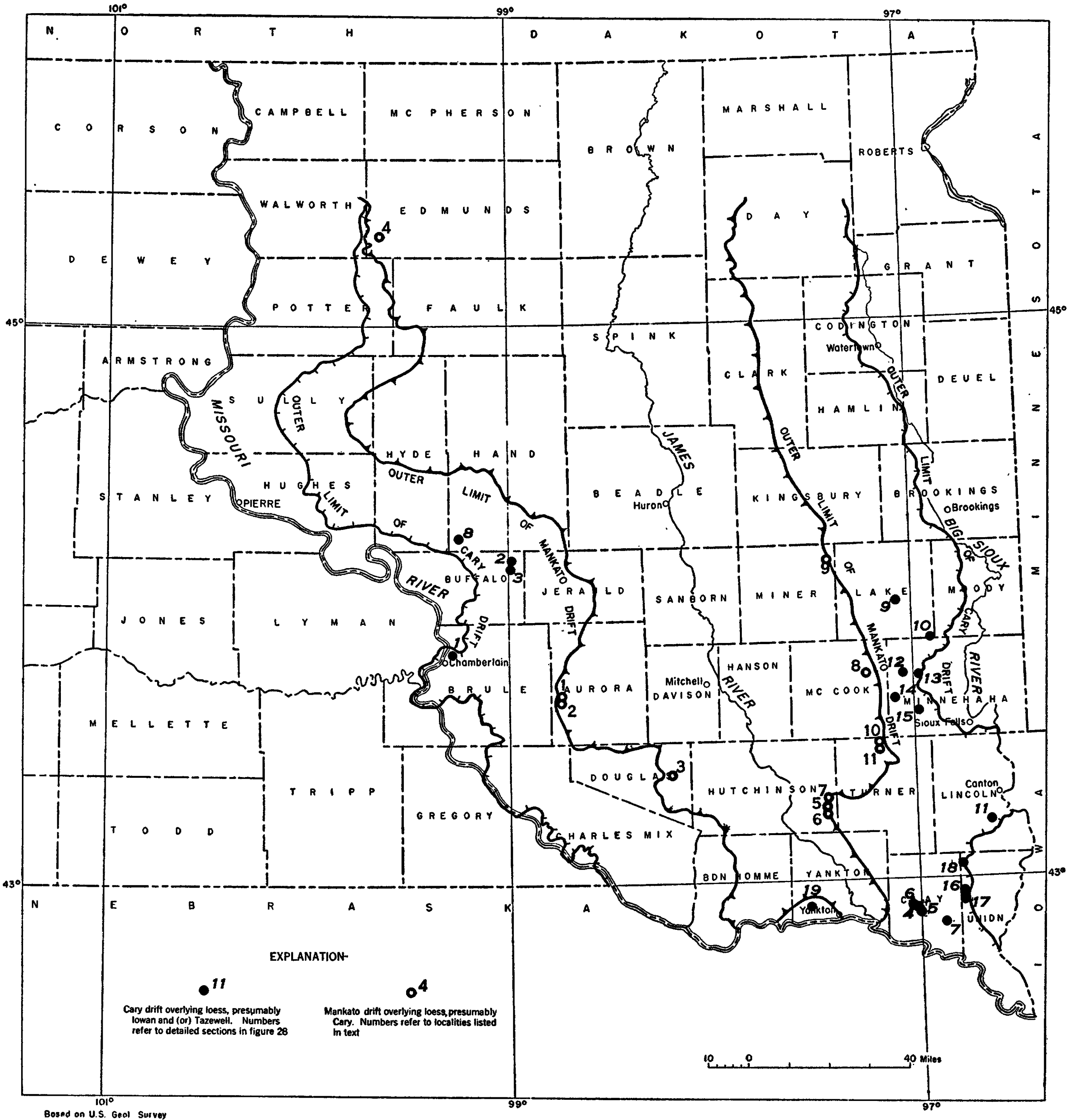


FIGURE 28.—Sections exposing Cary drift overlying loess. Dashed line represents inferred base of Cary drift. Sections were exposed in road cuts except as otherwise noted.



Based on U.S. Geol Survey map of South Dakota

FIGURE 29.—Map showing locations of sections exposing two or more Wisconsin drift sheets.

the drift in the base of the ice includes an increasing proportion of plowed-up loess. Erosion of loess by the ice becomes increasingly difficult, with the result that upon deglaciation, some loess still remains beneath a covering of till having a matrix composed partly of loess.

The presence of ice, occurring as frozen subsurface water in the pores of loess, would have made the body of sediment still more resistant to glacial erosion.

In many of the sections listed above, the loess is much more compact than in undisturbed sections; in one of them it was found to be so tough that little impression could be made on it with a small pickaxe. It is suggested that extra compaction was induced in the loess by pressure caused by the weight of overriding ice. Similarly, in some of the sections listed the upper part of the loess is markedly fissile in a direction parallel with its upper surface. Fissility has not been observed in undisturbed loess. Hence it is suggested that the fissility too was glacially induced. The smeared appearance of some till-loess contacts likewise is logically attributable to the drag of ice flowing across the surface of the loess.

Most of the localities exposing Cary drift overlying loess are in the southern part of the James lobe of Cary drift. This fact suggests that loess was more completely removed by Cary glacial erosion from the region farther north, where the glacier ice was thicker, and flowed across pre-Cary terrain through a longer period, than in the southern region.

TOPOGRAPHIC EXPRESSION

The topography of the Cary drift differs from that of the Iowan and Tazewell drifts in that it has a pronouncedly morainic surface. Slightly more than half the total area of Cary outcrop has been mapped as ground moraine. The Cary ground moraine, with an average relief of no more than 10 feet, is characterized by swells and swales with shorter diameters and less gentle slopes than those seen in the pre-Cary drifts. The swells and swales constitute a fine-textured topography. Undrained basins are numerous, containing ponds, marshes, or whitish saline deposits. The basins are not kettles; they are the result of the uneven lodgment of till upon the ground as the Cary ice flowed over it.

The characters of Cary ground moraine just described pertain to areas where the Cary drift is thick enough to mask the relief of the pre-Cary surface. In many areas, however, particularly in the western part of the Coteau des Prairies, the Cary drift constitutes no more than a thin veneer over an older surface of considerable relief.

In the breaks flanking the Missouri River trench in Charles Mix and Brule Counties the Cary drift thins out with a ragged edge and disappears, exposing pre-Cary drift and bedrock, just as do the earlier drift sheets in similar topographic positions. The morainic form of the Cary drift is seen down within the trench in a few places where post-Cary dissection has been less than usually severe, indicating that the trench came into existence before the arrival of the Cary ice.

In southeastern Lincoln County the surface of the peripheral part of the Cary drift has a morainic appearance, with pronounced swells and swales that contrast with the faint swell-and-swale topography of the loess-covered Iowan drift to the southeast. The surface, however, is not that of true moraine, for it is underlain by loess, capped discontinuously with a till equivalent consisting of scattered stones, and with very thin smears of till. This pseudomorainic topography seems to have resulted from the plowing up and reworking of thick pre-Cary loess by the terminal part of the Cary glacier. Such topography has not been seen elsewhere than in the sector in which the Cary border overlies very thick loess.

In many parts of both coteaus the relief of the ground moraine abruptly increases and large kettlelike basins appear. These changes are related systematically to pre-Cary valleys and are merely the response of the Cary drift surface to the presence of notably greater relief and steeper slopes beneath it.

End moraines, which constitute nearly half of the total outcrop area of Cary drift, are generally more massive and more continuous than the pre-Cary end moraines believed to belong to the Tazewell substage. The Cary end moraines stand higher and with steeper slopes in the northern part of the State than in the southern, undoubtedly because each moraine position was occupied by the glacier margin for an increasingly long period with increasing latitude.

The Cary end moraines are not continuous, nor does their number show any consistency from place to place. In Day County, for example, there are three principal Cary moraines, in Lake County there are two, and in a considerable sector between these counties there is only a single end moraine. On the western side of the James lobe there is similar inconsistency, nor is the pattern there a mirror image of the pattern on the eastern side. The conclusion seems justified that local factors must have played an important part in the location and shaping of the Cary end moraines.

As the individual moraines in the James lobe are not continuous, they can not properly be correlated with moraines identified in the Des Moines lobe. Todd (1908, p. 4) erroneously correlated end moraines in Union and Clay Counties with the Altamont moraine of the Des Moines lobe. The age of the Altamont moraine, determined in its type locality, is Mankato, not Cary.

The most continuous single end moraine in the Cary drift is the Bemis moraine, described earlier as marking the drift border of the Des Moines lobe. Because of its position contouring the flank of the Coteau des Prairies, against which the glacier pressed during a long period, this moraine is unusually high and narrow. It ranges in width from 1 to 4 miles, and in height from 30 to 60 feet. Its local relief (the difference in height between knolls and adjacent depressions) ranges from 15 to 30 feet.

Another kind of expression is evident in Minnehaha County, where almost the entire belt of Cary drift west of Sioux Falls consists of a single bundle of subparallel end-moraine crests, together forming a mass nearly 15 miles wide and more than 100 feet high.

In contrast, the Cary end moraines in Clay County are broad smooth swells with extremely gentle slopes standing only a few feet higher than the adjacent country.

Still another kind of end moraine is seen in the N½ sec. 10, T. 104 N., R. 68 W., Brule County. Here an end moraine half a mile wide and 20 feet high bulges southward into a small draw less than 20 feet deep, indicating that the ice must have been very thin at that place and time. South of the moraine is a broad outwash fan, separated from it by a depression that must have been occupied by ice while the outwash was being built.

Evidence of the presence of thick Wisconsin pre-Mankato till, which probably constituted a Cary end moraine before it was largely overridden by Mankato ice, is present in the vicinity of Parker, Turner County. The data are presented in figure 30, a profile and section along a major prediversion valley. As shown on the map (pl. 1), this valley induced local lobation of the Mankato ice; comparison of the map with figure 25 strongly suggests that a similar lobation, accompanied by the building of end moraine, earlier characterized a retreatal phase of the Cary glacier. In other words the Mankato end moraine stands on a pedestal consisting of an eroded end moraine of earlier date.

Where the Cary end moraines cross prediversion valleys on the coteaus, they reflect the influence of the premoraine topography. The moraine crest becomes lower, or the entire moraine descends the valley side slopes, or, in extreme cases, the moraine merges into an end-moraine equivalent—a belt of boulders having the width of the moraine itself. Examples of these features are found in the following localities:

Lowered crest: Sec. 13, T. 120 N., R. 53 W., and sec. 23, T. 121 N., R. 53 W., Day County.
Descent of entire moraine: Northwest part of T. 105 N., R. 68 W., Brule County.
End-moraine equivalent:
  SE¼ sec. 25, T. 109 N., R. 69 W., Hand County.
  Sec. 15, T. 109 N., R. 70 W., Hand County.
  Sec. 26, T. 111 N., R. 70 W., Hand County.

STRATIFIED DRIFT

The proportion of easily recognizable stratified drift to till in the Cary substage is substantially greater than in the earlier Wisconsin substages. No doubt the difference results partly from the thick blanket of loess that obscures many of the details of the pre-Cary drift sheets, but it is believed to be chiefly intrinsic. Melt water played a larger part in rearranging the drift in Cary time than in pre-Cary time, and this inference is consistent with the evidence that the James lobe in Cary time was thinner than its Tazewell predecessor, and therefore possessed a broader peripheral zone of ablation.

Near the border of the Cary drift sheet, sections exposing till overlying stratified drift, probably outwash, are not uncommon. An example, well exposed in 1947, is a sand pit in the SW¼ sec. 20, T. 103 N., R. 51 W., Minnehaha County. Such sections record minor oscillations of the glacier terminus during the accumulation of stratified drift.

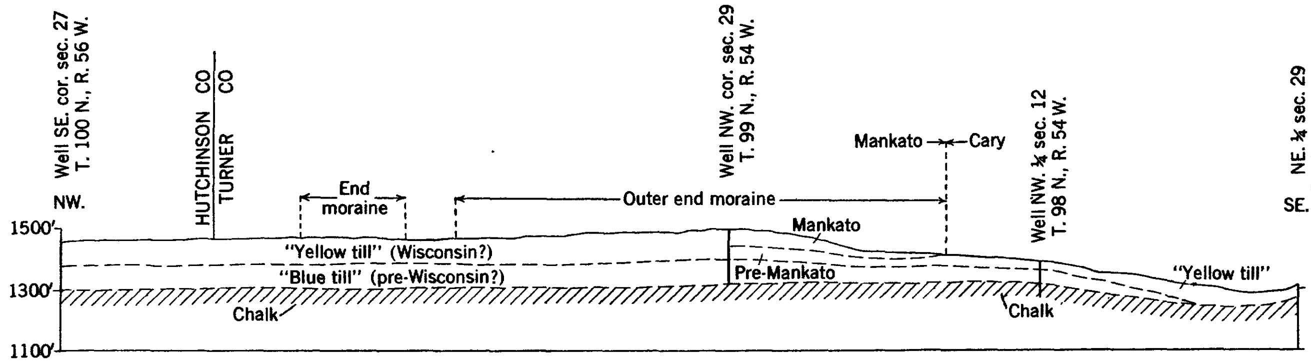


FIGURE 30.—Profile and section, 21 miles long, from near Silver Lake, Hutchinson County, to near Hurley, Turner County. The section as a whole trends approximately S. 40° E., but it includes a slight bend at the location of each of the two intermediate wells. Subsurface data inferred from four well logs. Interpretation is suggestive only.

In the Cary substage ice-contact stratified drift is represented mainly by kames of sand and gravel, occurring mostly in groups or clusters on dissected uplands. One such group is found on the summit and flanks of Turkey Ridge in Turner, Clay, and Yankton Counties, and another, smaller, group lies on and north of Yankton Ridge. A third group stands in the southeastern part of T. 103 N., R. 52 W., Minnehaha County. The fact that these places are high relative to their surroundings suggests that the kames represent thinning and stagnation of the terminal zone of the glacier, after the end moraines in each of these areas had been built.

In Day County many cuts in areas of collapse topography show the Cary and post-Cary loess to be immediately underlain by parallel-bedded silt, apparently lacustrine. These relations imply that during retreat of the Cary glacier margin temporary lakes developed, in part over buried Cary ice. The thickness and maximum extent of such deposits cannot be known until the results of detailed mapping have become available.

The heads of some of the Cary outwash bodies, also, are of ice-contact character. They are pitted with large kettles or have collapsed surfaces, recording the building of outwash sediments over thin marginal ice. Some of the many examples are:

The area between Lake Kampeska and Pelican Lake, Codington County.

The large area, in western Codington County, embracing the chains of lakes between Lake Kampeska and the Clark County line. Here the Cary end moraines merge into outwash bodies so complexly pitted and collapsed that their surface forms are hardly distinguishable from the moraines themselves. They are mapped on the basis of exposures which show sand and gravel in contrast with the predominant till in the moraines. Two subparallel end moraines, about 8 miles apart, are involved in the complex. The fact that the pitted outwash appears to be common to both, indicates that the buried ice from the time of the earlier moraine survived the building of outwash from the later one, and thereby suggests that the two moraines were not separated by a great length of time.

The area, in eastern Day County, north and northeast of Blue Dog Lake. Here the distal slope of the outermost Cary end moraine is mantled with an outwash apron 1 to 2 miles wide, reaching back almost to the crest of the moraine. At Enemy Swim Lake, which lies in a pre-Cary valley, the moraine is abruptly replaced by an ice-contact outwash head. Evidently the outwash sediments, pouring eastward through the preexisting valley, quickly thinned, stagnated, and buried the marginal ice and thus inhibited the piling up of knobs and ridges of till in the form of end moraine.

The area between Lake Norden and Lake Poinsett, in Hamlin County.

Despite the striking development of collapsed and pitted outwash, normal outwash is areally much more extensive. Outwash aprons mantle the distal slopes of Cary end moraines in many places, as shown on the map (pl. 1). Outstanding examples are the outwash aprons in eastern Potter County, at the outer limit of the Cary drift. Other big outwash bodies, unrelated to specific moraines, occupy pre-Cary valleys. Among these are the Crow Creek body, derived from several moraines, in Buffalo and Jerauld Counties, the outwash lying between Madison and Chester in southeastern Lake County, and the bulk of the outwash along the Big Sioux River. The latter requires special comment.

Despite the fact that the position of the Big Sioux River indicates that it must have carried melt water during the Iowan, Tazewell, Cary, and Mankato substages, most of the outwash now exposed along its course is Cary. This is known from the fact that the main outwash body cuts the Iowan and Tazewell loess, is overlain by Cary and post-Cary loess, and is traceable, as terrace surfaces, up tributaries into Cary moraines. It can be inferred that Iowan and Tazewell outwash was partly buried beneath Iowan and Tazewell loess and was partly removed by Cary melt-water streams. As for the Mankato, it is not surprising that Mankato outwash is relatively unimportant. For whereas two great lobes of Cary ice poured melt water into the Big Sioux simultaneously, no Mankato melt water reached the Big Sioux from the west. Furthermore on the east side the Mankato ice was relatively far from the Big Sioux, and was facing an adverse slope that afforded traps and pockets to catch outwash sediment before it could be transported to the main drainage line. Hence, although Mankato melt water escaped along the Big Sioux, it carried little bed load and seems to have had a regimen that led to erosion rather than to deposition.

Owing to superposition from outwash prior to Cary time, the Big Sioux drops 20 feet over a ledge of quartzite at Dell Rapids, and 75 feet over another ledge at Sioux Falls. Through the intervening 20-mile segment the gradient is very gentle and the outwash sand and gravel body is capped by silt and clay 10 feet thick (Rothrock and Otton, 1947, pt. 1, p. 15–16, pl. 9). The fine-grained cover in this protected segment may represent Mankato outwash.

An excellent exposure of Cary outwash, showing ideal cut-and-fill stratification from which the direction of flow of the water can be inferred, and overlain by 3 to 4 feet of eolian sand and silt, is seen in a sand pit in the northeast corner of sec. 28, T. 110 N., R. 49 W., Brookings County.

Others, farther down the Big Sioux, include the Great Northern Railway gravel pit at the east quarter corner of sec. 10, T. 101 N., R. 49 W., Minnehaha County, exposing 5 feet of sandy loess on 25 feet of outwash on pre-Wisconsin till. Still farther downstream is a gravel pit in the NE¼ sec. 19, T. 98 N., R. 49 W., Lincoln County, where 4 feet of sandy loess overlie at least 9 feet of outwash. In the Big Sioux outwash body the diameters and angularity of the component fragments do not diminish downstream systematically. Probably this is the result of the interlobate character of the Big Sioux melt-water stream. Instead of being fed with outwash only at its head, it was fed simultaneously from many tributaries on both sides. Like many other bodies, however, it shows in places a lateral gradation from coarse grain sizes in its axial part to silt and clay in pockets and reentrants along its flanks.

At the Bruns gravel pit on Skunk Creek near Sioux Falls (SW¼ sec. 15, T. 101 N., R. 50 W., Minnehaha County) Cary outwash contains mammal bones. Dr. C. B. Schultz visited the locality with the writer and identified some of the bones as those of *Rangifer* sp. and *Equus* sp. *Rangifer* is a cold-climate genus. The *Equus* bones belong to a small form similar to the northern horse of the late Pleistocene of Alaska (C. B. Schultz, written communication). These facts are consonant with the occurrence of both forms in outwash sediments. The animals lived during the Cary deglaciation.

Terraces are well developed in the outwash along the Big Sioux and its tributaries, particularly Skunk Creek. Detailed study of them would reveal the sequence of events involved in the building and dissection of this complex valley train.

In many sectors where the distal toe of an end moraine faces rising ground, narrow outwash bodies, or melt-water stream channels without outwash are formed along the toe of the moraine, usually leading to some transverse, premoraine valley. Good examples are seen along the toe of the Bemis moraine throughout most of its course across Deuel County. West of Lake Hendricks and south of Oak Lake in northeastern Brookings County, the Bemis moraine lies along the northeast-facing flank of the Coteau des Prairies. In this sector a series of dry stream channels contour the slope at successively lower levels. Evidently they were cut by melt-water streams flowing along the margin of the Cary ice at successive positions of retreat. Within this group, minor channels in secs. 29 and 30, T. 112 N., R. 47 W., are discontinuous. In places they end abruptly, hanging above the regional slope. At these places they must have been flowing upon the thin margin of the glacier itself. Such channels were described in detail by Kendall (1902), who termed them in-and-out channels.

The system of channels just described leads into a dry master valley, or rather trench, a quarter of a mile wide and 150 feet deep, transecting the major divide that separates the drainage of the Big Sioux River from that of the Minnesota. At this point the margin of the Cary drift lies along the divide. Evidently melt water from the Cary glacier trenched the divide, the trenching keeping pace with the retreat of the glacier margin through a distance of at least 2 or 3 miles, for through that distance, as well as on the west side of the divide, the valley floor slopes southwest. The through valley or trench that transects the divide opens into the valley of Deer Creek, a capacious tributary to the Big Sioux.

The same divide was similarly transected by melt water (Hidewood Creek), in sec. 33, T. 115 N., R. 49 W., Deuel County; in sec. 24, T. 116 N., R. 51 W., Codington County; in sec. 1, T. 117 N., R. 51 W. (Willow Creek), Codington County; and in sec. 29, T. 119 N., R. 51 W., Codington County. At all these places the divide is cut through by narrow trenches 100 feet or more in depth. At least two of these transections were later reoccupied by Mankato melt-water streams.

The trench of the Missouri River, as the master stream of the region, might be expected to contain far more outwash than other valleys, but such is not the case. The terraces, including outwash terraces, along the Missouri constitute a special problem, discussed in another part of this report.

LOESS

Cary loess overlain by Mankato drift is exposed at only a few places. Most of the loess on the Cary drift, therefore, must be classified as Cary and post-Cary, for although most of it undoubtedly accumulated as the Cary glacier retreated, there is no proof that this was not added to later.

The variations in thickness and sand content displayed by this loess imply that it was derived from many sources, consisting of outwash bodies both large and small, as well as the freshly exposed Cary till itself. One source was the Missouri trench, for the loess on the Cary drift is 8 to 20 feet thick and notably sandy at and near the northern bluffs, but it thins and becomes finer within short distances to the north. Near the margin of the Cary drift in Sully and Hughes Counties this loess reaches 6 feet in thickness, and thins eastward within short distances. Aside from such local exceptions the Cary and post-Cary loess ranges generally from 2 to 4 feet in thickness. It is, however, patchy, being absent from steep slopes and also, surprisingly, from some nearly horizontal surfaces as well. Where its full thickness is exposed in ditches freshly made by road grading, or is found in auger borings, the Cary loess is seen to be thicker in swales than on swells. Probably the difference is in part initial, and in part accentuated by slopewash since deposition began.

The change in composition of the Mankato till from south to north, as noted on page 111, suggests that the Cary loess may not have been deposited in significant amount over the northern part of the James River lowland, but rather that the loess cover was laid down only in the southern part of the lowland.

Several pieces of an antler of a deer were collected from Cary or pre-Cary loess exposed in a road cut in the NW¼SW¼ sec. 26, T. 109 N., R. 68 W., Hand County.

A blanket of loess on the Cary drift has been reported from Minnesota and Iowa[37] and from south-central Wisconsin (Hole, 1943, p. 506).

BREAK BETWEEN CARY AND MANKATO SUBSTAGES

The interval between Cary deglaciation, in South Dakota, and deposition of the Mankato drift is represented by less conspicuous features than is the Iowan-Tazewell interval. The evidence is as follows:

The soil profile developed in Cary drift and overlying loess, where not covered by Mankato till, differs only very slightly from the profile developed in the Mankato substage.

Cary loess, exposed beneath Mankato till, is calcareous, recording no intervening alteration. However, it is possible that Mankato glacial erosion has removed the top of the Cary loess at the localities of exposure.

No well-developed or persistent soil within the Cary and post-Cary loess has been seen, although sections of loess overlying Iowan or Tazewell drift, outside the Cary drift border, do expose such a soil, believed to date from the Tazewell-Cary interval.

Differences of topographic expression between the Cary and Mankato substages, although recognizable, are very slight, indicating that only minor changes in the regimen of the ice sheet took place between these two glacial maxima. A part of the difference that is recognizable is probably the result of masking of details of the Cary topography by a thicker and much more continuous sheet of loess than that which overlies the Mankato drift.

It is possible (though not established), as suggested by outwash relations in southeastern Marshall County, that glacier ice buried beneath Cary outwash persisted until the return of the glacier to this district in Mankato time. If so, the intervening interval can not have been long. Persistence of buried ice throughout what appears to be the same interval was inferred by Cooper (1935, p. 23) in central Minnesota.

Three exposed sections and four well logs are believed to record the Cary-Mankato break. One of these sections in Charles Mix County (north abutment of Ft. Randall Dam, in the NE¼SE¼ sec. 5, T. 95 N., R. 65 W., 1,200 feet northeast of locality 4, p. 34) exposes 20 feet of Cary(?) till, with its upper part leached and humified, overlain by 5 feet of Mankato(?) loess. The leaching and humification are believed to represent the Cary-Mankato interval.

A second section, in the SE¼ SE¼ sec. 1, T. 93 N., R. 56 W., Yankton County, exposes loess overlying an older loess the top of which is humified. According to H. E. Simpson (written communication) the loess bodies are Mankato and Cary, respectively, and the humified zone represents soil making during the Cary-Mankato interval.

The third section (a road cut near the southwest corner of sec. 18, T. 33 N., R. 1 E., Cedar County, Neb.) exposes two loess sheets, of which the lower exhibits a faint weathering profile; near its surface are charcoal and charred bone representing a human occupation site. In the opinion of H. E. Simpson (written communication) the loess sheets are, respectively, Mankato and Cary.

The four well logs suggest the presence of fossil vegetation between the Cary and Mankato substages. The well logs furnish no real proof, because the stratigraphy established from them is not firm. They are listed below only as a possible guide to future investigation.

Aurora County: White Lake railroad station. Town well penetrated 80 feet of (Mankato?) till and at that depth fragments of wood including a root(?) 12 inches long and 3 inches in diameter were found (Todd, 1899, p. 120).

Clark County: Dug wells north of Clark, outside the Mankato drift border, passed through "beds containing wood and freshwater shells" at depths of 25 to 30 feet (Todd, 1899, p. 85). Apparently the wells were dug in Mankato outwash.

Grant County: A well in the S½ sec. 5, T. 120 N., R. 47 W., at Milbank, in the Mankato drift, penetrated 42 feet of till and 8 feet of sand containing fragments of wood before reaching bedrock (Rothrock, 1934, p. 17).

Hutchinson County: A well in the NW¼ sec. 21, T. 98 N., R. 60 W,. penetrated 73 feet of oxidized till (Mankato?) a layer of "lignite," and 78 feet of unoxidized till, before passing into bedrock (Todd, 1900b, p. 20).

During the Cary-Mankato interval it is probable that glacier ice withdrew entirely from South Dakota. Evidence supporting this belief occurs in exposures in Manitowoc County, Wisc., where a layer of peat is interbedded between Cary drift and Mankato till without apparent intervening erosion (Flint and Deevey, 1951, p. 261–263). The ecology of the peat is subarctic, suggesting that the glacier margin had not retreated far north, although the related deposits of the glacial Lake Michigan imply that the glacier must then have stood north of the Strait of Mackinac (Bretz, 1951). If in the longitude of Lake Michigan the ice sheet stood

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[37] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation, p. 88–93.

north of the Strait of Mackinac, and if the margins of the Mankato drift sheets in Wisconsin and South Dakota are contemporaneous, it is probable that the Cary glacier uncovered South Dakota completely.

The opinion that the Cary-Mankota interval was short, as measured by the character and thickness of the peat in Manitowoc County, Wisc., was expressed by L. R. Wilson (Flint and Deevey, 1951, p. 262). However, on the assumption stated above, the interval between Cary deglaciation and Mankato glaciation in South Dakota must have been longer than the corresponding interval at Manitowoc, by the time required for the uncovering and re-invasion of a wider belt of territory.

MANKATO SUBSTAGE

CORRELATION

The fourth and stratigraphically highest of the Wisconsin substages in South Dakota is the Mankato substage, consisting of a conspicuous sheet of drift overlain in favorable places by thin and very patchy loess. This drift sheet is identified as Mankato by continuous tracing from southwestern Minnesota and northwestern Iowa, where Mankato drift has long been recognized (Leverett, 1932; Kay and Graham, 1943, p. 203, modified by Ruhe[38]). Like the Cary, the Mankato drift forms two lobes separated by the Coteau des Prairies. Only the extreme northwestern part of the Des Moines lobe lies within South Dakota, but the James lobe is wholly within the State.

The Mankato substage is believed to be closely related to the Cary substage in time. But it is differentiated from the Cary drift because of several features. It is exposed overlying Cary loess. Its drift border and end moraines diverge importantly, in some sectors, from those of the Cary. It differs topographically from the Cary drift. It includes more stratified drift than does the Cary. The soil profile developed in its upper part is slightly less well developed than the soil profile present in the Cary drift. These five features are detailed in the discussion that follows.

This drift is correlated with the Mankato substage because it is the youngest of four Wisconsin drift sheets present in South Dakota. It has not yet been traced into South Dakota continuously and in detail from its type locality in southeastern Minnesota. However, it is continuous with all but the outer part of the drift in Minnesota and Iowa that has long been recognized as Mankato. The outer part of that drift, as stated earlier, is now classified as Cary.

DRIFT BORDER

POSITION

Topographically distinct from the Cary drift beyond it, and mostly free of a covering of loess, the Mankato drift is identified with comparative ease. Its border is marked by end moraine throughout the greater part of its extent in South Dakota, and through much of its extent it is fringed with outwash.

The Mankato drift sheet in South Dakota takes the form of a large lobe, the James lobe, as long as but much narrower than the James lobe of Cary drift. The northwestern flank of a Des Moines lobe of Mankato drift is also present. This, too, is less extensive than the corresponding lobe of Cary drift.

Between the Minnesota State line and the southeast corner of Roberts County the Mankato drift border is characterized by a high and massive end moraine named by Chamberlin (1883, p. 388) the Altamont moraine. In several sectors, notably the vicinity of Clear Lake, Deuel County, the sectors in Grant and Codington Counties, and the Day County sector, its distal base and even the greater part of its distal slope are covered with outwash. This moraine lies along the northeastern flank of the Coteau des Prairies. Rising toward the northwest, the drift border reaches the summit of the coteau in Marshall County, and swinging across it in a broad arc, follows its western flank, descending gradually southward.

From northern Clark County to Yankton, a distance of 150 miles, the border is fringed almost continuously by outwash. The outwash floors valleys made by the building of end moraine along the coteau flank. In most places the outwash neatly delineates the contact of Mankato drift on Cary drift; here and there, however, the Mankato drift forms narrow strips on the eastern, far side of the outwash.

The Mankato drift forms a blunt lobe projecting down a major prediversion valley in Turner County, loops back around the northern end of Turkey Ridge, and continuing southward, reaches the Missouri River trench. Here the lobate form of the Mankato drift sheet is split by Yankton Ridge. One part projects southeastward; the other part southwestward. The exact original extent of these parts probably will never be known, for each has been trimmed back by the Missouri River.

In view of the inferred system of prediversion valleys shown on plate 7, it might be asked why the Mankato ice failed to extend as far southeastward down the valley of the Ancient White River at Parker, as it did down two lesser valleys east and west of Yankton. The reason seems to be that near Parker a plug of pre-Mankato

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[38] Rure, R. V., op. cit.

drift, probably former end moraine, constituted an obstacle to flow of the Mankato glacier (fig. 30).

Traced northward, the Mankato drift border along the western side of the James lobe forms sublobes which project into prediversion valleys and from which outwash valley trains lead away along Choteau, Platte, Medicine, and Spring Creeks. The border, marked in most places by end moraine, climbs steadily northwestward, nearly contouring the eastern flank of the Coteau du Missouri. In southeastern Walworth County it overrides the outer border of the Cary drift and cuts obliquely across pre-Cary end moraines. At the North Dakota State line Mankato till reaches to within 15 miles of the Missouri River trench, and collapsed outwash in the valley of Spring Creek suggests that the Mankato glacier reached to within only 6 miles of the trench.

RELATION TO CARY MORAINES

The relation of the Mankato drift border to Cary end moraines is significant. Both flanks of the northern end of the Mankato James lobe extend across Cary moraines obliquely. On the Coteau des Prairies this lack of conformity is evident in the Roberts County-Marshall County sector and in northern Clark County. On the Coteau du Missouri it is evident in southeastern Hand County and in southeastern Walworth County. The abrupt lack of conformity between the trends of Mankato and Cary end-moraine crests on the western flank of Turkey Ridge (pl. 1) is more apparent than real. The flank of this ridge is so steep that abrupt bends in the moraine are expectable, and lack of conformity is not therefore established.

TILL

Mankato till does not seem to differ appreciably from the Cary and other Wisconsin tills. Mankato till more than 30 feet thick has not been seen in any continuous exposure. Probably this results from a scarcity of deep exposures, for it seems certain that in the largest end moraines, at least, the Mankato till has a greater thickness. In most exposures, however, this till is thin; its actual or average thickness is unknown.

Concentrates of stones and boulders, in positions related to the present topography, are seen on steep slopes, but no such concentrate has been seen exposed in section beneath Mankato loess, and no ventifacts have been noted on Mankato drift save in southeastern Sully County, immediately east of a large outwash body, and in the area of Fox Hills sandstone in Campbell and McPherson Counties, where fine sand is ubiquitous and wind cutting of rock fragments may be in progress even today.

The proportion of boulders to smaller-size fragments seems to be greater at and near the surface of the Mankato till than well down within the till. This difference seems to be independent of residual surface concentration by erosion, because it exists in flat, nondissected areas as well as in areas where slopes are appreciable. The explanation of this distribution of boulders is not known. Possibly, however, the surface boulders represent coarse material that was transported well above the base of the glacier ice. In such positions the boulders would have escaped lodgment farther north, upstream, and would have been let down upon the lodged till only during final melting and thinning of the terminal zone of the glacier.

STRATIGRAPHIC RELATION TO PRE-MANKATO DEPOSITS

Sections exposing Mankato till overlying Cary loess are not as numerous as those exposing Cary till on pre-Cary loess. The chief cause of the difference may be simply the relative thinness of the Cary loess, which may have been removed fairly easily by the oncoming Mankato ice. It is unlikely that the causes include failure of the Cary loess to extend far to the north, for this loess is present, in Potter County and in Day County, as far north as the Cary drift is exposed in outcrop area. As the Mankato and Cary tills are similar, and as stone concentrates are rarely formed at the surface of the Cary till, sections exposing the tills in direct superposition would not be readily apparent. None has been identified with certainty.

However, shrinkage of the Cary ice, accompanied and followed by the deposition of loess, followed in turn by reexpansion of the glacier and deposition of Mankato till, is established by 12 sections exposing Mankato till overlying loess and 3 sections exposing Mankato till with a matrix consisting chiefly of loess. All are located at or very close to the Mankato drift border and most occur in the southern half of the James lobe. These facts suggest either that Mankato till is generally too thick to permit exposure of underlying loess in the shallow cuts present or, more likely, that the thin Cary loess was largely removed by Mankato glacial erosion except in the southern part of the James lobe, and at its extreme periphery.

The locations of the exposures are given below, and also are shown in figure 29. All are in road cuts except locality 3, a creek bank, and locality 6, an abandoned gravel pit.

Localities where Mankato till overlying loess is exposed

1. Southwest corner of sec. 33, T. 103 N., R. 66 W., Aurora County; also 0.1 mile south of that point.
2. Southwest corner of sec. 4, T. 102 N., R. 66 W., Aurora County.

3. Northwest corner of sec. 20, T. 99 N., R. 62 W., Douglas County.
4. 0.2 mile north of the southwest corner of sec. 3, T. 121 N., R. 73 W., Edmunds County.
5. NE¼ sec. 34, T. 98 N., R. 56 W., Hutchinson County.
6. NE¼NW¼ sec. 11, T. 97 N., R. 56 W., Hutchinson County.
7. NE¼ sec. 23, T. 98 N., R. 56 W., Hutchinson County.
8. 0.3 mile south of the northeast corner of sec. 7, T. 103 N., R. 53 W., McCook County.
9. N½NE¼ sec. 22, T. 108 N., R. 55 W., Miner County.
10. West quarter corner of sec. 13, T. 100 N., R. 54 W., Turner County.
11. Southwest corner of sec. 24, T. 100 N., R. 54 W., Turner County.

Localities where Mankato till with loess matrix is exposed

NW¼NE¼ sec. 23, T. 95 N., R. 60 W., Bon Homme County.
NW¼ sec. 7, T. 104 N., R. 53 W., McCook County.
SW¼ sec. 8, T. 103 N., R. 53 W., McCook County.
SE¼SE¼ sec. 16, T. 114 N., R. 74 W., Sully County.
North line of sec. 28, T. 94 N., R. 56 W., Yankton County.

Soil surveys (Glenn Avery, U. S. Soil Conservation Service, written communication) confirm the impression gained from this reconnaissance, that in the northern part of the James lobe the Mankato till is relatively rich in clay, whereas in the southern part it is richer in silt. The cause of the difference is not certainly known, but it may be that the southern till deposited earlier, was greatly diluted with loess, whereas the till farther north, deposited during later shrinkage of the glacier, was deposited by ice that flowed across Mankato till and not across Cary loess.

TOPOGRAPHIC EXPRESSION

GROUND MORAINE

Drift with nonlinear topography, mapped as ground moraine, covers a much smaller proportion of the region of Mankato glaciation than does end moraine. In the James River lowland and in parts of the Coteau du Missouri the local relief of the ground moraine rarely exceeds 10 feet, and over considerable areas it scarcely exceeds 3 feet. To the casual observer the surface appears flat. In contrast, in the extreme northern parts of the coteaus, in Campbell, McPherson, and Marshall Counties, where pre-Mankato relief reaches 75 to 150 feet, the little relief inherent in the Mankato drift is dwarfed by the larger relief of the surface over which the Mankato drift is spread.

Analysis of the Mankato ground moraine, in areas where it appears flat, shows that it consists of unsystematic swells and swales. The swales, 100 to 1,000 feet in diameter, lie 1 to 10 feet below the swells; average slope is therefore less than one percent. Generally the swales are distinctly visible because, owing to poor drainage, the vegetation in them differs from the vegetation on the swells. The average diameters of the swells and swales are less than those of the corresponding elements in the Cary ground moraine.

END MORAINE

HISTORY OF THE TERM

Most of the Mankato drift in South Dakota, and nearly all of it in the James River lowland, consists of end moraine. So large a proportion of end moraine to ground moraine is unknown in any region of comparable extent elsewhere in North America. This unique situation calls for detailed description of these features and an attempt to explain their development in South Dakota. Hence, although end moraines have been discussed briefly in connection with the Tazewell and Cary substages, full consideration of these features has been postponed for discussion at this point.

The term "moraine" is of French origin, but its exact derivation is uncertain. It appeared in the literature as early as 1777 (Böhm, 1901, p. 18), and in the clear descriptions of Saussure (1786–1796, v. 2, p. 10); as used, it carried a topographic implication. If the implications in these and many later references are followed, moraine can be defined as an accumulation of drift having a constructional topographic expression in detail that is independent of the surface of the ground underneath it, and having been built by the direct action of glacier ice. In this unqualified sense the word is used without a preceding article, that is, moraine.

Moraine is subdivided into two principal types: ground moraine and end moraine.

Ground moraine has always connoted the concept of accumulation beneath the glacier, back from its margin. The first worker to recognize this concept may have been Martins (1842, p. 343), who used the term "moraine profonde." This term was later translated into the German "Grundmoräne" and so into the English "ground moraine." As used by various geologists the term was given several different shades of meaning. One meaning widely quoted was expressed by Salisbury (1907, p. 257): "The drift deposited by the ice but not aggregated into thick belts at its edge is ground moraine." This meaning is not precise, in that it includes thin drift, covering but not masking predrift relief, and itself possessing no constructional topography. Such drift is not properly moraine.

In accordance with current general usage, ground moraine can be thought of as moraine with low relief devoid of transverse linear elements. Ordinarily the term is used without an accompanying article. This definition implies no specific mode of deposition, a desirable fact in that mode of deposition is not always apparent. Much ground moraine is the result of the rubbing off or lodgment upon the ground, of drift contained in the base of flowing ice. Some ground moraine, however, includes drift let down, from the upper surface of thin stagnant glacier ice, on to the ground, in consequence of ablation of the ice. While still on the glacier such drift possesses seemingly sharp local relief, most of which, however, is attributable to irregularities in the surface of the ice immediately beneath it. Penck (1879, p. 151), who was possibly the first to describe such drift, termed it "Oberflächenmoräne." Tarr (1908, p. 85, 88) applied the term "ablation moraine" to drift of this kind still resting on glacier ice in Alaska. Such drift, which is referred to here as ablation drift, is commonly so thin that after deposition it may or may not possess local surface irregularities. If there are irregularities, the drift is usually classed as ground moraine, differing little or not at all externally, though differing internally, from lodged drift. If there are no irregularities, the drift is not properly moraine at all, and is considered merely a part of a till sheet.

The history of the term "end moraine" is somewhat confused. This term has always connoted the concept of accumulation at the outer margin of a glacier. The concept was implicit in the original description by Agassiz (1840, p. 97, 124, 125), who referred to the feature as "terminal moraine," regarded it as superglacial, and apparently thought of it as accumulated at the terminal margin rather than at the lateral margins of a valley glacier. In the next year Charpentier (1841, p. 48) referred to the ridgelike accumulations of drift beyond the termini of valley glaciers as "frontal moraines." A quarter century later the term "end morraine" (in the German form), as a synonym of terminal moraine, was introduced (Dollfus-Ausset, 1864–1872, v. 8, p. 395–396), and the same author distinguished between terminal moraines and lateral moraines (Dollfus-Ausset, 1864–1872, p. 395, 410).

Since that time usage has been both varied and confused, meanings have been vague, and definitions have been often implied rather than stated explicitly. This has been true especially of the terms "end moraine," "terminal moraine," and "lateral moraine." For example, T. C. Chamberlin (1883, p. 302) proposed to restrict terminal moraine to "those moraines that mark the termination of important glacial advances," and to use another term for "those much more numerous and unimportant ones that only signify a temporary halt, or insignificant advance." This usage is undesirable because the relative importance of a particular moraine usually can not be determined until after much detailed field study of the region in which it occurs, and in many sectors the outer limits of major glacial advances are not marked by moraines of any kind. The outer limit of the Iowan drift in South Dakota is an example. Apparently these difficulties were sensed by later workers, inasmuch as Chamberlin's proposal has been followed by few.

On the other hand Chamberlin (1883, p. 301) clearly recognized that lateral moraines are built along the sides of valleys by lobes of ice sheets as well as by valley glaciers of the Alpine type.

Taking into consideration the history of these terms, and attempting to adhere as closely as possible to their original meanings, the writer will use the following definitions in describing the drift in South Dakota:

An end moraine is a ridgelike accumulation of drift built along any part of the margin of a valley glacier or an ice sheet. Its topographiy is primarily constructional.

The term is commonly prefixed by an article, indicating that a specific, defined ridge is meant. It is used also without the article, to indicate an area or a part of an extensive end moraine, or a complex of two or more individual ridges.

A terminal moraine is an end moraine built along the downstream or terminal margin of any glacier lobe occupying a valley.

A lateral moraine is an end moraine built along the lateral margin of any glacier lobe occupying a valley.

This usage provides a general term, as well as two more specific terms for use where needed. None of the terms departs far from the earliest meanings recorded in the literature.

FORM

The form of any end moraine is the initial, ice-built form modified by the effects of erosion during and since building.

The initial form appears to be a result of the amount of rock material contained in the glacier and its vertical distribution within the ice, the rate of flow of the ice, the rate of wastage in the terminal zone of the glacier, and the relative amount of melt water operative in the terminal zone. The last three factors are controlled ultimately by climatic conditions. The greater the amount of rock debris in the glacier and the greater the rates of flow and wastage, the more massive the resulting end moraine will be. Another factor, related to the rate of flow of ice and the rate of wastage is the elapsed time during which the end moraine is built. If all other factors remain the same, the greater the elapsed time the bulkier the end moraine. The amount of melt water determines in part the proportion of till to stratified drift in the moraine. Under a moist climate, particularly a climate characterized by warm rains, melt water is abundant in the terminal zones of glaciers, the drift is worked over by running water before, during, and immediately after its release from the ice, some fines are removed, some drift is deposited in stratified arrangement, and some is left as coarse residual concentrates. Under a subhumid climate rainfall is less and a larger proportion of the total ice wastage would probably occur through sublimation; hence less water would move through the terminal zone and more of the drift would be deposited in the form of till. The proportions of till and stratified drift in an end moraine affect its form, inasmuch as accumulations of coarse, permeable material possess steeper slopes than do heaps of material rich in silt and clay, and are hence much less permeable.

If the effects of erosion on initial form are considered, it can be deduced that erosion will depend on climate (chiefly amount and character of precipitation and its distribution in time), composition (chiefly as it affects permeability), and initial slope. End moraines are eroded by stream-channel erosion (rill work and gullying), sheet erosion, and mass wasting, mainly soil creep. The relative proportion of these groups of processes, determined largely by compositon, plays a major part in the resulting erosional form of the moraine.

The extent to which the initial form is converted into erosional forms is of course a function of the factors enumerated above plus the time elapsed since the moraine was built. It is determined roughly by the extent of destruction of initial closed depressions, by the concentration of coarse rock fragments occurring as a residuum on slopes, and by the extent of removal of overlying loess believed to have been deposited on the moraine shortly after it was built and before much erosional modification occurred. A very slight difference in slope makes a very great difference in erosional removal, as shown by the common absence of loess, on an otherwise loess-covered drift sheet, wherever local slopes exceed angles of a few degrees.

The end moraines in South Dakota consist principally of clay-rich till containing conspicuous stones and boulders; very little stratified drift is present in them. They vary in width from a few hundred feet to as much as 6 or 8 miles, in height to as much as 100 feet or more, and in individual length to as much as many scores of miles. None of these figures is very significant, however, because individual ridges are difficult to define, both longitudinally and laterally. The ridges occur characteristically in groups or bundles, and the members of any bundle tend to merge with each other when followed in one direction.

Despite this lack of distinctness, the end moraines in South Dakota can be roughly classified, on a basis of their form, into three groups:

1. The long, rather straight, smooth ridge, 10 feet to 100 feet or more in height and commonly half a mile to 2 miles in width. This type of ridge has little topographic variation in detail; ordinarily it is no more than a broad smooth swell. It occurs chiefly as terminal moraine, and is the kind most common in South Dakota.

2. The ridge, irregular both in ground plan and in vertical profile, consisting of a maze of knolls, hillocks, and closed depressions superposed on a massive base. This type of ridge may be as high as 100 feet or so and may be several miles in width. It occurs commonly, as lateral moraine in particular, but is less abundant than the type described above.

3. The steep-sided, sharp-crested ridge, sinuous to multilobate in ground plan and ordinarily not more than 25 feet high. Such ridges are local and are not abundant. Many ridges of this type are unsymmetrical in cross profile, their proximal slopes being steeper than their distal slopes. This type of ridge is believed to be essentially a push moraine (Chamberlin, 1894b, p. 528) ridged up at the margin of the moving glacier as snow is ridged up by a plow. The other types are believed to have been built chiefly by the lodgment or plastering of clay-rich till on to the ground from the base of the ice behind the glacier margin.

All three types are gradationally related to each other. In a single ridge or mass, changes from one type to another may be abrupt. Very likely such changes are in part the result of variations in the abundance of rock fragments within the glacier, from one radial section to another. It seems likely, however, that the distribution of drift in the ice would not account for the abrupt changes in the bulk of a moraine from place to place along its length. It seems more probable that the bulky segments of an end moraine were built in radial sectors of relatively rapid glacier flow, and that the less massive segments accumulated in sectors where flow was slower, or even at times nonexistent.

Change in the character of a single end-moraine unit, particularly moraines of the second type, also occurs within distances of a very few miles. For example a single massive moraine will consist, in one sector, of a closely compressed series of subparallel narrow ridges. In an adjacent sector the hills will be irregular and nonlinear, imparting no apparent "grain" to the topography of the moraine. The difference is conspicuous in the Altamont moraine (Mankato substage) in Deuel County.

Such changes are sometimes more clearly evident in the standard aerial photographs (scale about 1:20,000) than on the ground itself, because in the photographs more can be seen in a single view. In some places there is distinct parallel ridging in the proximal part but not the distal part of an end-moraine segment. This relationship suggests that the ridges may consist essentially of minor push moraines made by ice thrusting against an end-moraine nucleus already deposited. An example is seen in photo prints nos. CBV4–96, 4–97, 4–93, and 4–94, in the massive Cary end moraine in eastern Potter County.

In a number of sectors end moraines of various substages lose their topographic detail and even their general ridgelike form, and merge into mere belts of boulders. In some places the change from a moraine to a litter of boulders coincides with a premoraine valley in which there is evidence of flow of proglacial melt water. This relationship leads to the hypothesis that the belts of boulders are the residuum left by flushing away of the clay, silt, sand, pebbles, and cobbles that constituted most of the till in the moraine. Such a belt of boulders, here termed an end-moraine equivalent, is useful in the reconstruction of former glacier margins. Specific occurrences are described in the discussions of the various Wisconsin substages.

Certain details of the end moraines deserve special mention. Moraines of the second type (p. 113) are characterized by a maze of knolls and closed depressions developed in till. Probably most of the depressions are not kettles (basins left by the melting of masses of ice separated from the glacier) because they are irregular in detail. They seem to be merely areas between heaped-up masses of drift, analogous to the depressions between individual dunes in a field of sand dunes. A large proportion of the depressions in this kind of moraine, otherwise similar to these minor basins, have no topographic closure; they drain into adjacent basins or into streamways. Such topographic details are not the result of postglacial dissection; they are primary constructional features dating from the building of the moraines.

However, in places, the proximal slopes of some of the knolled end moraines have smoothly ovate or circular closed depressions, as large as several hundred feet in diameter. The material surrounding them is till. Their symmetry precludes their interpretation as the fortuitous spaces between constructional knolls; probably they are kettles, created by the melting of masses of ice separated from the thin marginal zone of the glacier and buried beneath till.

A good example occurs in a moraine of Cary age both north and south of Cottonwood Lake, centering in sec. 19, T. 119 N., R. 53 W., Codington County. It seems likely that thin terminal ice behind the already-built main mass of a moraine may have stagnated and separated from the glacier, and may then have been thinly covered by drift deposited by overriding ice during a renewed forward thrust. Such conditions should lead to the creation of kettles in till in the positions observed.

The kettle complexes, mostly in till and occurring in end moraines at localities where the moraines traverse premoraine valleys may be related to these closed depressions. In such localities the moraines lose their irregular constructional local topography and also, in many cases, their ridgelike character and take on the aspect of a field of smooth, rather symmetrical closed depressions. A striking example, in an otherwise smooth broad end moraine, centers in sec. 13, T. 102 N., R. 56 W., McCook County, where the moraine crosses a major buried valley. The largest single depression in this group is nearly 4,000 feet in diameter. Apparently thin terminal ice here persisted in the premoraine valley, and when, soon afterward, renewed expansion of the glacier once more brought the ice margin across the valley, it overrode the residual ice and deposited thin till on top of it. With renewed deglaciation the buried ice masses melted out and the overlying till was let down or "collapsed" around them. In this way no true morainic topography was built; kettle or collapse topography was created instead.

STRATIGRAPHIC AND HISTORICAL SIGNIFICANCE

Detailed studies of end moraines within the Central Lowland have made it increasingly evident that these ridges consist principally of terminal thickenings of individual sheets of till—that each moraine normally represents the outer limit reached by the glacier that built it, during a climatic fluctuation that caused the glacier to expand. (Willman and Payne, 1942, p. 211–225.) Any end moraine of which this is true is therefore not only a topographic unit, but a part of a stratigraphic unit (a till sheet) as well. Probably most of the end moraines in South Dakota likewise represent thickenings of till sheets that extend inward from the moraines through variable distances. A number of surface exposures show loess interbedded between two tills in such positions as to suggest that this is the case. The truth of this relationship, however, can hardly be established without the evidence of large numbers of auger borings, which can be made only when more detailed study has been undertaken.

If most of the end moraines in South Dakota are the accumulated product of the smearing of clayey till from the base of the glacier on to the ground, the thickness of the till at any place, and hence the height of the moraine as a topographic feature, must result from the rate of recession or advance of the glacier terminus. On the assumption that drift in the terminal zone of the ice is transferred from ice to ground at a nearly uniform rate, a rapid advance or retreat of the terminus (not to be confused with rate of flow of the ice itself) would spread till thinly over a wide zone, and would result, under normal circumstances, in ground moraine.

On the other hand a slow advance or retreat across a particular zone would build up a thick deposit of till in that zone, the deposit therefore assuming the form of a ridge—an end moraine. It seems likely that once a small ridge had formed, it would act as a cleatlike impediment to the flowing terminal ice, and would therefore induce further accretions of drift upon itself, and particularly upon its proximal slope. Whether the ice rode up on it continuously, or repeatedly during a series of minor fluctuations, the effect should have been much the same.

Whether built up in this way or in some other, the height of a ridge above its base constitutes the general relief; and as this relief reflects the rate of movement of the glacier terminus, which in turn is largely dependent on climate, the masses and areal positions of end moraines constitute direct evidence of former climatic variations.

The average height of the component minor knolls above adjacent minor depressions constitutes the local relief of the end moraine. This, apparently, is dependent on very local conditions of deposition and seems to have no general climatic significance.

An end moraine, then, is built by advance, or retreat, or a combination of advance and retreat, of a glacier margin across a relatively narrow belt of terrain, at a rate slower than that across adjacent terrain. It is a reflection of climatic variations.

In the James River lowland the Mankato end moraines (pl. 1) have great continuity. Beginning at the north, each consists essentially of a lateral moraine trending southerly along or parallel with the flank of one of the inclosing coteaus. At some point it alters its southerly trend and, becoming a terminal moraine, trends in a broad arc toward the axis of the lowland. None of these terminals is complete because each is interrupted by a younger lateral, the product of a renewed advance of the glacier margin. Even the youngest and innermost terminals are interrupted, either by lake sediments which have covered them up or by the James River which has eroded a trench along the axis of the lowland from one end of it to the other.

Most of the laterals merge, not into one terminal but into several. Characteristically a lateral fans out into a bundle of two, or three, or even ten or more terminals. The pattern they form is like that of branches given off from a main stem. As a general rule the stemlike laterals are relatively high and narrow, whereas the branchlike terminals are relatively low and broad. This difference is gradational; generally the farther a terminal is traced from its stem toward the axis of the lowland, the lower and broader it becomes.

This pattern leads to the inference that each lateral stem, with its branchlike bundle of terminals, was built within a single unit of time involving a marked expansion and shrinkage of the lobe of glacier ice that occupied the lowland. If the inference is accepted, then the lateral margins of the lobe must have retreated through short distances, as recorded by the narrow lateral moraines, during the times required for the terminal margin of the ice to retreat (with minor readvances) through the much longer distances recorded by the related bundle of broad terminal moraines. Stated in another way, while the terminus of the lobe was retreating irregularly northward up the lowland through considerable distances, the sides of the lobe remained pressed firmly against the inclosing higher land.

At least two factors may be involved in this differential rate of retreat. One is that because of the orientation of the lowland, the terminal zone of the glacier lobe faced south, thus receiving a maximum amount of direct insolation, with resulting relatively rapid ablation. The other and probably more important factor is that in a long, narrow glacier ablational losses are made good more easily by the short-distance flow of ice outward from the center of the lobe to its sides, than by long-distance flow down the axis of the lobe. The thinner the ice the more significant this factor would be, and the James lobe, during the Mankato subage, was very thin.

The fact that the terminals consistently become lower and broader toward the axis of the lowland seems to preclude the possibility that they are push moraines, and seems to point to the view, expressed earlier, that they are primarily the result of the lodgment of basal drift upon the ground. If they were push moraines they would mark the position of each successive readvance of the ice terminus, and should be relatively narrow from end to end. But if they are viewed as moraines built by lodgment as the ice terminus slowly advanced and then slowly retreated, their systematic change of form is explained, for the rate of retreat was greatest along the central axis of the lobe, and diminished toward its margins.

It is quite possible that some of the terminals originated as push moraines at the outer limits of minor readvances, and that thereafter drift was lodged against the nuclei thus formed, sometimes in offlapping manner and sometimes by smearing during complete overriding of the nucleus. The presence of push moraines here and there among the more common broad terminals suggests that such a sequence of events may have occurred repeatedly. But as exposures are rarely deep, and as till fabrics in these moraines have not been studied, the matter remains speculative. Certainly a push-moraine nucleus is not prerequisite to the building of moraines such as those in the lowland. Any one of them could have been started merely through the accumulation of drift by lodgment wherever and whenever the position of the terminus became stabilized owing to stabilization of climatic conditions, resulting in near equilibrium between the rate of ablation and the rate of flow.

One can hardly look at the pattern made by the end moraines in the lowland without speculating on a possible periodicity in their construction. The crests are not regularly spaced, but along the James River, on the axis of the lowland, they are spaced less than 1 mile to more than 3 miles apart, with an average spacing of about 1.5 miles. Their spacing is very much greater than ridges in Iowa (Gwynne, 1942), Quebec (Norman, 1938, p. 73), and Sweden (De Geer, 1940, p. 112), to which an annual periodicity has been ascribed. Indeed, the rapidity of deglaciation of the lowland implied by annual periodicity finds no counterpart in observations on existing glaciers during the last hundred years of pronounced glacier shrinkage.

It seems more likely that the moraines in the James River lowland represent climatic variations of longer duration, whether periodic or not. It is conceivable that the implied variations were related to sunspot frequency, as was suggested by Lawrence (1950, p. 213–220) in explanation of the variations of glaciers in Alaska.

In a few places minor lineation, apparently caused by faint ridging, is visible in air photographs of end-moraine areas, and can even be seen on close inspection of the ground. The individual aligned ridges, averaging 10 or 20 to the mile, are much more closely spaced than the morainal ridge crests shown on the map, plate 1. They parallel the crests of the major ridges in the localities of their occurrence. Good examples occur in the area southeast of Alpena, Jerauld, and Sanborn Counties (S. 30° W.), and in the area east of Wilmot, Roberts County (S. 45° E.).

It seems probable that these ridges are essentially very minor end moraines. If this is what they are, they record some kind of rhythm in the fluctuation of the former glacier margin. Their spacing seems close enough to admit the hypothesis that the rhythm could be annual. So little is known about them, however, that their interpretation remains speculative.

MAPPING OF END MORAINE

The foregoing discussion raises a problem as to the recognition and mapping of end moraine. Depending largely on the abruptness of the inferred climatic fluctuations, an end moraine may stand abruptly and distinctly above the ground moraine adjacent to it, or it may grade imperceptibly into ground moraine, especially on its proximal side. Therefore it is not possible to differentiate ground moraine from end moraine on some arbitrary basis of height, steepness, or type of topography in detail, because an arbitrary basis of mapping has no significance for the genesis of the features mapped, and leads, not to a geologic map, but instead to a rather complicated sort of topographic map. An illustration of the futility of arbitrary mapping of moraines in eastern South Dakota is the fact that in that region single ridges, evidently built at the ice margin during single short units of time, can be traced with near continuity through distances as great as 100 miles. Within these distances a moraine may change from a massive ridge 100 feet high and with a local relief of 30 to 40 feet, to a broad swell 15 feet high and with a local relief of no more than 5 feet.

Accordingly, in the present study, end moraines are identified on a basis of their form and topography relative to the form and topography of adjacent areas. Absolute relief, rigidly interpreted, has no regional genetic significance, and hence it has been disregarded in the compilation of the map, plate 1. Readers familiar with end moraines in other regions will perhaps be surprised that this map shows a greater total area of end moraine than of ground moraine. Furthermore, much of the area mapped as end moraine has very small local relief. But the drift mapped as end moraine is ridged in subparallel fashion, and the ridges combine to form a systematic pattern understandable in terms of fluctuating glacier margins. Hence the mapping is believed to be justified.

The small scale of the map has compelled some generalization. For example many small areas of low relief inclosed wholly within areas of ridged, systematic higher relief are included as end moraine. Also, small isolated knolls in broad areas of ground moraine are mapped as ground moraine, although if very closely spaced they would have justified separate mapping as end moraine. Finally, the contact between an end moraine and the ground moraine adjacent to it on its proximal side, shown on the map as a line, is in fact a gradational zone of variable width. The line therefore represents an arbitrary convention that is inherent in any mapping on a small scale.

The mapping of end moraine in areas of conspicuous premoraine relief involves the problem of discriminating between true moraine on the one hand and, on the other, bedrock hills covered with knolled drift so that they resemble moraines. This problem is acute in McPherson County and western Campbell County, where the bedrock beneath much of the area is Fox Hills sandstone, intricately dissected into knobs, buttes, and mesas. Superficially the topography of much of this area resembles that of end moraine, but exposures in many of the hills show sandstone covered with only a thin coating of drift.

Without a detailed survey, involving much augering, the exact relation of end moraine to ground moraine in South Dakota can not be mapped. In the present study end moraine was mapped only where cuts in the hills do not expose bedrock, where the topography shows no indication of a systematically stream-dissected pattern, where the surface is notably boulder-strewn, where there is a general ridge having a distinct crest, and where outwash is present in favorable locations on the distal slope and beyond the distal toe of the ridge. The result, as shown on plate 1, is consistent, and the mapping is believed to represent the true relationship in a general way, even though the area as a whole probably includes additional end moraine not recognized through the methods used in the present survey.

In some localities abrupt change in the massiveness of an end moraine may result from the presence of an isolated bedrock high completely concealed beneath the drift. As the Altamont moraine (Mankato substage) is traced northwesterly through southeastern Deuel County, it suddenly increases in height by more than 100 feet and doubles its apparent width. The change occurs in secs. 25, 26, 35, 34, and 33, T. 115 N., R. 48 W. A comparably abrupt change in a Mankato end moraine, traced southward west of Faulkton in Faulk County, occurs in secs. 4, 5, and 7, T. 117 N., R. 69 W. Similar relations are seen in the extreme southeast corner of Potter County and in the northwest corner of Hand County. Although bedrock was not found exposed in any of these places, its presence beneath thin drift is strongly suspected. An apparently massive bedrock high has been inferred in Mankato end moraine in northwestern North Dakota (Howard, Gott, and Lindvall, 1946).

Postmoraine dissection presents a special mapping problem. In areas of considerable premoraine relief such as the dissected country fringing major valleys, erosion caused by rapid runoff has destroyed much of the constructional topographic detail of end moraine. Once this detail has been lost, an end-moraine unit can be recognized only as a ridgelike thickening of the till sheet of which it is a part. However, if the till is rich in clay and if it directly overlies the Pierre shale, the presence of the ridge ordinarily can not be detected without the aid of detailed subsurface information. Such thoroughly dissected areas, which can not be proved to be end moraine by virtue of their surface form, are mapped as ground moraine. On a detailed, large-scale map such dissected areas devoid of constructional topography, which are not strictly moraine, should be mapped with a separate convention. On the small-scale map accompanying this paper they are included with the ground moraine. This system of mapping has the advantage of being based on a topographic distinction readily observable in the field, rather than on subjective interpretation. Fortunately the dissected areas are sufficiently restricted so that their mapping as ground moraine does not obscure the pattern from which the details of the history of deglaciation are inferred.

RELATION OF MANKATO END MORAINES TO CARY TOPOGRAPHY

End moraine occupies a much larger proportion of the Mankato drift area than of the Cary drift area. This difference between the two drift sheets does not obtain on the coteaus; it holds true only in the James River lowland. On the coteaus the proportion of end moraine to ground moraine in both drift sheets is about the same. From this it is inferred that Cary end moraine was once as abundant in the lowland as Mankato end moraine is now, and that in that area the Cary topography was thoroughly rearranged by Mankato glacial erosion. Effectiveness of Mankato glacial erosion is indicated by the entirely systematic arrangement of the Mankato end-moraine crests. If substantial elements of Cary topography affected the present surface, they would almost certainly be reflected in interruptions to this system.

On the coteaus, however, in the peripheral part of the Mankato drift sheet, both exposed sections and topography reveal the influence of the Cary surface. Cary moraines are only partly destroyed and are covered by thin, variable blankets of Mankato till with its own morainic expression. This condition is well displayed in the southwestern corner of Edmunds County. In some areas, as in secs. 7 and 8, T. 128 N., R. 77 W., Campbell County, pre-Mankato relief is so great that Mankato end moraines are represented only by swaths of boulders and cobbles, from which the finer matrix has been sluiced away.

PATTERN AND SEQUENCE OF MANKATO END MORAINES

Where they lie against the steep flanks of the coteaus the Mankato end moraines are high, steep, and knobby. The outermost ridge exceeds 100 feet in height in Roberts County on the east flank of the Coteau des Prairies, at places in Day and Clark Counties on the west flank of that coteau, near Tripp in Hutchinson County on the east flank of the Coteau du Missouri, and at places in Yankton County on the west flank of Turkey Ridge. Where they are high and steep, the moraines are in the position of laterals. But the corresponding terminals are broad, low, and smooth, with heights above their bases as little as 10 feet and local relief no more than 2 or 3 feet. Such terminals are not ordinarily visible on air photographs, even when examined stereoscopically.

An unpublished statement, attributed to Leverett, as to the mapping of these features runs thus: "Lie down on your face and look along the ground. If you can't see into the next forty your are in end moraine."

In the general discussion of end moraine it was pointed out that terminals "peel off," as it were, from the laterals, in sequence, and can generally be traced continuously into a main (lateral) stem. A few Mankato terminals are not connected with a stem. Examples are the small terminal northwest of Plankinton, Aurora County, and the terminals northwest of Wetonka, McPherson County. Probably the cause lies in a local lack of drift within the glacier, or in adverse factors in the local regimen of the ice.

The laterals tend to merge imperceptibly into ground moraine on their proximal sides. The terminals, on the other hand, are generally separated from each other by broad swales, some without continuous gradients and others slightly modified by proglacial stream flow. The intermoraine swales take on the trend of the swells between which they lie; they form an arcuate drainage pattern shown distinctly on the map (pl. 1). The corresponding map of Iowa does not show such a systematic arcuate stream pattern in the area of the Des Moines glacial lobe. Possibly this is because the bedrock in central Iowa is much more resistant than the Pierre shale, thus retaining a stronger pre-Mankato relief that interrupts the symmetry of an ideal glacial drainage pattern.

The fact that the trends of laterals abruptly transect the trends of older terminals immediately beyond their distal margins demonstrates irregular sequence in the building of some of the end moraines. That is, the transected terminals must represent the eroded stumps of moraines that were formerly more nearly continuous. Evidently these were abandoned during retreat, and were transected by the glacier when it later reexpanded in the form of a vigorous but narrower lobe.

As the tills of the successive readvances are not distinguishable, the fluctuations of the glacial lobe can be inferred solely from the pattern of the moraines, supported by the pattern of the outwash bodies. On this basis two principal expansions of the James lobe during Mankato time are inferred, and, in addition, a number of lesser expansions following shrinkages of unknown extent and duration.

The sequence is shown on a sketch map (fig. 31). The ice margins reconstructed on it constitute the best interpretation that can be made from the data at hand. They involve uncertainties and probably can be improved when the end moraines in adjacent parts of North Dakota and Minnesota have been mapped in detail.

In figure 31 the various positions of the James lobe are grouped into an *A* series and a *B* series, each of which clearly began with a conspicuous expansion of the ice lobe. Although there is no physical continuity between any end moraine on the eastern side of the Coteau des Prairies and any one on the western, nevertheless it is likely that the *A* series of the James lobe is the representative of the Altamont moraine of the Des Moines lobe, and that the *B* series is the correlative of the Gary moraine (Chamberlin, 1883, p. 388) and younger moraines of the Des Moines lobe.

Although they have good standing just as far as the features to which they apply can be traced without break, the names Altamont and Gary are not applied to moraines in the James lobe. This omission emphasizes the fact that correlation has not been firmly established. Not only are all the end moraines of the James lobe interrupted by breaks, but each differs in bulk and appearance from place to place in response to a number of variable factors. The practice, followed rather generally in the older literature, of naming end moraines is avoided here, not only for this reason, but because such names clutter the literature without producing a commensurate return in the form of a better understanding of glacial history. Plate 4 seems to provide all the interpretation, tentative as it must be, that is currently justified, without recourse to the complication of names.

In figure 31 it appears that the Mankato history of the James lobe involved two expansions of the glacier. The first (*A*1) carried the ice to the maximum extent it reached during the Mankato subage. The second (*B*1) succeeded a shrinkage of unknown extent. The earlier part of the shrinkage was marked by a series of minor reexpansions in offlapping sequence (*A*2, *A*3, *A*4, *A*5, *A*6). In some sectors (as *A*2 in McCook County) transection of earlier moraines proves readvance; in the others readvance is inferred by analogy, and as more probable than pause of the retreating ice margin without readvance.

The end moraine that marks the second expansion everywhere transects the earlier moraines. Its building was followed in apparently quick succession by retreat of the ice margin, punctuated by a succession of minor offlapping readvances (*B*2–*B*8), some of which transected moraines of earlier positions.

The later history is obscured by the fact that younger end moraines are partly or wholly buried beneath the deposits of Lake Dakota; indeed it is likely that in parts of Spink and Brown Counties melting of the glacier margin by the waters of the lake inhibited the building of terminal moraines altogether.

The suggestion made earlier, that the moraines of the *A* series are the correlatives of the Altamont moraine,

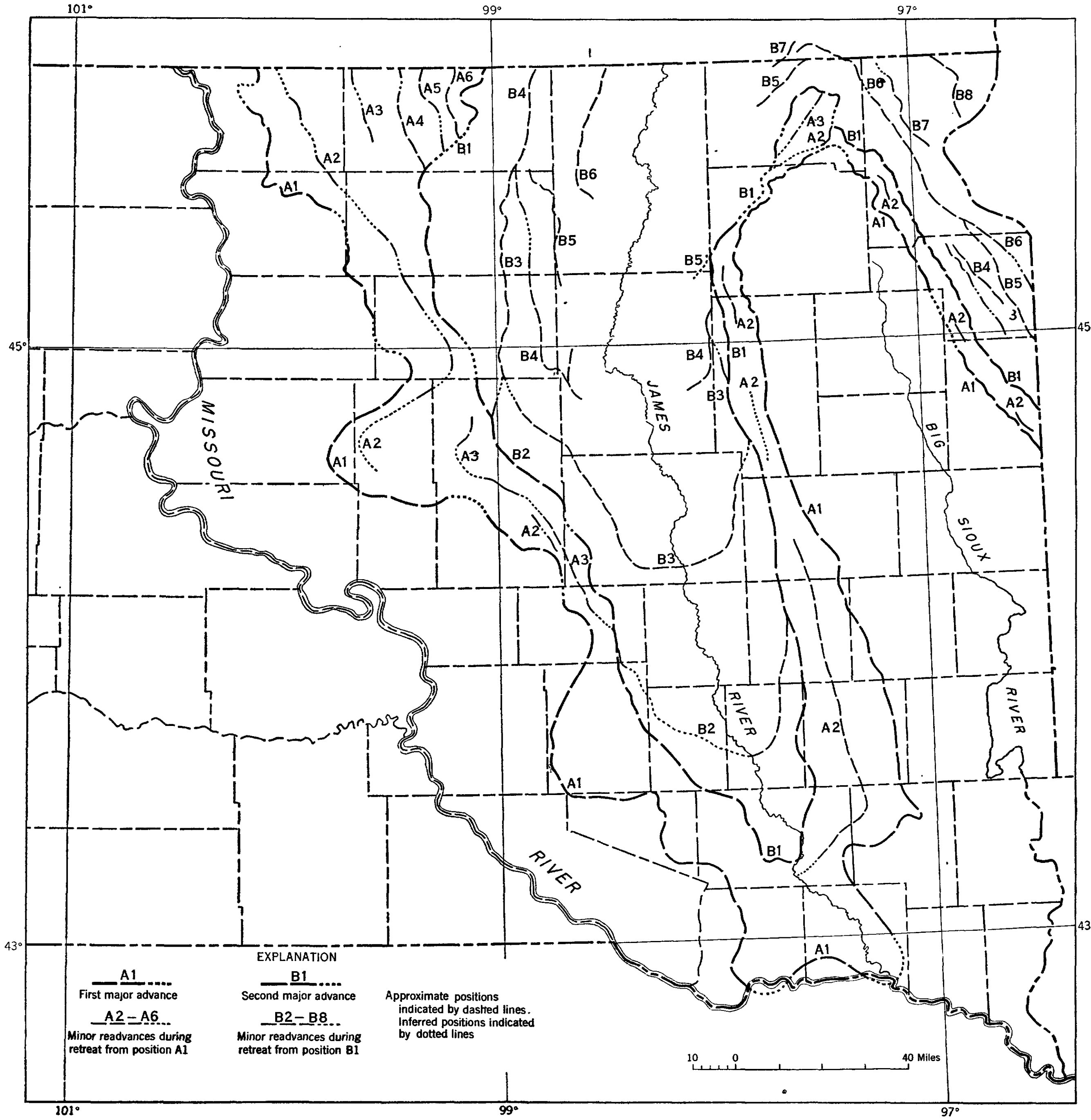

FIGURE 31.—Sketch map showing inferred successive positions of the glacier margin in South Dakota in Mankato time.

and that those of the *B* series are the correlatives of the Gary moraine, is strengthened somewhat by the fact that in most sectors the Gary moraine is less massive than the Altamont, while the same is true of the *B* moraines as compared with the bulkier *A* moraines in the James lobe. Apparently the later advance was less strong and of shorter duration than the earlier.

According to the early interpretation by Todd (1909, fig. 4), the drift identified in this paper as Cary and Mankato was marked by three well-defined and nearly continuous end moraines, each constituting the border of a drift sheet.

The interpretation presented here recognizes the discontinuities in end moraines and is based upon the demonstration that a single drift border is not everywhere marked by end moraine. It also recognizes the coalescence of terminals to form laterals. If the glacial history were to be inferred solely from the few nearly parallel end moraines of the Des Moines lobe in Grant and Roberts Counties, many details would be lost. For the probable correlatives of these ridges in the James lobe reveal complications that are obscured along the coteau where many minor ridges are crowded into a single composite moraine.

STRATIFIED DRIFT

The Mankato substage includes more stratified drift and is cut by more glacial drainage channels than the Cary substage. A part of the difference may result from the blanket of Cary and post-Cary loess, which obscures some of the Cary drift; but most of the difference is intrinsic. It indicates greater discharge of melt water in Mankato time than in Cary time. Probably the greater volume of melt water resulted in part from the fact that the Mankato ice in this region was demonstrably thinner than the Cary ice, so that its terminal zone of ablation covered a greater area. This cause is favored by the large amount of stratified drift, knolled and pitted or collapsed, which must have been built over zones of ice many miles in width. The sandy Mankato drift in Minnesota includes vast areas of collapsed outwash. Such features would be more evident in South Dakota if the drift there did not consist principally of clay and silt. These fine sediments were flushed away and were not deposited extensively on this ice at the glacier margin.

Another cause of the abundance of Mankato stratified drift may have been a climate less cold than the Cary climate, resulting in more rapid melting than that which took place in Cary time. A less-cold Mankato climate is suggested by the smaller area and thickness of Mankato ice than of Cary ice.

Whatever the causes, much melt water drained away from the minor sublobes of the James lobe, and even more conspicuously, deposited outwash along the margins of the lobe, forming narrow valley trains from 20 to more than 50 miles in length.

The directions of crossbedding and of change in grain size in these marginal outwash bodies show that the melt water flowed along the edge of the ice, usually at the proximal base of an abandoned older end moraine, and received fanlike increments of sediment from the ice at irregular intervals.

At first glance it seems surprising that the James River, which, owing to its axial position, must have discharged melt water throughout the entire time of melting of the James lobe, should not be fringed by a large outwash valley train. Actually the James has scarcely any outwash, for the outwash and alluvium shown along it on plate 1 consist mostly of alluvium. Outwash deposits and broad remnants of terraces without sand and gravel veneers are invariably at high levels and are best developed at the mouths of tributary streams. Particularly good examples occur at and below the mouth of Pierre Creek in Hanson County.

The explanation lies in the fact that the James River trench, more than half a mile wide, was created largely by the water discharging from Lake Dakota after all outwash deposition had ceased. The creation of this wide and deep trench destroyed most of the evidence of earlier melt water flow. The terrace remnants hanging high above the floor of the trench are the chief remaining record of the discharge of melt water down the James during the building of the end moraines. At that time the river was flowing on a high profile, intrenched only slightly below the general surface of the James River lowland.

A much better record of outwash deposition is gained from examination of the valleys of some of the principal streams tributary to the James: Wolf, Rock, Redstone, Marsh, and Shue Creeks on the east, and Twelvemile, Firesteel, Sand, and Cain Creeks on the west. Not having been eroded by Lake Dakota waters, these valleys still retain substantial areas of outwash. Plate 1 shows that at one place or another nearly all these valleys have "islands" of till, mostly remnants of end moraines, surrounded by outwash and alluvium. Most of the islands are small, but some, like those in Davison County, are 6 miles or more in length.

The islands were created by melt water streams that flowed around them either simultaneously or in time sequence. In order to isolate the islands the streams must have breached morainic interfluves, and the breaching in turn implies that the waters rose high enough to spill sideways out of the intermoraine depressions that confined them at first. This could have been accomplished either by deepening the water or through the deposition of sand and gravel, on which the profile of a stream could rise even though the water remained shallow.

Probably "spillovers" occurred in both ways, but most of them seem to have been of the latter sort. This is not remarkable, even though the outwash deposits are only a few feet in thickness, for the morainic interfluves are low and their crests have saddles and sags that are within only a few feet of the floors of the intermorainic swales. The whole development, in other words, was made possible by the extraordinarily low relief of the drift surface, despite the thinness of the outwash sediments.

The two largest individual areas of outwash, conspicuous on plate 1, are in northwestern Sanborn County and southwestern Spink County, respectively. The former body, lying east of the town of Woonsocket, forms a channeled plain with an area of more than 50 square miles. The sediments were brought in by Sand

Creek, which still follows the northeastern margin of the plain, at a time when the glacier lay immediately to the north. They were spread out southwestward through a broad complex intermoraine depression. The main avenue of escape for the water was southeastward down the James, but at first, owing to blocking of the main channel by the glacier margin, or to a very great volume of melt water, the discharge spilled over two low interfluves and cut temporary channels, one west of Letcher and one east of that town. The outwash body grades from pebbly sand on the northeast to silt and clay on the southwest, and its surface slopes gently downward in the same direction. The eastern margin of the plain is capped with sand dunes 5 to 6 feet high, reworked from the coarser part of the outwash.

The other large outwash mass, of nearly equal area, centers near the town of Tulare, Spink County. It surrounds many islands of till consisting of the higher parts of end moraines not buried beneath outwash sediments. The deposits, consisting mainly of sand and silt, were laid down by streams entering from the west and northwest, and the water escaped southward and eastward to the James. The large area immediately east of this body, mapped on plate 1 as outwash and alluvium, is a terrace cut into till and dotted with boulders residual from erosion of the till; it has almost no outwash deposits on its surface. The terrace dates apparently from the time of the earliest escape of water from Lake Dakota.

Other conspicuous outwash bodies occur at the margins of the sublobes projecting from the James lobe at the sites of major prediversion valleys. One lies in the triangle formed by the towns of Parker, Hurley, and Davis, in Turner County. Its surface is a faintly channeled and terraced plain more than 30 square miles in area, with an apex at Parker. The sediments are mostly less than 10 feet thick, grading from sand and pebbles near Parker to clayey silt along the southeast margin of the plain. The material was derived from ice at the site of Parker. Little was added from the substantial ice-front sector between Parker and Turkey Ridge. This can only mean that the glacial drainage extended well back upon or within the ice, and was already well integrated where it emerged. The water escaped southward down Vermillion River.

Outwash derived from the sublobes on both sides of Yankton is largely a matter of speculation, as the Missouri River has effectively undercut and destroyed most of the Mankato features standing higher than the surface of the flood plain.

A thin outwash body heads in moraines at the margin of the Mankato sublobe in southeastern Douglas County and extends southward into Choteau Creek.

A larger body fringes the margin of the sublobe in southwestern Aurora County. The sand and pebble gravel have a knolled and pitted surface, showing that they were built partly over thin ice and later collapsed as the ice melted. The chief source of melt water was the western periphery of the sublobe, which is fringed with tributary outwash through a distance of 35 miles. The water escaped southwestward via Platte Creek. The extensive area of outwash and alluvium shown on the map (pl. 1) along the southern side of the sublobe is principally silt deposited in slack water held up by the outwash body to the west. Very little sediment was contributed to the outwash from this direction.

The sublobe in southeastern Sully County created a large body of outwash, likewise fed principally by melt water that flowed along the northwestern margin of the sublobe through a distance of more than 30 miles. A secondary source, slightly later in date because its outwash lies intrenched on a profile cut into the mass just mentioned, was the stream that drains the axis of the sublobe. The time relations of the two contributions are made clear by reference to the ice-border map, figure 31. Outflow from the second source continued after the deposition of sand and gravel had ceased and cut an impressive series of stream terraces into the outwash and the till underlying it along the present route of North Medicine Creek. Escape was southwestward through North Medicine Creek.

The outwash body in Campbell and Walworth Counties is conspicuous chiefly by reason of the extensive collapse to which it has been subjected. Occupying parts of two large prediversion valleys, the outwash surface has collapse topography varying in degree of development through a 30-mile distance from south to north. As, however, the long axis of the collapsed area parallels the ice margin, this does not mean that the ice was buried beneath outwash through 30 miles back from its terminus. In the valley of Spring Creek collapsed outwash extends through a 10-mile distance from east to west; this measures the approximate maximum width of the sediment-mantled marginal ice. Most of the melt water escaped westward down Spring Creek to the Missouri River. The western (downstream) part of the outwash mass, in the neighborhood of Pollock, includes parallel-bedded lacustrine facies that suggest a blockade of some kind in the Missouri trench. The blockade may have been outwash derived from farther up the Missouri, whose present flood plain lies 95 feet below the tributary outwash at Pollock.

The heads of most of the smaller outwash bodies are collapsed in the vicinity of their places of emergence from end moraines, usually where the moraines cross prediversion valleys. A good example of both surface form and stratigraphic section, is in the W½ sec. 6, T. 102 N., R. 53 W., McCook County.

In the area of outcrop of Fox Hills sandstone in McPherson County outwash bodies are perched on the tops of sandstone-capped buttes. For example the butte 150 feet high in sec. 30, T. 127 N., R 68 W., lying midway betwen Long Lake and Leola, is partly mantled with pebble gravel. Doubtless this sediment accumulated as the thinning Mankato glacier exposed the butte top flush with the surface of the ice.

Small kames and clusters of kames occur on many parts of the Mankato drift sheet, principally on the crests and distal slopes of major end moraines. Many of them seem to be partly collapsed ice-contact outwash fans.

Mankato outwash played a very small part in the history of the Big Sioux River drainage. At no point did the eastern flank of the James lobe reach high enough on the Coteau des Prairies to send melt water into the Big Sioux. The western flank of the Des Moines lobe overtopped the coteau, and poured sediment into the Big Sioux, in parts of a 25-mile sector in Roberts, Day, and Marshall Counties only. There the distal slope of the Altamont moraine near Summit, near Hurricane Lake, and from there northward almost continuously is mantled with fanlike aprons of sand and gravel, some of which are intricately knolled and pitted. This outwash partly buries Cary end moraines in places, and also overlaps identical outwash whose relationships indicate that it must be Cary. The sequence of features here is confusing, and the position of the Mankato drift border therefore is mapped with reservations. The Mankato waters dropped their loads comparatively close to their sources, and escaped southward to the Big Sioux through channels west of Hurricane Lake and at Ortley.

These waters were supplemented by increments pouring through the deep narrow channels transecting the coteau divide in Codington and Deuel Counties. The transections, described in connection with Cary outwash, were accomplished in Cary time, and at least two of the channels were reoccupied by Mankato melt water contemporaneous with the building of the Altamont moraine. These supplementary streams carried no bed loads, for sand and gravel deposits are not found on the valley floors. The Mankato history of the Big Sioux, therefore, is largely one of erosion rather than deposition by melt water.

In the general discussion of Wisconsin outwash in South Dakota it was stated that the Cary outwash body found in borings beneath the Big Sioux valley floor lies in a basin whose northern and southern ends consist of quartzite. Overlying the outwash in this basin, with sharp contact, is a covering of 10 feet of very fine sand, silt, and clay (Rothrock and Otton, 1947, fig. 9). It is probable that the fine-grained cover is Mankato outwash, deposited here only because the proglacial stream was retarded by a quartzite barrier. Elsewhere in the Big Sioux valley, between Roberts County and this area, the Mankato streams left no depositional record that has been recognized as yet.

Local readvances of the glacier margin during outwash deposition are recorded by sections exposing till interbedded with sand and gravel in an outwash body. An easily accessible example, well-exposed in 1949, is seen in two pits in the NE¼ sec. 25, T. 105 N., R. 54 W., Lake County. At this place the outwash surface forms terraces 36 feet above the broad valley floor. Here, as elsewhere in the region, with the exception of major streams such as the Missouri and the Big Sioux, postglacial runoff probably is inadequate to have accomplished such intrenchment. The postoutwash cutting is better explained as the work of melt water flowing past this point after the glacier had retired from the immediate vicinity. The notoriously small bed loads carried by such streams lend credence to this explanation.

Fine-grained outwash sediments occupying a depression between two of the younger Mankato end moraines in Edmunds County have yielded the skull and several bones of a mammoth, collected in 1949 in sec. 26, T. 124 N., R. 66 W., and identified as *Archidiskodon* sp. by Dr. J. D. Bump, South Dakota School of Mines and Technology.

LAKE DEPOSITS

MINOR GLACIAL LAKES

Small areas of parallel-bedded silt and clay, chiefly on the coteaus, record the former presence of local and temporary lakes ponded between the margin of the shrinking Mankato glacier and higher ground beyond it. Like most small lakes dammed by glaciers, these water bodies seem to have been short lived because no strand lines or other shore features were formed around the margins of the lacustrine deposits. Many are too small to be shown on the scale of the map, plate 1. Those shown on the Coteau du Missouri occur in secs. 33 and 34, T. 118 N., R. 71 W., Faulk County, and in Hand County in the northern part of T. 112 N., R. 69 W., and the eastern part of T. 114 N., R. 70 W. In the Coteau des Prairies similar sediments are shown in the southern part of T. 125 N., R. 55 W., Marshall County, and in T. 120 N., R. 58 W., and adjacent townships in Day County. In the latter occurrence an outwash fan on the distal slope of an end moraine grades outward (in secs. 7, 8, and 9, T. 120 N., R. 58 W.) into lacustrine silt.

It is probable that other lakes—perhaps many others—existed, held between glaciers and the slopes of the coteau, and that their sediments have been either buried beneath till during readvances of the glacier margins or washed away by local runoff after the lakes were drained.

GLACIAL LAKE DAKOTA

Eastern South Dakota includes parts of the areas of two large former glacial lakes. As a part of the shoreline of each of these lakes was the glacier itself, the lakes existed only as long as glacier ice on their northern sides acted as a dam. The smaller of the two, Lake Dakota, was named (Todd, 1885, p. 393) and described by Todd (1894, p. 125; see also Todd, 1896, p. 52–53; 1899, p. 125; Upham, 1895, p. 266) who first conceived it as having extended from the northern end of the State southward as far as Mitchell and as having attained a depth of 150 feet. The great southward extent inferred by Todd apparently grew out of his early interpretation of ground moraine and end moraine of very low relief as part of a lake floor, and possibly also out of the presence of Sioux quartzite exposed in the floor of the James River trench, below Mitchell, as a logical dam for a lake. After further study, Todd (1909) reduced the inferred area of the lake to approximately that shown on plate 1 in the present paper, and viewed the water as the temporary expansion of a flood of melt water, escaping from the glacier in southern North Dakota, and retained by a bottleneck, the narrow valley of the James River. In this general interpretation the present writer concurs. Aspects of Lake Dakota are treated briefly by Hard (1929, p. 40–41) and by Rothrock (1946b, p. 13, 20–21).

DESCRIPTION OF LACUSTRINE FEATURES

Lake Dakota is now represented topographically by a plain of remarkable flatness, having a local relief (exclusive of sand dunes) of less than 3 feet. The northern end of the plain lies along a northwest trending end moraine near the town of Oakes, Dickey County, N. Dak., about 15 miles north of the South Dakota State line (Hard, 1929, pl. 2). The southern end funnels into the James River trench near the Spink County-Beadle County line. The area of the plain within South Dakota exceeds 1,800 square miles. Near the State line the average altitude of the plain is 1,305 to 1,310 feet. Near its southern end, its average altitude is 1,295 to 1,300 feet. The southward slope is therefore very slight.

Although flat, the plain is not level. Its northeastern part is partly covered by conspicuous sand dunes. It slopes imperceptibly inward toward the James River from both sides, and in places slopes faintly in other directions, perhaps in part reflecting the surfaces of buried end moraines and in part owing to thin overlying windblown sand and silt. The plain is cut not only by the James River, which flows down its axis, but also by a number of subparallel and interconnecting shallow channels of later date than the plain itself.

The sediments underlying the plain are thin. As reported by drillers the maximum thickness of the Lake Dakota sediments occurs along the general line of the James River and reaches 30 to 40 feet. In the North Dakota part of the body, Hard (1929, p. 41) reported thicknesses of 5 to 35 feet.

The lacustrine deposits consist primarily of silt, with accessory fine sand and clay. The silt is grayish yellow to yellowish gray and is little compacted. It is parallel laminated subhorizontally, except in the uppermost 1 to 2 feet, where lamination is not evident. The nonlaminated upper part may have lost its stratification through the mechanical action of frost, plant roots, worms and other animals, and cultivation, or it may have been reworked by the wind. Most of the silt is calcareous, but the uppermost part is leached in places to depths as great as 1.3 feet. A conveniently situated exposure of the silt is a cut on State Highway 47 in the NW¼ sec. 30, T. 113 N., R. 61 W., Beadle County.

The clay occurs chiefly as rare laminae interbedded with the silt, from which it is not sharply separated. Some of the sand occurs similarly in close association with the silt. However, along the James River in northern Brown County, sand predominates and is distributed in such a way as to suggest facies change, with coarse sediment along the river grading eastward and southward into silt and clay.

No erratic stones were seen imbedded in the lacustrine sediments, but, as exposures are few and shallow, this does not mean that erratics do not exist.

In view of the very large proportion of clay in the till, the fact that clay is a minor constituent of the Lake Dakota deposits, at least as seen in exposures, requires explanation. Probably at least two factors are involved in the discrepancy. The lesser factor is that only the stratigraphic upper part of the sequence of lake sediments is exposed. This part was laid down relatively late in the history of the lake when the bottom had been built up by earlier sedimentation, when the water was therefore comparatively shallow, and when current velocities were correspondingly great. Such conditions would have been optimum for bypassing of the lake floor by clay particles suspended in the water. The clay fraction in transport should have been carried through the lake and into the outlet stream, to be exported from the region. The factor that is probably more important is the extension of this concept to the entire thickness of Lake Dakota deposits. Probably there was a considerable current flowing through the lake, and the presence of wave-built features at and near the margins of the area of lake sediments records wave activity that would have operated to keep the bottom deposits stirred up. It seems likely that conditions quiet enough to permit the settling of clay particles may have existed only locally and temporarily on the lake floor.

The eastern and western limits of the area of lacustrine sediments are marked in some places by a distinct steepening of the slope, where the sediments rest against the flank of an end moraine. In other places, particularly in Day and Marshall Counties, the contact of silt on till must be located by auger borings, as it is not visible in the surface except through a zone 2 or 3 miles wide, through which the topography becomes subtly more irregular. The blanket of eolian sediments that covers the eastern part of the plain, and that extends several miles eastward from it, tends to make the contact even less distinct.

Constructional shore features are present locally along the eastern margin of the lake sediments from southwest of Conde to west of Doland, in Spink County, and are shown on the map, plate 1. They take the form of ridges as much as 3 miles long, 350 feet wide, and 18 feet high. Of several good exposures, perhaps the best is in a gravel pit at the north quarter corner, sec. 11, T. 118 N., R. 61 W., 2 miles west of Turton, where a 6-foot section of sand and pebbles, poorly sorted in crude beds that dip gently west, parallels the western slope of the ridge. The pebbles are worn but are not well rounded. The ridges are clearly wave built, their sediments having been derived from till in their immediate vicinity. Probably storm waves moved the sand and pebbles inshore, piling them up on beaches or bars, at the same time shifting the silt and clay westward into deeper water.

The ridge at the place described above lies 2 miles west of the contact between lake sediments and till. Hence, if it was built at the time of maximum extent of the lake, the ridge must have been a bar separated from the mainland by a lagoon. If built during the shrinkage of the lake, it may have been a beach thrown up at the shoreline itself. Similar ridges farther south, however, lie very close to the contact, and are therefore best described as beaches.

The highest parts of the ridges are less than 20 feet higher than the lowest part of the lacustrine plain along the James River in the same latitude. This figure, however, does not necessarily measure the depth of water at the time of beach building. For there is reason to believe that the lake contracted slowly from its extreme extent, and that deposition continued in the central part of the area after the strandlines at its outer margin had been abandoned.

The fact that recognizable wave-built features are confined to the southern sector of the eastern shore of the former lake strongly implies the operation of northwest winds. Shore features have been found nowhere else, despite the lack of conditions for their erosional removal. The implication is clear that only northwest winds, which are today the strongest winds in the State, were able to create beach-building waves. It is interesting to compare this implication with the development of wave-cut cliffs by small recent lakes, particularly on the Coteau des Prairies. The cliffs are almost invariably best developed in the southeastern segments of those shores, implying the effectiveness of northwest winds.

This evidence of the effectiveness of northwest winds in times of glacial climate as well as more recently agrees with evidence from the distribution of loess, which is generally thickest southeast of suitable source areas, and of dune sand (p. 132).

RELATION TO END MORAINES

In a few places very broad, low end moraines continue southward as topographic features beyond the points where their crests become covered with lacustrine sediments. The sediments are so thin that they do not wholly mask the morainic ridges, in some cases through distances of several miles. This situation is seen southwest of Britton, Marshall County, between Aberdeen and Warner, Brown County, and in southeastern Spink County.

The relationship described implies that the moraines were built before lacustrine deposition came to an end. Some confirmation is derived from the log of a well at Northville, Spink County, which penetrated 45 feet of "yellow fine sand" and then 25 feet of "blue" (that is, unoxidized) till before entering bedrock. The first-named sediment probably represents a contribution of sand by a tributary, Snake Creek. The unoxidized character of the underlying till, unusual for Wisconsin till in this region, suggests that submergence occurred as or soon after the melting glacier ice uncovered the till.

More substantial confirmation comes from the character of the end moraine on which the town of Britton, Marshall County, is built. The distal slope of this moraine is mantled with outwash, which grades southeastward with diminishing grain size into the silt and clay of Lake Dakota. It seems clear that the glacier terminus was standing along the line of this moraine while the lake was still in existence. A high-standing mass with irregular topography, 6 to 10 miles northwest of Britton, although covered with lacustrine sediment, probably is another slightly younger moraine that may be the equivalent of the Oakes moraine (Hard, 1929) in North Dakota. This mass, too, antedates the draining of the lake.

It may well be that end moraines were not generally built in the ice-margin sectors that lay in the central part of the lake. The lake water in those sectors may have been able to remove fine sediments in suspension, and the coarse fraction may not have been sufficiently bulky to create a moraine.

OUTLET

At the southern end of the Lake Dakota area the lacustrine sediments thin out along a line that is sharply convex toward the south, in southern Spink County. The line is marked by no topographic change. South of it the surface continues to be flat, but instead of being underlain by silt, it consists of till with a concentrate of boulders scattered upon it. This surface is flatter than any ground moraine; this fact and the concentrate of boulders indicate that it was planed by flowing water. With an area of about 75 square miles, this surface narrows southward and funnels into the James River, not at the level of the floor of the James River trench, but well above it, and not far below the altitude of the morainic surface into which the trench is cut. The flat surface cut into till, like the lacustrine plain north of it, is itself sharply incised by the James River trench.

From these relations emerges the concept of a lake spilling southward across a broad low divide consisting of till, the outflowing water having eroded till at the divide, although it was unable to transport the boulders it discovered.

East of the broad cut surface, in part separated from it by a peninsular mass of end moraine and approximately flush with it in altitude, is an area of 30 square miles of lacustrine silt, incompletely masking the crests of at least two very low end moraines. This appears to represent an embayment or backwater at the extreme southeastern end of the former lake, in which fine sediment was trapped, but which did not undergo the later planation that affected the till surface west of it because it was protected from the outflowing current by a morainal barrier.

The James River trench, downstream from the broad planed surface just described, is the cut made by the discharge that spilled out from the lake, and that continued even after the lake had been drained. It is a simple, steep-sided trench with a flat floor that averages more than half a mile in width. The floor narrows to a quarter of a mile where resistant bedrock is exposed and widens to a mile or more where only the weakest glacial deposits form its walls. Fifty feet deep at Huron, the trench deepens to more than 100 feet near Mitchell, a depth which it maintains to within a few miles of its mouth.

The trench is a single cut. Except near its mouth it does not contain terraces. Its form is not that of a nested series of funnel-shaped channels, each related to one of the recessional end moraines transected by the river. Hence the trench is not the product of erosion by melt-water streams originating in the many end moraines. Evidently it postdates all the moraines.

The trench is cut into till, but in many places in Davison, Hanson, and Hutchinson Counties it cuts through the till into bedrock (the Codell sandstone member, Carlile shale, and Sioux quartzite). The rock outcrops are responsible for variations in the width of the trench and also the gradient, which steepens appreciably through the segment embraced by the outcrops of quartzite and sandstone. Despite its resistance, however, the bedrock has not caused rock-defended terraces to form.

Sloping surfaces of Sioux quartzite are exposed in the trench floor at two places in Hanson County, but in neither place does the quartzite completely floor the trench. In one of them, 6 miles southwest of Alexandria, the quartzite forms a massive boss, with a summit 40 feet above the river, standing in the center of the trench and showing little evidence of stream erosion. The rock preserves delicately striated and polished surfaces, thus clearly showing that erosion of the overlying drift was very rapid; the flowing water did not pause long enough at any one profile to permit abrasion of the quartzite, although such abrasion is evident on similar quartzite exposed in the beds of quite minor outwash streams.

The broad surface cut into till at the lake outlet continues down the James, through most of Beadle County, as narrow, discontinuous benches cut into till and dotted with residual boulders.

The floor of the James River trench, which is also the flood plain of the river, is graded to an extensive terrace in the Missouri River trench, standing 5 to 20 feet above the Missouri River flood plain, and 15 to 30 feet above the mean low-water profile of the Missouri (H. E. Simpson, written communication). This fact leads to the inference that at the end of the episode of great discharge that cut the James River trench, the Missouri River was flowing on a profile some 5 to 20 feet higher, measured at Yankton, than its present profile.

The larger tributaries to the James, nearly all of which are intermorainal, have flood plains graded to the floor of the James River trench. Above these flood plains stand the remnants of outwash valley trains, as thin caps on terraces cut into till (fig. 15). The flood plains possess steeper gradients than the dissected outwash bodies in the same valleys. These relations indicate that the outwash streams flowing down the intermorainal valleys on gentle gradients, and carrying small bed loads, widened the valleys and deposited gravel and sand on their floors but deepened them very little. Conversion of the valley trains into terraces took place chiefly during the episode of deep trenching by the James, when the James glacial lobe had shrunk to and beyond the northern limits of the State. Trenching by the James caused progressive headward rejuvenation of its tributaries. As in the James River trench itself, rapid incision is indicated by the lack of intermediate terraces in the tributary valleys. Only a few tributaries, such as Firesteel Creek in Davison County, have an intermediate terrace.

Not only is the James River trench reflected in intrenchment by its tributaries; the trench itself extends north, upstream, into the Lake Dakota plain. The cut is about 45 feet deep at Redfield and 25 to 30 feet deep in the latitude of Aberdeen. It continues northward to and far beyond the northern end of the lacustrine plain in North Dakota.

The data on the James River trench, outlined above, point to erosion by the outflow from a lake, persisting throughout the duration of the lake and continuing for a considerable time thereafter. The hypothesis that the trench was primarily a response to incision by the Missouri is rejected because of the narrowness of the James trench and because of its lack of terraces. The great width of the Missouri trench and its freedom from Mankato glacier ice, downstream from the Yankton area, require that any incision by the Missouri at that time should have been very slow. And slow downcutting by the Missouri could not have been the sole cause of a trench like that of the James.

INFERRED HISTORY

The history of Lake Dakota and its outlet begins with the ponding of water between the James glacial lobe and the proximal slope of an end-moraine complex in northern Beadle County. Northward from this area the general slope of the till-covered bedrock surface is toward the north, through the breached Ancient Redfield divide (p. 149) and down its northern slope. Hence the lake, once formed, could persist as deglaciation progressed, as long as erosion of its outlet failed to lower the lake to the point of extinction. With deglaciation, the lake lengthened until it reached its maximum length of more than 100 miles, and the glacier margin stood at the Oakes moraine in North Dakota (Hard, 1929, p. 40). From its inception the lake had spilled southward through the James River valley, then a high-level, shallow valley created by the runoff of melt water from the James lobe throughout the time between the Mankato maximum and the beginning of ponding. The lake had no sharply localized dam. The dam consisted of the entire segment of till traversed by the James from northern Beadle County to its mouth, a distance of well over 100 miles. In order to drain the lake the outlet had to be lowered 40 feet or more throughout part of this segment. The outflowing water, carrying fine silt and clay but free of coarser sediment, planed the till at the northern end of the dam, funneled into the James, and established a profile graded to the Missouri. The vertical position of the Missouri at Yankton at that time is unknown; probably it was not far above the terrace to which the James River flood plain is graded.

The position of the outer margin of the lake sediments is so obscure that it has not been determined whether this margin represents a single, contemporaneous shoreline. It seems likely that it does not; that the margin is of various dates in various latitudes, determined by glacier shrinkage and by lowering of the outlet. At least fluctuation of level was small enough to permit the accumulation of a broad deposit of lake sediments, having a nearly uniform surface, throughout a very large area. Depth of water cannot be inferred from strand lines, for sedimentation undoubtedly continued in the central part of the basin after the area of the lake had contracted owing to lowering of the outlet. All that can be said is that the maximum known thickness of lacustrine sediment—perhaps 45 feet—measures the minimum depth of the water at the same point.

Although the lake sediments consist chiefly of silt, sand is present along the James River in northern Brown County, and continues into North Dakota. Exposed sections, which are both few and shallow, do not establish the time relationship between sand and silt; it may well be, however, that the sand was deposited at a relatively late date, when the lake had shrunk considerably and when its depth was correspondingly reduced.

As the lake shrank, tributary streams extended themselves across the emerged floor, and the main discharge, coming from North Dakota, concentrated along the line of the present James River. During this process the current occupied an elongate network of temporary overflow channels (pl. 1) in southern Brown County and western Spink County. Lake Dakota, therefore, came to an end by degrees and was only gradually converted into the James River. Trenching by the James continued, however, long after the lake itself had disappeared, as shown by the fact that the lake sediments are trenched from end to end. This implies a continued large inflow of water from north of the lake area.

Such an inflow did in fact continue for a considerable time after the shrinking glacier abandoned the Oakes moraine (Hard, 1929, p. 40). It came via the upper James, which was then draining a substantial segment of the glacier margin in North Dakota. According to R. W. Lemke (oral communication) the James River in North Dakota continued to carry glacial water long after the draining of Lake Dakota. It carried outflow from the southwestern part of the Lake Souris basin, possibly originating in glacial Lake Regina, down to the time shortly before the inception of glacial Lake Souris.

The volume of drift and rock eroded by the stream discharging from Lake Dakota was large, but only a very small proportion of it consisted of fragments large enough to be moved along the stream bed. Most of it consisted of clay and silt sizes, which entered into the suspended load along with the fines received from Lake Dakota. It is not likely that much of this fine sediment was deposited in the Missouri Valley immediately downstream from the mouth of the James. Probably most of it was exported entirely from the State.

POSSIBLE EARLIER LAKE DAKOTA

Two features of the till in western Spink County suggest that an earlier Lake Dakota, antedating the Mankato drift in this district, may have existed. One is that the Mankato till in this region is conspicuously rich in silt, in contrast with the till in eastern Spink County, which is very rich in clay. It is possible that the silt was concentrated by lacustrine agency, and that it was plowed up by the Mankato ice from the district to the north and east, and incorporated in the till. This is the district in which a pre-Mankato Lake Dakota could be logically expected. The second feature, which reinforces the evidence to some extent, consists of the presence of a large mass of laminated silt and fine sand, compacted and incorporated in till in a cut exposed in 1948 in the southeast corner of sec. 32, T. 114 N., R. 65 W.

Both bits of evidence are put on record for the benefit of future more detailed study.

GLACIAL LAKE AGASSIZ

Glacial Lake Agassiz, the most extensive of the glacial Great Lakes, is well known through the work of several geologists, notably Upham (1895). Larger, when at its maximum extent, than the present Great Lakes combined, Lake Agassiz occupied the basin of the Red River, and a wide region to the north, and overflowed southeastward through the Minnesota River to the Mississippi.

The outlet of this great lake, and a small part of its now-dry floor, lie in the northeastern corner of South Dakota. The lake and outlet features in this area were mapped in detail by Leverett (1932, pl. 5 and p. 119). Leverett's mapping is reproduced without important change in plate 1 of the present paper, and his interpretation of the lake history, in part after Upham, is very briefly summarized here.

The earliest phase of Lake Agassiz is represented in South Dakota by a sand beach at 1,100 to 1,120 feet and by accompanying lake-floor silt. These features record the early and short-lived Milnor phase, when Lake Agassiz was relatively small. The outlet of that early phase was through two Y-shaped branches of Cottonwood Slough emptying into the Lake Traverse channel in the SW¼ T. 126 N., R. 49 W., Roberts County.

Later phases of the lake are represented by a series of beaches and lake-floor deposits at successively lower altitudes. Of these the Herman, Norcross, and Tintah strand lines are present in South Dakota. After the Milnor phase ended, the outlet stream flowed first westward and then southward via the east fork of the Y-shaped Milnor outlet. This is known because the floor of the west fork hangs 60 to 80 feet above the floor of the east fork. Later the Milnor outlet was abandoned in favor of the main outlet, the deep trench now occupied by Lake Traverse and Big Stone Lake, which was used (possibly with a long interruption during which Lake Agassiz ceased to exist) until deglaciation opened a lower outlet eastward through Canadian territory. Like the James River outlet of Lake Dakota, the segment of the main Lake Agassiz outlet that lies within South Dakota is cut into drift and, in places, into the bedrock beneath the drift.

CRUSTAL WARPING

Warping of the crust, in consequence of the building up and removal of the extra loads created by massive glaciers, has been inferred in many regions from the warped attitude of strand lines made by glacial lakes and by the sea during deglaciation.

The Lake Agassiz strand lines (Upham, 1895) have long been known to be warped up toward the north, but the rate of increase in their altitudes decreases toward the south in such a way that Leverett (1932, p. 132) concluded that the extreme southern area of the lake bed may not be warped at all. At least no evidence has been brought forward to show warping of the Lake Agassiz area within South Dakota..

Because most of the bed of Lake Dakota lies south of the area of Lake Agassiz, little if any warping of the Lake Dakota area is to be expected. Upham (1895, p. 267) concluded, by reasoning from indirect evidence, that "the long area of Lake Dakota has experienced only slight differential changes of level, at least in the direction from south to north, since the departure of the ice."

It is probable that Upham was right, but as the strand-line features are the only known basis of accurate determination of such warping, and as precise leveling measurements on them have not been made, the question remains unanswered. The relative thinness of the James glacial lobe in Mankato time, shown by the failure of the Mankato drift to overtop the Coteau des Prairies except at its extreme northern end, militates against crustal warping beneath that ice lobe at that time.

However, glacier ice is known to have overtopped the coteaus in Iowan time; hence if any warping occurred in northeastern South Dakota, it is more likely to have been brought about by Iowan ice than by one of the post-Iowan glacial invasions.

LOESS

Eolian deposits of recognizable thickness overlie the Mankato drift only very locally, principally in three kinds of occurrence: cappings, 2 to 4 feet thick, on outwash bodies; areas along the drift border, particularly the western border of the James lobe, in the vicinity of major bodies of outwash and lacustrine sediments; the outcrop area of the Fox Hills sandstone.

Fine sand constitutes a conspicuous proportion of these sediments, perhaps because the more hospitable Mankato climate permitted vegetation to cover the source areas more quickly than in earlier subages, thereby protecting them against the long-continued deflation necessary to build up a general silt blanket far to leeward. Much of the Mankato eolian material, therefore, is not strictly loess. But as it includes loess and is genetically the same as loess, it is treated as loess in this discussion.

The thickest and most general Mankato loess blanket occurs in Bon Homme and Yankton Counties; its source was certainly the Missouri trench which then was covered by fine-grained outwash. Sandy loess as much as 6 feet thick is seen at the crest of the river bluff in Bon Homme County, thinning within a few miles to unrecognizability. Thicknesses as great as 5 feet have been found in eastern Yankton County. The loess, patchy at best, thins out northward and disappears.

One to three feet of loess are found upon the peripheral part of the Mankato drift at the western margin of the James lobe.

A belt of country from 1 mile to 5 or 6 miles wide, lying immediately east of the Lake Dakota plain and overlapping the plain itself, is mantled with a thin, discontinuous covering of wind-blown silt, indistinguishable, except for its lack of stratification, from the lake deposits from which it was obviously derived. Similar veneers of eolian silt overlie lacustrine deposits on the Coteau des Prairies at various places in Day and Marshall Counties.

Except for occurrences within the Missouri River trench, this material seems to have accumulated during the deglaciation of the State and not to have received important increments within very recent time. Soil profiles in Cary and post-Cary loess on flat surfaces in Sully County within 10 miles of the Missouri River trench, examined in conference with pedologists, include secondary clay developed within the topmost 12 inches of the profiles, thereby suggesting that no loess has been deposited there since the Mankato maximum and possibly not since Cary time.

SOIL PROFILE

The soil profiles developed in both the Cary drift and the Mankato drift are very immature. In both, downward movement of carbonates has been slight, and the formation of secondary clay has been even slighter. Nevertheless, according to W. I. Watkins, formerly of the Division of Soil Survey, U. S. Department of Agriculture (oral communication), who is familiar with these soils in South Dakota, there is a faint difference between soil profiles developed in these two drifts, in that those in the Mankato drift are slightly more immature.

In a few places loess overlying deposits believed to be Mankato contains buried soil zones, recording alternating episodes of loess accumulation and soil development. The most striking of these exposures is described in the following measured section:

Cut bank in face of terrace near southwest abutment of Fort Randall Dam, in the SW¼ sec. 8, T. 95 N., R. 65 W., Gregory County, S. Dak.

[Exposed in July 1946. Thicknesses, within total vertical range, in part estimated from a boat, as bank is vertical and caving into river]

	Feet
Nearly flat surface of terrace.	
9. Loess, yellowish-gray, sandy; no soil zone	2.0
8. Humified soil zone	0.7
7. Loess, like unit 9	5.5
6. Humified soil zone	2.0
5. Loess, like unit 9	8.0
4. Humified soil zone	0.7
3. Loess, like unit 9	15–28
Contact sharp, horizontal, parallel with stratification of unit 2.	
2. Silt and clay, parallel-laminated horizontally, compact	15–30
Sharp erosional unconformity.	
1. Gravel, containing waterworn boulders, and cobbles with overlying laminated silt, maximum	20
Total exposed	48.9–76.9
Unit 1 in borehole below river surface	11.0
Actual vertical thickness	86

A similar exposure 1,000 feet farther southwest, visited in September 1950, showed the same sequence but with somewhat different thicknesses.

Too little is known about this section to justify correlation in detail. Unit 1 is believed to be probably Cary; 2, probably Mankato. If unit 2 is Mankato, then units 3 through 9 postdate the Mankato maximum and the soil zones possess no substage value. Unit 9 is probably very recent, as no soil zone is developed at its surface.

DATE OF MANKATO MAXIMUM

The Mankato substage is the only one of the stratigraphic units in eastern South Dakota whose date can be even approximately fixed in absolute terms, that is, in terms of the number of years elapsed since its deposition. Dating is made possible through correlation with the till overlying a layer of peat and wood at Two Creeks, Manitowoc County, Wis. The peat layer represents a subarctic spruce forest that was submerged in a lake dammed in front of the advancing margin of the Mankato ice sheet, overridden, and covered with till. As the forest locality is less than 25 miles inside the limit of the Mankato drift sheet, it is probable that the trees were killed by drowning only a few hundred years at most, and perhaps much less than that, before the Mankato maximum.

Specimens of tree trunks, a tree root, and the peaty plant matter in which the trees grew have been dated by the radiocarbon method (Arnold and Libby, 1949) and have been found to have died about 11,400 years ago. From this date it is inferred that the Mankato maximum occurred about 11,000 years ago or a little earlier (Flint and Deevey, 1951, p. 263).

The Laurentide Ice Sheet in Mankato time, responding to fluctuations of climate, may have reached its maximum extent at different times in various sectors. If the Mankato drift in South Dakota is of the same age as the drift currently called Mankato in Wisconsin, then it is of the order of 11,000 years old. The immaturity of the soils developed on Mankato drift is believed by soil scientists who have studied them to be consistent with a date of drift deposition of this order of magnitude (James Thorp, Soil Correlator, Great Plains States, U. S. Department of Agriculture, written communication).

SUMMARY OF WISCONSIN STRATIGRAPHY

The data assembled in the foregoing discussion afford a firm basis for the belief that the Wisconsin stratigraphy of eastern South Dakota is four-fold. They indicate further that the Tazewell-Cary interval is represented by a much more important break than are either the Iowan-Tazewell interval or the Cary-Mankato interval. Indeed the two lesser intervals may have been so unimportant as to constitute grounds for questioning the substage value of the stratigraphic units they separate. This question cannot be settled on a basis of the evidence so far uncovered in South Dakota. It is a regional matter, which must be viewed throughout the whole sector from the Missouri River to the Great Lakes.

The fourfold stratigraphy of the Wisconsin stage stands in contrast with the simpler stratigraphy recognized thus far within the pre-Wisconsin glacial stages, for, not only in South Dakota but elsewhere in North America, no distinct substages have yet been identified in the pre-Wisconsin drifts, although the presence of buried soil zones in the Loveland loess in eastern Nebraska may prove to indicate substages within the Illinoian stage. As the pre-Wisconsin glacial deposits have lost much by erosion and are relatively poorly exposed, the difference between Wisconsin and pre-Wisconsin may be only apparent instead of real. Whether this is the case, or whether there is an intrinsic difference between the Wisconsin drift sheet and its predecessors, remains an unanswered question.

RECENT DEPOSITS AND RELATED FEATURES

ALLUVIUM

Since the disappearance of glacier ice from each part of the region, glacial melt water has been replaced in the stream valleys by discharge from local precipitation; glacial regimens have been replaced by the regimens now in operation. This change occurred in various parts of the glaciated region at somewhat different times.

Because of the small scale of the map (pl. 1), alluvium is not differentiated from outwash. Included in it also are areas of swamp muck, eroded till, bedrock, and Lake Dakota silt occurring beneath valley floors with no recognizable stream deposits overlying them.

In the James River lowland, alluvium is rather generally distinguished from outwash by the fact that it covers valley floors, whereas the outwash covers terraces. This clear distinction arises from the episode of valley deepening within the James River drainage system that accompanied the draining of Lake Dakota. A similar distinction is not met with in the other drainage systems of the region.

Along the smaller streams deposits believed to be postglacial are thin and relatively fine grained, reflecting the small gradients and small competence of most of the streams. During the spring season these streams overflow, their valley floors become swampy, and silt and clay are deposited. During the rest of the year stream activity is negligible.

The Missouri River, however, carries large quantities of fine sand and silt through the region, and continuously alters the channel pattern along its valley floor. The thickness of the postglacial part of the fill that lies within its bedrock valley has not been ascertained because the date of the sand, with subordinate silt and clay, that constitutes the bulk of the alluvium beneath the river is unknown.

Only in the region extending downstream from the vicinity of Yankton does the river possess systematic meanders. Upstream from that point its valley is narrow, and the stream seems to be in a condition intermediate between a meandering regimen and a braiding regimen. This condition may result from its heavy bed load of fine sediment, too great to permit meandering yet not great enough to cause ideal braiding.

Strong sedimentary upbuilding of its valley floor by the Missouri has affected many tributaries carrying less sediment than the main stream. Where these tributaries enter the Missouri River trench they do not continue directly to the channel of the main stream. Instead they turn down the trench, hugging the trench wall through considerable distances in some cases before joining the Missouri. The following tributaries shown on plate 1 behave in the manner described: Big Sioux River, Vermillion River, Clay Creek, Platte Creek, Okobojo Creek, Little Cheyenne Creek, and Blue Blanket Creek. The pattern of all of them is believed to be the result of more rapid sedimentation by the Missouri than by the tributaries.

FROZEN-GROUND PHENOMENA

In many parts of North America and Europe, peripheral areas of Wisconsin drift sheets are marked by structures attributed to freezing and thawing of the ground. Most of the structures are confined to the uppermost few feet of a deposit of unconsolidated material, and consist both of conspicuous rearrangements of stones and finer-grained particles, and of intense disturbance of stratification.

Such structures were searched for during the field examination of eastern South Dakota, without success. A doubtful exception is a road cut 0.1 mile west of the southeast corner of sec. 20, T. 94 N., R. 55 W., Yankton County. Here pocketlike concentrations of stones were exposed in 1946, in the uppermost 2 feet of a 25-foot section of Mankato till. The pessibility that concentration had been brought about by glacial activity rather than by freezing and thawing after deposition was not eliminated. A frost wedge in Cary(?) sand in the northwest corner SW¼, sec. 26, T. 42 N., R. 42 W., Knox County, Nebr., is reported by H. E. Simpson (written communication). Failure to find evidence of intense freeze and thaw implies negative evidence supporting the view that shrinkage of the successive Wisconsin glaciers in this region was not accompanied by climates as rigorous as those which prevailed in some other peripheral sectors of the Wisconsin drift sheets. Possibly in South Dakota the water table stood so low that despite rigorous climates, freezing and thawing of ground moisture failed to produce visible structures.

The study of frozen-ground phenomena is in its infancy, and much remains to be learned before the inconspicuousness of these features in eastern South Dakota can be evaluated in terms of Pleistocene history. Meanwhile the fact is recorded as a possible aid to future study.

WATER-TABLE FLUCTUATIONS

Many basins in the drift, caused by nondeposition or by collapse over residual masses of buried glacier ice, contain lakes, and many other basins, now dry, show by the presence of abandoned wave-cut cliffs and shorelines that they contained lakes formerly. A considerable number of the basins that still contain lakes possess abandoned strand lines several feet higher than the existing shorelines. Good examples are the lake, about 1,500 feet long, in the NE¼ sec. 10, T. 106 N., R. 65 W., Jerauld County, which possesses a strand line 12 feet higher than the lake level of August 1946, and the lake in the NE¼ sec. 36, T. 110 N., R. 53 W., Kingsbury County, which has strand lines respectively 2.5 feet and 6 feet higher than the basin floor (nearly dry in June 1949). Other basins in southeastern Kingsbury County have abandoned strand lines at various heights above lake surfaces or basin floors.

Evidently the abandoned strand lines are the result of fluctuation of the water table, which in turn is related directly to climatic fluctuation.[39] No evidence of the time or times when the water table stood higher than now has been found. The times must have coincided with climates somewhat cooler and moister than the climate now prevailing. It is known that relatively cool, moist climates prevailed during the world-wide expansion of glaciers that culminated late in the 18th century, and during an earlier period culminating in the 15th century. No doubt there were cool episodes still earlier, but evidence of their existence is not very definite. Perhaps the strand lines are referable to one of these times. This seems more likely than that they date from the Mankato deglaciation, because the farther back in time the strand lines are placed, the less likely are they to have persisted as recognizable topographic features. Accordingly it is thought likely that they are recent rather than ancient.

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[39] See the discussion by Condra, Reed, and Gordon (1950, p. 63–64).

Only one basin with an abandoned strand line high above its floor was noted. That is the twin basin of Stink Lake and Long Lake in secs. 2, 10, 11, 12, 13, 14, and 23, T. 117 N., R. 55 W., Codington County, in an area of Cary drift. There the strand line consists of a discontinuous bench as much as 500 feet wide, veneered with 12 to 18 inches of poorly sorted sand and gravel, and terminating shoreward in a gently sloping wave-cut cliff cloaked with colluvium. The bench stands 40 feet above the basin floor. Its great height and the eroded appearance of the cliff put it in a different class from the strand lines described earlier. The Stink Lake—Long Lake strand line may well date from the Mankato maximum, though less likely from the time of retreat of the Cary ice.

EOLIAN FEATURES

ABRASION

Evidence of extensive wind abrasion during retreat of the Iowan and Tazewell glacier margins and of weaker and more local abrasion during later glaciations has been presented. Here and there throughout the entire region surface boulders and cobbles are found that exhibit some degree of pitting, fluting, or beveling by wind-driven sand and silt. All the Wisconsin drift sheets are affected, the Iowan and the Tazewell more so, however, than the Cary and the Mankato. In general, abrasion is most evident on surface boulders situated immediately east of outwash bodies that could have served as sources of windborne fine sediment. In general, also, abrasion is more evident on the western sides of large boulders that are unlikely to have changed their orientations, than on their other sides. These general observations point to winds having a west component, as the effective agents of abrasion.

Although no conspicuous wind abrasion of bedrock, as distinct from abrasion by running water, was observed in eastern South Dakota, such abrasion was seen in southwestern Minnesota. In the southwest corner of sec. 26, T. 104 N., R. 45 W., Rock County, Minn., an exposed flat-lying surface of Sioux quartzite has glacial striations partly obliterated by pitting and faceting by the wind. The facets are cut along the eastern interfaces of south-trending joints, thereby recording effective winds from a westerly direction. As the locality lies within the area of outcrop of the Iowan drift, the abrasion can be dated as either Iowan or post-Iowan, probably the former.

DEFLATION

The impression made on the observer by deflation features in eastern South Dakota is that winds have removed a large amount of drift and bedrock from the region during Pleistocene time, and that deflation is still in progress today.

The concentrates of stones at the surfaces of the Iowan and Tazewell tills imply strong deflation during short periods following the Iowan and Tazewell glacial maxima, and the abrasion of the stones testifies further to the efficacy of winds during those times.

Shallow closed depressions in the drift on the Coteau du Missouri, having an apparently random distribution and closely resembling the basins in bedrock west of the Missouri trench, may be in part the work of deflation of drift. Deflation of loess is indicated by the occurrence (especially west of the Missouri River, in Gregory County) of closed depressions 100 feet or more in diameter and 2 or 3 feet in depth, in the surface loess. Such basins seem to be to the loess what the so-called blowouts are to accumulations of windblown sand: evidence of renewed erosion, possibly in consequence of local destruction of a covering of grass.

Bedrock surfaces west of the Missouri River show more evidence of deflation than does the drift itself. Interfluves in the areas of outcrop of the Pierre shale and the Fox Hills sandstone are marked by thousands of shallow closed depressions believed to have been excavated by the wind. The basins are subcircular to ovate, and mostly elongate, with the long diameters of some exceeding 2,000 feet, although most are less than 300 feet in length. There is a strong tendency towards orientation of the long diameters of the basins in a southeast direction.

Closures as great as 15 feet have been measured, though the majority are probably no more than 5 feet. Side-slope angles are generally less than 3 degrees, except in basins characterized by wave-cut cliffs during their occupation by former lakes. Examination of air photographs has shown that the cliffs, where present, are better developed at the southeastern ends of basins than elsewhere.

Holes dug with a spade at various points around the margins of basins have established the fact that those basins have been excavated in bedrock; in one instance the side slope of the basin was seen to cut the stratification of the rock.

The basins occur at many different altitudes, even in closely adjacent positions, and thus bear no visible relation to the bedrock stratigraphy. In some basins wind-cut residual stones lie on the surface.

The origin of the basins seems to be capable of only two possible explanations, solution and deflation. The possibility of solution is ruled out by the absence of any considerable proportion of soluble substances in the bedrock. This leaves only deflation, a process which was earlier appealed to as an explanation by Searight and Moxon (1945, p. 10) and by Baker (1948, p. 6–8) in South Dakota, and by Lugn (1935, p. 163) in Nebraska and adjacent States. Perhaps the earliest detailed description of these features is that of Gilbert (1895), who identified basins in shale in the Arkansas River basin as a product of deflation, "less because its process was understood than because each other suggested hypothesis seemed barred by some insuperable obstacle."

Deflation of a poorly consolidated fine sandstone such as the Fox Hills sandstone is expectable, and the same is true of the chalky Mobridge member of the Pierre shale. The basins, however, occur abundantly also in clayey members of the Pierre shale, and at first thought it may seem improbable that deflation could be effective in such material. Nevertheless, at least some parts of the Pierre shale disintegrate readily, on exposure, into small flakes of approximately sand size. As the clay minerals have lower specific gravities than quartz, and as the flakes have more area per unit of weight than have grains of quartz sand, the disintegration flakes are readily transported by the wind.

During the dry, "dust-bowl" years in the 1930's dunes consisting entirely of flakelike aggregates of clay minerals were piled 10 feet high along fences and other obstacles in Tripp County, S. Dak., and during the same years new basins appeared in surfaces underlain by Pierre shale. (Glenn Avery, U. S. Department of Agriculture, Soil Conservation Service: oral communication.) Similar depressions in sandy and silty materials in western Kansas and eastern Colorado are known to have been excavated by the wind during the same dry period (Lugn, 1935, p. 163).

No definite evidence of the date of excavation was obtained. It seems likely that effective deflation may have been intermittent, occurring at very dry times ever since the creation of the highest upland surfaces still represented by erosion remnants west of the Missouri River.

SAND

Windblown sand occurs both as dunes and as thin spreads in eastern South Dakota. It is commonly present as a thin capping on outwash bodies, even small ones, and may extend over the drift through short distances east and south of the outwash itself. In a few places in Grant and Roberts Counties, eolian sand occurs at or near the crest of the massive Altamont moraine.

The dune sand shown on the geologic map (pl. 1) constitutes only a small part of the windblown sand present in the region. It consists of that part which is thick enough to form distinct dunes. The specific areas mapped are mentioned below.

Campbell County.—An area of dune sand more than 7 miles long, with individual dunes more than 25 feet high, in places still active today, centers in T. 125 N., R. 76 W. It lies at the eastern margin of an outwash body more than 5 miles wide, and the sand is piled against the western slope of a Mankato end moraine. It seems clear that the sand was built by westerly winds from a source in the outwash.

Brown and Marshall Counties.—An area of dune sand centers near the line separating these two counties, near their junction with the North Dakota State line. The area extends northward into North Dakota. In its western part the sand is built up into transverse dunes, with steep southeast slopes, that reach heights of 20 feet. Farther east the dunes diminish in height to less than 10 feet and lose their distinct transverse pattern, becoming irregular hummocks. At the eastern edge of the area mapped as dune sand, dunes cease to be distinct as such, but eolian sand 2 to 3 feet thick covers the country to the east and south in patches through distances of several miles. This sand is spread over the surface of a till ridge, probably an end moraine, and in places it overlies the deposits of glacial Lake Dakota. It is thought to have been derived, through westerly winds, from the sandy facies of those deposits which lie immediately west of the dune area. Additional areas of sand reworked from Lake Dakota sediments are mentioned below.

Sanborn County.—Two areas of dune sand occur east and southeast of Woonsocket, along the eastern margin of a major body of sandy Mankato outwash. The dunes are low, irregular hummocks without distinct pattern; their relation to the outwash body is so close as to leave no doubt of their origin.

Buffalo County.—The area of dunes with long axes oriented northwest to southeast, in the northwest part of T. 106 N., R. 70 W., is described on p. 158 as a group of longitudinal dunes built by northwest winds, probably from a body of Iowan(?) and Tazewell(?) outwash in the Missouri River trench. The position of the dunes at the southeast end of a long northwest-trending segment of the trench is peculiarly favorable, with respect to source of sand and sweep of wind, for accumulation.

Not mapped are spreads of windblown sand and silt, 2 to 3 feet thick, overlying the eastern and southern parts of the outcrop area of the Lake Dakota sediments in Brown and Spink Counties. Air photographs in these areas show distinct southeast lineation, suggesting activity by northwest winds. Good examples occur in secs. 25, 26, 27, and 28, T. 118 N., R. 67 W., and in the vicinity of sec. 30, T. 118 N., R. 64 W., both in Spink County. These sediments were probably derived from the newly exposed bed of Lake Dakota.

Low sand dunes occur on the floor of the Missouri River trench south of Yankton and at the mouth of the James River trench.

West of the Missouri River, in the area of outcrop of the Fox Hills sandstone, there are considerable spreads of eolian sand reworked from that sandstone. In places the sand is built into low dunes. The map (pl. 1), however, does not show dunes west of the Missouri River trench.

PHYSICAL FEATURES OF THE ILLINOIAN AND WISCONSIN GLACIERS

Descriptions of the physical geology and stratigraphy of the drift do not in themselves explain the physical features of the glaciers by which the drift was deposited. Therefore in the following discussion there are assembled physical and stratigraphic data from which inferences concerning the glaciers themselves can be drawn. Most of the discussion pertains to the Wisconsin glaciers and only a short section pertains to the Illinoian. So little is known about the Nebraskan and Kansan drift sheets and about the topography during the corresponding glacial ages that a reconstruction of the glaciers of those times is hardly possible.

AREAL PATTERN OF THE DRIFT SHEETS

The areal pattern of the various drift sheets is shown on plate 3, which includes not only South Dakota but also parts of adjacent States, because the relations in South Dakota, to be fully understood, must be viewed within a larger framework.

Plate 3 shows that the Tazewell, Cary, and Mankato drift sheets are alike in taking the form of two lobes, a James lobe in the James River lowland, and a Des Moines lobe in the lowland drained by the Des Moines River in north-central Iowa. Only the northwestern part of the Des Moines lobe is shown. These two major lobes are separated by the highland of the Coteau des Prairies, and the western side of the James lobe is determined by the Coteau du Missouri. It is therefore evident that during Wisconsin time the successive ice sheets that invaded this region were strongly influenced by topography. That this influence extended to details is shown by the sublobes formed by the several drift sheets, particularly on the western side of the James lobe. Each sublobe coincides with the valley of a major existing or prediversion stream or with a weak-rock lowland. Clearly the corresponding glaciers must have been thin enough to conform, by flowing, to a topography having no more than a few hundred feet of relief.

DIFFERENCES AMONG THE WISCONSIN DRIFT SHEETS

Broadly speaking, the Iowan, Cary, and Mankato drift sheets lap off upon each other in order of decreasing age. The Iowan drift is the most extensive of the three; the Mankato drift least so. Furthermore the James lobe of each of these drifts is narrower than its predecessor. It is also slightly shorter, in that it reaches less far south, but the progressive diminution in length is far less than the diminution in width. Indeed the Iowan drift is extensive enough to cover the Coteau des Prairies, so that its James lobe is separated from its Des Moines lobe by only an indistinct reentrant.

These facts are believed to indicate that each of the three corresponding glaciers was thinner than the one that preceded it. Progressive glacial deepening, widening, and smoothing of the James River lowland undoubtedly facilitated progressively the flow of the glaciers and helped to make the younger lobes nearly as long as the older ones, but thickness of the ice is believed to have been the chief factor in creating the pattern, and this is substantiated by the altitude data cited hereafter.

The Tazewell drift border suggests that the James lobe of this drift is shorter than the corresponding lobe of Cary drift. The Tazewell border lies beneath the Cary drift on the west side of the Des Moines lobe and on the east side of the James lobe; it is believed to do so on the west side of the James lobe as well. Furthermore detailed studies in the Chamberlain and Yankton districts have failed to discover evidence of more than one Wisconsin till older than the Cary till. That one pre-Cary till is interpreted as Iowan, and the Tazewell till is believed not to extend as far south as the Iowan. The position of its southern margin beneath the Cary drift can only be conjectured. However, the altitude of the Tazewell border on the east flank of the Coteau des Prairies is higher than that of the Cary border. The inference seems warranted, therefore, that climatic warming put an end to the Tazewell glacial expansion before the ice reached the limit it had attained during Iowan time.

AREAL PATTERN OF THE ILLINOIAN DRIFT

Very little drift established as even probably Illinoian exists in eastern South Dakota. The till in the valley of the Ancient White River, near Chamberlain is dated as Illinoian on indirect evidence. Till in a boring in Sully County (pl. 6, locality 2) and drift in exposures at 12 other localities (fig. 6, localities 3, 4, 6, 8, 9*A*, 9*B*, 18, 20, 21, 28, 29, 30) are considered to be probably Illinoian, but in most cases these sediments can be proved only to be pre-Wisconsin. Although the argument that eastern South Dakota was glaciated during Illinoian time is fairly convincing, the indefiniteness of the age of the pre-Wisconsin drift in most exposures makes it necessary to fix the extent of the Illinoian ice on other evidence.

Fortunately such evidence is at hand in the position of the Missouri River. Transection of the many east-west divides within the prediversion drainage system could have been accomplished only if the margin of an ice sheet had occupied approximately the position shown on plate 3. The demonstration by C. R. Warren that the ice sheet was post-Kansan, pre-Wisconsin, and therefore Illinoian, is set forth on page 51, The Illinoian glacier may have extended farther west than the position shown, and probably did so in one or more sectors, but if so it must have shrunk back before outflow of the ponded water began.

The Illinoian border as thus defined shows parallelism with the border of the Cary drift. Like the Cary border it projects westward in the Great Ree Valley in Sully and Hughes Counties, in the valley of the Ancient White River in Brule County, and at the sites of the Ancient Grand and Moreau Rivers. At the crossing of the Ancient White the Illinoian protuberance is broader than that of the Cary drift. This is expectable because the creation of the Missouri trench intervened between the times of these two glaciations, and provided a pocket into which the Cary ice could flow, a pocket that was not present in Illinoian time.

East of Yankton the position of the Illinoian ice margin can not be inferred from the course of the Missouri, because in that sector the river occupies an ancient, prediversion valley. The river therefore sets only an outer limit to the inferred Illinoian ice margin. Presumably the edge of the ice sheet trended eastward or northeastward from Yankton. If pre-Wisconsin till in Lincoln and Minnehaha Counties should prove to be Illinoian, as is now suspected, then the position of the ice margin of that time could be fixed within limits of less than 40 miles. Throughout South Dakota the inferred Illinoian ice margin lies inside (east and north of) the border of the Iowan drift.

In northwestern Iowa Illinoian drift has not been identified with certainty beneath the overlying Wisconsin drift and loess, although a pre-Iowan till exposed near Ida Grove, Ida County, is believed by G. D. Smith (oral communication) to be possibly Illinoian.

If the Missouri trench is taken as marking the approximate boundary of the Illinoian ice sheet, there was no James lobe in Illinoian time. Instead, the Illinoian ice seems to have spread southward and westward across the eastern half of South Dakota forming sublobes in the prediversion valleys, to be sure, but with no James lobe even of the broad, ill-defined sort indicated by the southern border of the Iowan drift. Two possible causes are apparent: Probably the Illinoian glacier was thicker than the Iowan glacier, and certainly the James River lowland in its present extent and depth did not yet exist. The major valleys of the Ancient Cheyenne, the Bad, and the White were present, but they were much narrower than the modern lowland, and the Ancient Redfield divide still must have stood high as an impediment to strong lobation of the ice.

ALTITUDES OF MARGINS OF THE WISCONSIN DRIFT SHEETS

Some useful inferences can be drawn from the vertical relations of the drift sheets. However, altitudes measured along the margin of a drift sheet must be considered not individually but as a group, because variations in topography between one district and another produce discrepancies in altitudes of the drift border that can not be understood unless they are viewed as part of a general picture.

A case in point concerns the relative vertical positions of the Cary and Mankato margins. Along the northwestern side of the Coteau des Prairies the margin of the Cary drift reaches altitudes consistently 50 to 100 feet higher than does that of the Mankato drift. Farther south, however, in Kingsbury, Brookings, Lake, and Moody Counties, the situation is reversed in that the Cary margin is 50 to 100 feet lower than the Mankato. This does not mean that in these four counties the glacier was thicker in Mankato time than in Cary time. In these counties the Cary drift border lies within the depression formed by the Big Sioux valley; in order to reach that relatively low district the east-flowing Cary ice had to surmount the higher part of the coteau that lies farther west. The Mankato ice, in contrast, failed to surmount the highland, but it rose to a higher altitude on the upstream slope of the highland than the altitude of the Big Sioux valley lying eastward beyond it.

Still farther south, in Turner and Lincoln Counties, the Cary border is again higher than the Mankato. The probable explanation is that there the Mankato border is down within a major prediversion valley, whereas the Cary glacier was just enough thicker to flow across the valley and rise high against the upstream slope of the interfluve to the southeast.

The Iowan drift border, measured at interfluves rather than at valley crossings along the west side of the James lobe, declines from about 2,100 feet in Corson County through about 2,000 feet in Stanley County, 1,800 to 1,900 feet in Lyman County, to 1,700 feet in Knox County, Nebr. Although necessarily rough, these figures are consistent. It can be argued that if the Iowan ice reached an altitude of 1,700 feet in northeastern Nebraska it should have extended farther south in the region east of Sioux City, Iowa, than is indicated by the Iowan drift border shown on plate 3, where the highest altitudes are everywhere less than 1,500 feet. There is little doubt that the Iowan drift border is essentially as mapped, but the ice itself may have extended beyond the present limit of the drift, which was thin when deposited and is now much dissected.

Altitude data for measuring the relative thickness of the Tazewell ice in Moody, Brookings, Deuel, and Hamlin Counties, the only district in which the border of the Tazewell drift is definitely known, are not useful because the border there lies along the valley of the Big Sioux. To reach this valley the Tazewell glacier had to surmount land, nearly 300 feet higher, now covered by Cary drift. All that can be said with assurance is that the Tazewell glacier was thinner than the Iowan but thicker than the Cary.

The Cary drift border reaches above 1,900 feet on the eastern side and northern end of the Coteau des Prairies. On the western side of the coteau the drift border is lower, latitude for latitude, because it lies within the valley of the Big Sioux River. In southern Lincoln County and northern Union County, the only sector in which the drift border lies along high ground, its altitude is about 1,500 feet. On the western side of the James lobe the altitude of the Cary drift border declines from 1,900 feet in Walworth County, where it lies beneath the Mankato drift sheet, to 1,800 feet at the base of the Bijou Hills in Brule County. Its altitude along the Missouri trench is unknown because erosion in the trench has destroyed the border, except at the highlands in Charles Mix County which the Cary glacier failed to surmount. The Cary drift border in their vicinity lies between 1,700 and 1,800 feet.

The Mankato border stands at about 1,850 feet at its northernmost point on the Coteau des Prairies in Marshall County. From that point it declines to 1,800 feet in Clark County, 1,700 feet in Lake County, 1,500 feet at the northern end of Turkey Ridge in Hutchinson County, and slightly more than 1,400 feet against Yankton Ridge in Yankton County. On the west side of the James lobe the border ascends through 1,750 feet against the Wessington Hills and 1,850 feet against the Rees Hills to about 1,900 feet at the North Dakota State line.

According to these figures the Mankato drift border lies generally 50 to 100 feet lower than the Cary border, and therefore the James glacial lobe can be thought of as comparably thinner in Mankato time than in Cary time.

An interesting fact revealed by the figures cited is that at any latitude the borders of both the Cary and Mankato drift sheets are higher on the western side of the James lobe than on the eastern. In some latitudes the differential exceeds 100 feet. Whether the same is true of the Iowan and Tazewell drifts is not known, as comparisons cannot be made. T. C. Chamberlin (1883, p. 390–391) made a similar observation with regard to the Des Moines lobe, called by him the Minnesota valley glacier (lobe). Chamberlin attributed the difference to postglacial differential warping of the crust, but to the writer it seems more likely that the explanation lies in inequalities in nourishment and flow in various parts of these lobes. This hypothesis is suggested also by the greater height and bulk of end moraines and the greater amount of outwash, on the western side of the James lobe than on the eastern, a fact that cannot be explained by postglacial influences.

INFERRED THICKNESSES OF THE JAMES GLACIAL LOBE

In order to arrive at even a rough estimate of the thickness of the James glacial lobe at any latitude, the altitudes of the eastern and western drift borders (on interfluves) and of the bedrock surface beneath the drift in the central part of the intervening lowland, for that latitude, must be known. At the latitude of Redfield, where bedrock lies nearest the surface, the lowest known point on the bedrock surface is at 1,155 feet, whereas the mean altitude of the Mankato drift borders on the two coteaus in the same latitude is 1,825 feet. The difference, 670 feet, measures the minimum thickness of the Mankato glacier near Redfield, on the assumption that the base of the glacier was in contact with bedrock. The actual thickness, however, was much greater, because all active glaciers are thicker in their medial parts than at their lateral margins. Comparison of data on existing broad glaciers suggests that the actual thickness may have been 50 to 100 percent greater than the minimum value—that is, 1,000 to 1,300 feet thick. Calculated in the same manner, minimum thicknesses north and south of Redfield, where the bedrock surface lies at lower altitudes, are about 800 feet in the latitude of Aberdeen and 550 feet in the latitude of Woonsocket. Actual thicknesses at those latitudes are estimated at 1,200 to 1,600 feet, and 825 to 1,100 feet, respectively.

These data are based on the Mankato drift borders. The same kind of calculation based on the Cary borders gives values roughly 100 to 200 feet greater.

These values compare fairly well with data calculated by C. E. Erdmann (written communication) in the region of the Kevin-Sunburst dome, Toole County, Mont. According to Erdmann the latest ice that covered the region had a minimum thickness of 1,000 to 1,200 feet. The ice was certainly Wisconsin, but its age is not known more precisely.

All these thicknesses are much smaller than those recorded in northeastern North America. No doubt the explanation lies in the comparatively dry climate of the

Dakotas and eastern Montana, where the Laurentide Ice Sheet was less well nourished than it was in the Great Lakes region and on the Atlantic slope.

The altitudes of the borders of the Wisconsin drift sheets suggest that deglaciation cleared South Dakota of ice after each glacial maximum, and that when the ice sheet next invaded the State it was thinner than it had been at the preceding maximum. The suggestion implies that the intervals separating the Wisconsin maxima were long enough to permit widespread thinning of this sector of the ice sheet. No doubt thinning resulted not only from ablation but also from decrease in nourishment, thus diminishing the replenishment of an ice sheet that was continually spreading and thinning as a result of outward flow. Thinning attributable to the second cause is independent of thinning by ablation.

Unfortunately the data available do not justify a calculation of the relative lengths of the intervals of deglaciation as a check on the stratigraphic data presented elsewhere in this paper.

PHYSICAL CONDITIONS DURING IOWAN AND TAZEWELL SUBSTAGES

In the peripheral part of the region of Iowan glaciation the Iowan drift is both very thin and lacking in end moraine. Nevertheless, as has been shown, the Iowan ice was thicker in this region than were any of the post-Iowan glaciers. The presence of thin drift despite thick ice, together with the absence of end moraines, points toward the view that the time during which the Iowan ice occupied the outermost belt of territory it covered was very short. This view is supported also by evidence, detailed on page 144, that western rivers tributary to the Missouri were ponded by the encroaching Iowan ice for only a short time.

Apparently the Iowan ice spread rapidly out to its extreme limit; it then rapidly shrank back as the climate became warmer. The absence of end moraines suggests that shrinkage was not interrupted by pauses or reexpansions, and may have been reversed only by the climatic change that brought about the glacial expansion of Tazewell time. Of course the Iowan glacier, thicker than its successors, would have responded to minor climatic fluctuations less sensitively than would the thinner Mankato glacier. It seems possible that small climatic fluctuations, such as those to which the Mankato ice responded by building minor end moraines, might have had very little influence on the position of the margin of the much thicker Iowan ice.

Rapid shrinkage of both Iowan and Tazewell glaciers is suggested also by the thick loess that accumulated during Iowan and Tazewell deglaciation on both sides of the Missouri River in northeastern Nebraska, southeastern South Dakota, and western Iowa. Apparently the loess was derived from floods of outwash sediment deposited by the Missouri. Rapid accumulation of outwash, and hence rapid melting, are implied. Wind velocities, too, may have been greater near the Iowan and Tazewell maxima, when glacier ice was thicker and more extensive than during the Cary and Mankato. The combination of high winds and abundant fine sediment exposed at the surface is suggested also by the widespread occurrence of ventifacts in the stone concentrates at the surfaces of the Iowan and Tazewell tills. The greater abundance of ventifacts east of the James River lowland than west of it suggests further that the atmosphere was drier in the former region than in the latter. Indeed it does not seem unlikely that on the Coteau des Prairies, the narrow belt of ice-free country lying between two major glacial lobes may have been characterized by particularly dry and turbulent atmospheric conditions.

SOURCES OF THE DRIFT

Comparison of the lithology of the Wisconsin tills with their possible bedrock sources thus far indicates only that the ice sheet invaded South Dakota from the north. Study of the lithology of the drift in North Dakota and northern Minnesota, coupled with detailed investigation in South Dakota, would probably yield more information about the centers of outflow and directions of flow of the glacier ice that entered South Dakota during the Wisconsin age.

STONE COUNTS

In an attempt to see what could be learned from the relative frequency of the various groups of rock types in the drift, stone counts were made at 34 localities distributed throughout the region east of the Missouri River trench. Most of the samples for counting were taken from road cuts. The method used was to clean the exposure of superficial wash and to mark out on it an arbitrary area, estimated to expose 200 or more stones. All the stones more than a quarter of an inch in diameter, exposed within this area, were collected without exception. A few stones larger than pebble size are involved, but more than 98 percent of those counted were in the pebble-size grade. Each stone was broken to facilitate field identification. The identified stones were classified into selected groups, and a histogram was made for each collection, the histogram bars representing the standard groups selected.

The method is rough and has limitations, the chief being that it fails to represent shale in its true proportions. Shale is the commonest bedrock type in the region and pebbles of it are abundant in the till. However, shale pebbles generally disintegrate when handled, and no method of determining their real frequency was found. Hence the stone counts made in the present study actually represent the more durable rock types—the pebble-size constituents exclusive of most of the shale.

The empirically determined groups (including both rocks and minerals) are: Granitic rock, basic igneous rock, foliated metamorphic rock, quartzite, sandstone, limestone and dolomite (Paleozoic age), chalk, shale, vein quartz, chert, chalcedony, and iron-oxide concretion.

Owing to the fact that the results revealed no significant details, and that it has been found possible to draw from them only rather broad generalizations, the histograms and the corresponding map locations are not reproduced in this report.

The samples are much alike. As a group they show clearly that in the pebble-size grade (and largely exclusive of shales—an important exception, as noted above) the most abundant constituents are Paleozoic limestones and dolomites. In many samples these exceed all other types combined. Next in abundance are granitic rocks, and third, in most samples, are basic igneous rocks.

Although limestone and dolomite outnumber granitic rock in the pebble-size grade, in boulder sizes the reverse is true. In large boulder sizes the predominance of granitic types is overwhelming. In an area of approximately 1,200 square miles within the James River lowland, Waring (1949) counted 1,600 boulders more than 4 feet in longest diameter. Of these 91.7 percent were granitic types, and only 1.8 percent were limestone and dolomite of Paleozoic age. The cause of these differences probably lies in wider spacing of joints and absence of stratification in the granitic rock, resulting in greater durability during glacial erosion and transport.

The limestone and dolomite of Paleozoic age, in some of which Silurian fossils have been identified, are believed to have been brought from the large outcrop area in Manitoba south and west of Lake Winnipeg. This source implies a general flow of glacier ice into eastern South Dakota in a direction almost due south. The igneous rocks could have traveled in the same direction, from a source in the Canadian shield north of Lake Winnipeg, or they could have traveled southwestward from sources in northern Minnesota and western Ontario. They do not include an appreciable proportion of the granite exposed in northeastern South Dakota; that granite has a very distinctive appearance.

In any case the essentially similar frequencies of these types in all four substages of the Wisconsin stage in South Dakota suggests that each of the corresponding glacial invasions of the State took place in the same general direction. This suggestion is supported by the evidence of the striations, detailed on p. 57–58. It stands in contrast, however, with findings by Howard (1947) in western North Dakota, where successive layers of drift are identified in part on a basis of lithology. Probably the absence of a lowland trough, to channel the ice repeatedly along the same path, is the explanation of the differences in North Dakota.

From what has been said it is evident that most of the large-size rock fragments in the till are far traveled, having been derived from well outside South Dakota. This is expectable in that most of the bedrocks underlying eastern South Dakota (fig. 4) are such that when subjected to mechanical erosion they would break down into particles much smaller than pebbles. Four exceptions may be mentioned: the pre-Cambrian (?) granite exposed in the northeastern part of the State, the quartzitic phase of the Ogallala formation, concretions from the Pierre shale, and the Sioux quartzite.

The granite has a very small outcrop area and has not made a significant contribution to the drift. Quartzite of the Ogallala formation breaks characteristically into large slabs, but the outcrop areas of this rock type are so small, and lie so close to the outer limit of continuous till, that there contribution to the drift is negligible also. The resistant concretions, mostly of iron- and iron-manganese composition, occurring at some horizons within the Pierre shale, are locally conspicuous components of the drift, but the Pierre shale is so rarely exposed outside the Missouri River trench that its stratigraphic subdivisions are little known in the region covered with thick drift; hence the occurrences of concretions can not be compared with the source rocks.

SIOUX QUARTZITE IN THE DRIFT

The Sioux quartzite, on the other hand, is an important constituent of the drift in and south of its outcrop area (fig. 32). It tends to break away from parent ledges along widely spaced joints and hence appears in the drift as boulders and cobbles. These fragments are so abundant that farmers have collected them from their fields and have piled them into great heaps along their fence lines. North and west of the outcrop area, however, quartzite fragments disappear abruptly, and limestones, dolomites, and granitic rocks, undiluted by Sioux quartzite fragments, become at once more conspicuous.

The distribution of Sioux quartzite in the drift supports the inference that the main direction of glacier flow was almost due southward. Because the western limit of quartzite fragments appears to be about the

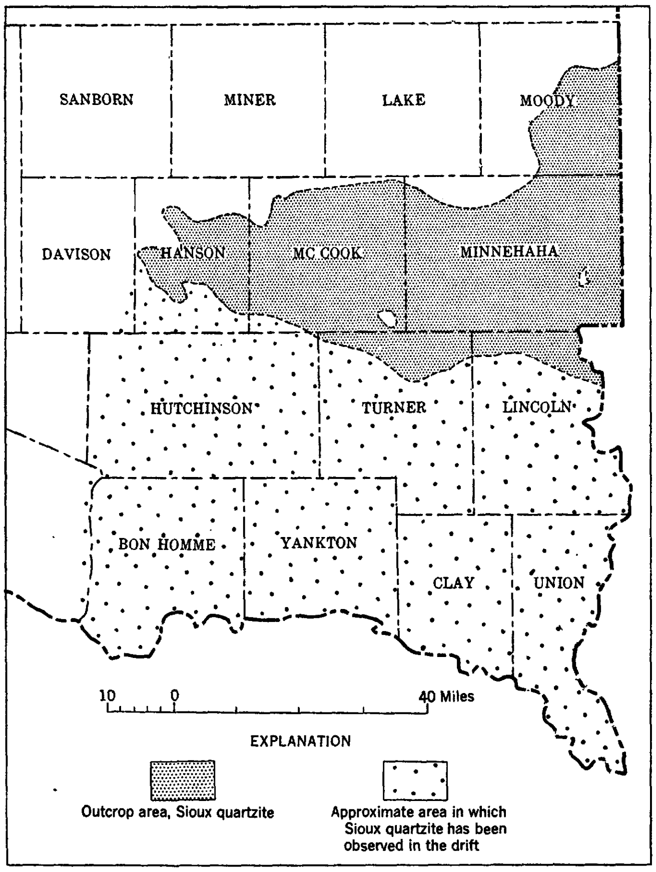

FIGURE 32.—Map showing relation of Sioux quartzite fragments in the drift to outcrop area of source bedrock in southeastern South Dakota.

same in both the Cary drift and the Mankato drift, the inference is supported that at least these two Wisconsin glacial invasions of South Dakota followed the same path.

Todd (1903b, p. 3) noted also that in exposures of thick Wisconsin till, quartzite has a greater frequency in the basal parts than in the higher parts of the sections. Although this difference did not appear to the writer to be conspicuous, it is expectable. The large quartzite fragments, being difficult to move mechanically and nearly indestructible chemically, accumulate on the surface as a residue during the erosion following a glaciation. The succeeding glacier comes upon the concentration of boulders and reworks it into the base of the till it deposits. It seems quite possible that many of the quartzites now at the surface have been thus reworked repeatedly, having been torn from the bedrock as long ago as early Pleistocene time.

CLOSE RELATION OF TILL TO BEDROCK

Wherever till is seen exposed in contact with bedrock, the lithology of the till partakes strongly of the character of the bedrock. A striking example occurs in a road cut 0.1 mile south of the northeast corner of sec. 12, T. 95 N., R. 55 W., Yankton County, on the west flank of Turkey Ridge. Here olive-brown and olive-gray shale (Pierre shale) is exposed, overlain by till consisting almost entirely of the same shale, reworked into a jumbled mass of shale fragments of various sizes inclosed in a clay matrix.

The till overlying chalk that is probably the Mobridge member of the Pierre shale, exposed at the west quarter corner of sec. 14, T. 116 N., R. 64 W., Spink County, is mostly chalk, some in large blocks. Through an area of several square miles lying south of this place both the till and the stratified drift are notably rich in chalk.

In the area of outcrop of the Fox Hills sandstone in northwestern McPherson County the till resembles the sandstone so closely that in some places the two can be distinguished only after a very detailed examination.

Wherever the chalky Niobrara formation is known through exposures or well borings to underlie the drift, the latter is rich in chalk.

In northern Campbell County and in the adjacent part of North Dakota, the drift contains many cobbles and boulders of silicified rock containing the stems of plants. Such material is common in the Hell Creek and Fort Union formations exposed on the North Dakota side of the line.

This close relationship between bedrock and overlying drift makes it possible to guess the lithology of the local bedrock by examining the lithology of the drift in areas where neither well logs nor bedrock exposures exist. Thus the presence of much chalk in the drift on the south side of Yankton Ridge, in contrast with the nonchalky drift in the lowland north of the ridge, implies that the ridge consists at least in part of the Niobrara formation, whose chalk is exposed in the Missouri River bluffs to the south.

Similarly the extremely high chalk content of the drift throughout a large area in the southwestern part of Douglas County and the adjacent part of Charles Mix County implies that chalky bedrock underlies the drift there; yet no exposures of bedrock were found. The chalk could belong either to the Niobrara formation or to the Mobridge member of the Pierre shale. Both are exposed in the hills along the Missouri River about 12 miles southwest. They are, however, separated by about 500 feet of nonchalky Pierre strata, and as they are essentially flat lying, tentative correlation can be made on a basis of vertical position. As the high area covered with chalky drift lies at 1,700 feet, the same altitude as the Mobridge member, and 500 feet higher than the top of the Niobrara, the inferred chalk bedrock in Douglas County is judged to be probably Mobridge.

Additional exposures of chalk-rich drift occur in northern Charles Mix County and in southeastern Brule

County. From what is known of the direction of flow of the ice this chalk could not have been derived from bedrock in the high area discussed in the preceding paragraphs, but should have come from farther north, probably in western Aurora County. It is possible, therefore, that remnants of the Mobridge member are or were present beneath the drift in that district as well.

Till exposed among the high buttes in T. 122 N., R. 76 W., north of Lowry in Walworth County, contains considerable though varying amounts of chalk and grayish-yellow to very pale orange fine sand with concretions. These materials are probably, respectively, the Mobridge member (the Niobrara formation is known to lie far below the surface in this part of the State), and the Ogallala formation, occurring as small caps concealed beneath drift at the tops of the buttes.

Till of distinctive composition occurs in the eastern part of the James River lowland. It contains abundant fragments and blocks (most of them deformed by glacial flow) of olive-gray Pierre shale, and the matrix appears to consist principally of the same material. This is reflected in a relatively high clay content of the till, in its color, which is olive gray when moist and light olive gray when dry, and in the development upon it of Solonetz soils, which characterize areas of poor drainage.

Till of this kind has been found in many auger borings (Fred Westin and W. I. Watkins, oral communications). Its thickness ranges from 2.5 to 4.5 feet, and it is horizontally discontinuous. It is believed not to be a stratigraphic unit but rather to consist of extensive lentils and other masses inclosed in a body of till of a more typical kind. The inclosing till includes larger proportions of silt and sand sizes and is correspondingly more friable and paler in hue. Its color is moderate olive brown when moist and dusky yellow when dry.

The dark-hued clayey till occurs only in the outcrop area of the Mankato drift and at shallow depths in many places in eastern Spink, western Clark, northeastern Beadle, western Kingsbury, and western Miner Counties. The area of occurrence, elongate northward along the western flank of the Coteau des Prairies, suggests that it may top the belt of outcrop of a member of the Pierre shale exposed, prior to the glaciation that deposited the till, along the base of the coteau. The dark till is believed to be chiefly Mankato, but the possibility that much of it may antedate the Mankato subage has not been excluded. Indeed the till whose upper surface is a striated boulder pavement, in sec. 26, T. 113 N., R. 60 W., described on page 58, is of this lithologic type and is very likely pre-Mankato, although probably not pre-Wisconsin.

A very unusual component of the drift was seen at the Bruns gravel pit in the SW¼ sec. 15, T. 101 N., R. 50 W., Minnehaha County, in Cary outwash. The outwash, worked at that place in 1949, included many waterworn pebbles and small cobbles of lignite, similar to lignites in the Fort Union strata in southern North Dakota, 200 miles to the north. Fort Union strata are unknown in eastern South Dakota, but the unlikelihood that fragile lignite, especially in quantity, could survive glacial transport through a 200-mile distance justifies the suspicion that an outlier of lignite-bearing strata may exist or may have existed in Cary time not far north of this locality.

CONCLUSIONS FROM LITHOLOGY OF THE DRIFT

The foregoing discussion, which is almost entirely qualitative and is based on little more than random notes made in the course of general reconnaissance, does nevertheless lead to two inferences:

1. The close relation of drift lithology to bedrock lithology is independent of stratigraphic substages; it appears to characterize all the Wisconsin drift sheets alike. Hence drift sheets in South Dakota must be identified on evidence other than their content of various rock types.
2. The lithology of the drift, lacking essential differences from one substage to the next as far as the generalized data now at hand are concerned, suggests that the Wisconsin glaciers repeatedly followed the same general route across eastern South Dakota.

In connection with both matters it should be noted that several drift sheets have been discriminated in northwestern North Dakota on a basis of differing lithologies (Howard, 1947), presumably with the implication of changes in direction of glacier flow. There, however, the ice is believed to have been thicker than it was in eastern South Dakota, and it was less hampered by topographic barriers such as the Coteau des Prairies. Consequently it could have reached any particular area at different times by flowing in from the northeast, north, or northwest, whereas in South Dakota the ice repeatedly followed the James River lowland and in Cary and Mankato time was not thick enough to spread even a short distance out of this pathway.

DRAINAGE HISTORY OF CENTRAL AND EASTERN SOUTH DAKOTA

MISSOURI RIVER

EXISTING DRAINAGE

The Missouri River in South Dakota possesses three anomalous features: Its direction of flow is not eastward down the regional slope, but southward nearly at a right angle to that slope; its trenchlike, steep-walled valley is narrower and more youthful than those of its chief tributaries; although it receives five large western rivers as tributaries, no streams of comparable importance enter it from the east. Its pattern is therefore one sided.

REARRANGEMENT OF DRAINAGE BY THE ICE SHEET

The outer limit of the glacial drift (pl. 1) lies a short distance west of the Missouri trench, and is nearly parallel with the course of the Missouri. Because of this fact, and because of the anomalies mentioned above, it was recognized long ago (G. K. Warren, 1869, p. 311) that the Missouri River owes its course through South Dakota in considerable measure to glacial rearrangement of an earlier, quite different drainage pattern.

Most of the pioneer study of Missouri River is the work of J. E. Todd, who in 1914 summarized the results of many years of reconnaissance study (Todd, 1914; 1923). Todd recognized the presence, east of the Missouri, of eastward-trending valleys partly filled with drift and containing no through-flowing streams. He drew the inference that these represent parts of major preglacial drainageways that had been overwhelmed by ice flowing from the northeast and that were, in consequence, partly choked with glacial deposits. He thought that the James River lowland was cut by a large river made by the five western streams combined, and that this river flowed north to the region of Hudson Bay. He considered the Missouri to have formed along the margin of the blockading ice sheet, along which all streams reaching it from the west were obliged to detour. Todd's reconstruction of the preglacial drainage pattern, and the reasoning that led to it, represent an important contribution to knowledge. The principle on which it is based forms the basis of the reconstruction presented here, although more recent investigation has resulted in substantial changes in the pattern. No doubt still other changes will be made as the geology of the region is examined in increasing detail.

EVIDENCE OF FORMER DRAINAGE

Evidence of a former drainage pattern, differing markedly from the existing pattern, is fivefold:

Abandoned major valleys east of the Missouri River.—Several major abandoned valleys lead eastward from the Missouri River trench, all apparently cut into bedrock by large streams before at least the latest major glaciation of the region. Some continue the courses of western tributaries to the Missouri River without a break at the Missouri itself; others leave the Missouri at various distances up or down the Missouri from the mouths of western tributaries. Each valley is distinct in the vicinity of the Missouri trench, and each becomes obscure or is obliterated altogether as it extends eastward beneath an increasingly thick blanket of glacial drift. If later dissection by small streams is discounted, the floors of these abandoned valleys lie more than 115 feet higher than the present channel of the Missouri, thus implying that incision of this amount has occurred since abandonment of the valleys. Accurate determination of floor altitudes, however, awaits more detailed study, inasmuch as near the Missouri the floors are greatly dissected, and farther east they are effectively buried beneath drift.

Former major divides.—Two relatively high areas, in which bedrock lies at or close to the surface, trend eastward at right angles to the existing drainage. They are believed to be breached former divides. One, the Ancient Redfield divide, formerly extended across the James River lowland. The other, the Ancient Mitchell divide, crossed the site of the present James River, but did not extend entirely across the lowland.

Anomalies in the pattern of the Missouri River.—The looplike bends of the Missouri River near the mouth of the Cheyenne River and between the mouths of the Bad and White Rivers are sporadic, atypical, and not part of a systematic series. Therefore they are believed to be not incised meanders, but segments of former minor valleys that were enlarged to form parts of the Missouri and that were quickly smoothed and rounded in ground plan by virtue of the ease with which the Pierre shale is eroded by lateral planation.

Variations in width of the Missouri River trench.—Throughout most of its course from the North Dakota State line to the mouth of the James River the floor and terraces of the Missouri River trench, combined, vary in width from about 1 mile to nearly 3 miles. In general the greater widths occur near the mouths of major western tributaries, whereas the smaller widths occur about midway between those tributaries. As the rocks are flat lying and as no lithologic control is apparent, the differences are attributed to the crossing and local occupation of former valleys, and the crossing of former divides, respectively, by the Missouri. Downstream from the mouth of the James, the Missouri trench widens to 10 miles. This change is believed to be caused by the Missouri River entering the valley of a former major river.

Anomalies in upland slopes near the Missouri River trench.—In many segments of the Missouri trench the upland (plains) surface slopes gently toward the trench both from the west and from the east throughout a belt several miles wide. Such slopes are normal; they reflect the erosional grading of the upland surface in the immediate vicinity of a major valley. However, in other segments the upland surface adjacent to the Missouri trench slopes not toward the trench but away from it, so that the highest parts of this surface are at the edge of the trench itself (fig. 33). A traveler approaching one of these segments of the river is unaware of its presence until he has reached the very brink of the trench. Such slopes are abnormal. In the absence of any lithologic or structural influences that could have controlled them, they seem to indicate a date of origin for the trench so recent as to preclude the grading of the immediately adjacent upland that would occur in time. In other words these anomalous segments of the Missouri are conspicuously younger than the segments with more normal upland slopes.

The anomalous segments are believed to be the sites of small tributary valleys and former divides. During the diversion, divides were transected and tributaries were suddenly occupied by great discharges of water. The result was rapid erosion which, in creating and enlarging the trench, engulfed a number of small valleys, together with the fluted upland surface immediately tributary to them. Thus the fact that the upland slopes away from the Missouri River in these segments is an anomaly only at first sight, for it finds a satisfactory explanation in the sequence of events implied by the abandoned valleys and other features described. The existence of these slopes implies that immediately before the drainage diversion the upland possessed small but distinct relief.

METHOD OF DIVERSION

The five lines of evidence outlined above, amplified by the description of the ancient drainage given on pages 147–152, justify the belief of G. K. Warren and Todd that the Missouri River is a product of the radical reorientation of an earlier east-trending drainage pattern by an ice blockade. The means by which diversion of the former eastward-flowing streams was accomplished is believed to have been as follows: One of the pre-Wisconsin ice sheets, entering eastern South Dakota from the northeast, had an average thickness of at least several hundred feet, compared with a general relief of the country invaded, of the order of 350 feet. Hence that ice sheet probably buried even high points on the Missouri Plateau. Flowing southwestward, this ice lobe blocked all elements of the ancient eastward drainage as far west as the site of the present Missouri River. Because of the ice blockade, the steepest remaining component of the former eastward slope of the land became a slope toward the southeast. The streams became ponded; the main valleys filled with water that gradually backed up into tributaries.

In time each pond rose high enough to spill over the lowest part of the interfluve that separated it from the major valley southeast of it. Most of the low points occurred between the heads of two opposed tributaries. The overflow through each temporary spillway thus formed became quickly intrenched into the underlying rock, which in most places was the extraordinarily weak Pierre shale. In effect the water flowed up one former tributary and down another opposed tributary. As the glacial blockade shrank, it failed to clear the ancient valleys until after the temporary diversion routes across the interfluves had become so deeply intrenched that the diverted waters were unable to return to their former paths. The floors of the ancient valleys, partly filled with drift, were left standing somewhat above the new profile of the diverted water—the initial profile of the present Missouri River.

According to this reconstruction, various segments of the Missouri originated in various ways under the influence of blockading glacier ice. Some segments—chiefly those which cross former divides, as shown on plate 7—originated by direct glacial control, along the immediate margin of the glacier. Other segments originated by more remote glacial control, along tributaries, or segments of tributaries, in the prediversion valley system. In these segments the adjacent upland surface generally slopes away from the trench on one or both sides. A third group of segments came into existence through the occupation, by the nascent Mis-

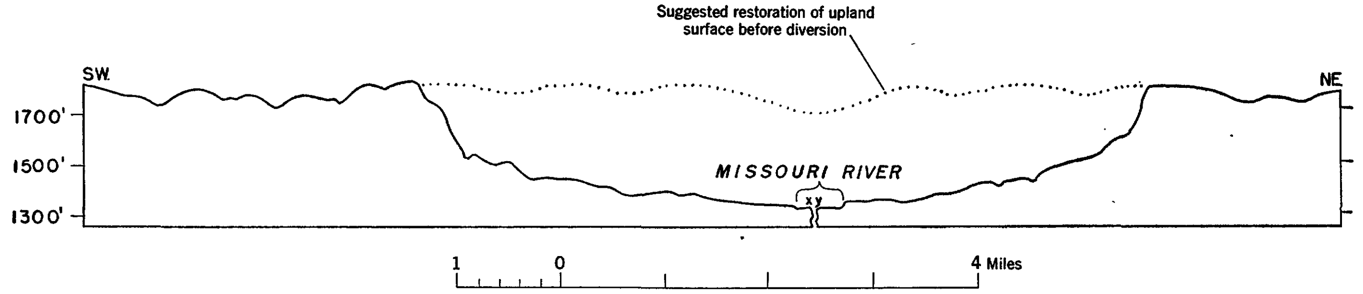

FIGURE 33.—Anomalous upland slopes adjacent to Missouri River trench. Profile north of Chamberlain, showing the upland immediately adjacent to the trench sloping away from instead of toward the trench. The dotted line (conjectural) suggests a possible restoration of the upland surface prior to diversion.

From the center line of the river in sec. 33, T. 106 N., R. 71 W., the profile extends southwest from point *x*. From point *y*, in sec. 16, T. 105 N., R. 71 W., 3 miles downstream from *x*, the profile extends northeastward. In the profile, points *x* and *y* are shown as though they were very close together, in order to avoid distortion caused by bends in the river. Source: Chamberlain quadrangle, U. S. Geological Survey.

souri, of parts of the valleys of major prediversion rivers. Examples are the reoccupied Ancient Cheyenne River segment in Potter, Armstrong, and Sully Counties and the reoccupied Ancient White and Niobrara River segment downstream from Yankton. In both these segments the adjacent upland surface slopes toward the trench.

The margin of the blockading glacier must have lain directly along the course of the Missouri River at the crossings of the ancient divides and close to the Missouri in the remaining segments.

Although the actual time involved in the advance of the glacier margin to its extreme southwestern position (the line of the Missouri River), and in its retreat, is not known, it seems likely that some diversion did occur east of the route described. Indeed such diversion is probable. Most parts of the country east of the Missouri River are so well mantled with drift that one or more diversion channels may be concealed beneath the drift cover. In particular, drift-covered breaks in the Ancient Redfield divide both west and east of Redfield may represent earlier diversions that could have escaped southeastward via the Ancient White River system.

It is probable that the main diversion was accomplished in sequence, from north to south, during the expansion of the glacier. This deduction follows from the northwest-southeast orientation of the ice margin. As the more northerly ancient valleys were invaded, any waters that spilled over and intrenched interfluves north of the Ancient Redfield divide would have been able to escape for a time via the drainage network south of that divide until it too became blocked.

Ponding of the ancient, prediversion valleys by the encroaching ice sheet must have resulted in the deposition of lacustrine deposits. However, little evidence of such deposits can be expected to have survived, inasmuch as the western tributaries to the Missouri have been deepened since diversion by at least 150 feet (measured at the Missouri), and no doubt widened correspondingly in the nonresistant shale into which most of them are cut. In this erosion lacustrine sediments would have been washed away very soon. Except in the vicinity of the glacier, such sediments would have consisted chiefly of clay, derived from the underlying Pierre shale.

In discussing the diversion Todd (1899, p. 52) inferred the presence of an ancient temporary lake, called by him Red Lake, in Brule County. During the present reconnaissance no evidence of such a former lake was seen, and the writer doubts that the water body envisaged by Todd existed.

After the present route of the Missouri River had become established, that stream incised itself deeply below the altitudes of the floors of the prediversion valleys which it now crosses. In the vicinity of its crossing of the Ancient White River, the incision, measured from the ancient valley floor to the bedrock floor beneath the Missouri, amounts to 200 feet, of which about 85 feet lies beneath the present Missouri River.

This incision may have been brought about at least in part by crustal warping. However, as C. R. Warren (written communication) has remarked, warping is not required. From the moment of diversion, the Missouri carried a volume of water much greater than that carried by any one of the prediversion rivers. This would have been true even in the segment downstream beyond the limits of South Dakota, where perhaps no diversion occurred, because, as detailed hereafter, an increment of water that had formerly drained toward the Arctic was being carried down the Missouri toward the Gulf of Mexico. The augmented discharge would have produced a gentler gradient than that of any prediversion stream, and a gentler gradient implies that the long profile of the Missouri would have had an altitude, at any point in South Dakota, lower than that of any prediversion stream at the point of intersection.

It is worth noting at this place that study of the Missouri River in western North Dakota led Alden (1932, p. 44–45) to conclude that diversion of the Missouri from a former Arctic route to its present route occurred at a time when it was flowing on a profile 200 feet or more above its present profile. This figure is comparable with the heights of prediversion stream floors above the present Missouri in South Dakota.

DATE OF DIVERSION

The Missouri trench, at or near its present floor, contains Wisconsin drift (probably including Iowan drift) in many places. Hence the trench, and the diversion, antedate the Wisconsin glacial age. More exact dating is furnished, as yet, in only one area, that in which the Missouri River crosses the ancient valley of the White River. As set forth in the section on pre-Wisconsin nonglacial features, the relations in that area are believed by C. R. Warren, with good reason, to indicate that the Missouri River was born in Illinoian time. Before Warren's evidence (Warren, 1951) was discovered, the present writer (Flint, 1949b, p. 71) had suggested a Kansan date for the diversion, and still earlier Leverett (1932, p. 19) had expressed the opinion that the diversion occurred in Nebraskan time. Warren has shown that the ancient, prediversion White River was still in existence in late Kansan time, as indicated by the vertebrate fossils in its alluvium, and that a very long interval elapsed between the date of the fossils and the diversion itself.

Corroborative evidence is found in the till exposed at the north abutment of the Fort Randall Dam in Charles Mix County (section at locality 4, page 34). The till, evidently of pre-Wisconsin date, immediately overlies a clean bedrock surface and incorporates large quantities of the bedrock in its basal part. These facts suggest (though they do not prove) that the till is the product of the earliest glacial invasion of the locality. The base of the till, here occupying the floor and slopes of a prediversion valley, lies 200 to 260 feet above the bedrock floor of the Missouri trench. (John Trantina, Chief, Engineering Branch, Fort Randall Dam Project, U. S. Engineers: oral communication.) Hence it apparently antedates the diversion that created the trench. However, a glacier margin sufficiently thick and sufficiently long lived to have built more than 100 feet of till in this place would have diverted the ancient drainage. The only record of such diversion is the Missouri trench itself. Hence the glacier that built this till is probably also the one that created the Missouri River.

As indicated on pages 32 and 34, the thickness and physical character of the till point strongly to a pre-Wisconsin date for this deposit. However, the western limits of the Nebraskan and Kansan drift sheets in eastern Nebraska lie well east of the Fort Randall damsite, and evidence of no more than one pre-Wisconsin drift sheet has been seen in southern South Dakota west of the Coteau des Prairies. Hence, when the regional topography is considered, it is unlikely that Nebraskan or Kansan ice penetrated as far west as the site of Fort Randall. By elimination this line of reasoning identifies the thick till body at Fort Randall as probably Illinoian and places the drainage diversion as probably in the Illinoian age.

The presence of Loveland loess in the vicinity of Yankton (localities 9*B*, p. 34; 9*A*, p. 40; 10, p. 52) implies the probability that Illinoian outwash existed in that district and hence that an Illinoian glacier reached the neighborhood of the present Missouri River, at least in the Yankton sector.

Evaluation of facts from the eastern part of South Dakota fails to identify any that are in disagreement with an Illinoian date of diversion; the general evidence therefore is permissive. Accordingly this date is tentatively accepted, pending the discovery of more evidence.

POSSIBLE EARLIER DIVERSION

If the south-trending segment of the Missouri River was created at the time of the Illinoian glacial maximum, the drainage relations during the Nebraskan and Kansan glacial maxima must be considered. There is little or no direct evidence as to the diversion of drainage at those times, probably because the surfaces that must have existed then have been largely or wholly destroyed by erosion, particularly in the region of the James River lowland. Hence any segments of valleys cut by early Pleistocene streams may have been obscured or entirely destroyed.

The positions and trends of the Kansan and Nebraskan drift borders in northeastern Nebraska (pl. 3) suggest that one or both of the corresponding glacier margins may have continued northward across eastern South Dakota. If so the eastward-flowing streams, meeting the ice, should have been diverted southward at least temporarily. The most likely path for such diverted water to have followed, without leaving direct evidence, is down some part of the James River lowland. It would then, however, have had to continue southward across eastern Nebraska as long as glacier ice blocked the preexisting valleys leading eastward. The valley profile or profiles across eastern Nebraska would have had to be at least as high as the present land surface in that region, because no abandoned or buried south-trending valleys of pre-Wisconsin time are known there.

Any valley floor as high as the present land surface in northeastern Nebraska would have had a minimum altitude of 1,600 to 1,700 feet. Upstream, in South Dakota, its altitude necessarily would have been even greater. As such altitudes would have been approximately 400 feet above the floor of the existing James River lowland, little evidence of any former valley of the kind sketched can be expected to have survived. Therefore reconstruction of major pre-Illinoian drainage diversion in eastern South Dakota is speculative.

POST-DIVERSION EVENTS

INCISED MEANDERS

Through the first 15 miles westward, upstream, from its mouth the valley of the White River has conspicuous incised meanders. The valleys of the Bad, Cheyenne, Moreau, and Grand Rivers likewise have elongate upland spurs between meanders that suggest the remnants of incised-meander forms now nearly destroyed by valley widening. In these valleys, too, the forms suggestive of incised meanders are confined to the segments within a few miles of the valley mouths. Upstream from these segments the valleys are normal, open trenches.

It was suggested by C. R. Warren (written communication) that the meanders may have developed on lacustrine fills accumulated when the valleys were blocked by the glacier responsible for the diversion. Incision by the newly created Missouri River, to form the Missouri trench, would have rejuvenated the truncated western rivers, and if they meandered, immediately following the draining of the temporary lakes, the meanders would have become superposed on the underlying bedrock. If such meandering and incision did in fact occur, they are the only direct record thus far found of pre-Wisconsin ponding of the western streams.

VALLEYS WEST AND SOUTH OF THE MISSOURI RIVER IN THE WISCONSIN AGE

In the sector extending eastward from the mouth of the Niobrara, the Iowan glacier crossed the Missouri River into Nebraska. In that sector, where there were no large streams flowing northward into the Missouri, extensive ponding of drainage by the glacier is not expectable. However, in Knox and Cedar Counties, Nebr., there are capacious high-level channels, blanketed with loess and apparently younger than the Loveland loess. They are interpreted by H. E. Simpson[40] as temporary diversion routes of the Missouri, around the margin of the blockading Iowan and Cary glaciers

Inasmuch as the Iowan glacier attained an extreme limit many miles west of the Missouri River in South Dakota, it may well be asked why the events of the Illinoian diversion were not repeated, at least on a reduced scale, in Iowan time. Search has failed to disclose any divide transections, which, if any had been created, should have been cut quickly into the weak Pierre shale.

It is likely that expansion of the Iowan glacier, westward from the site of the Missouri River to the limit of glaciation, took place very rapidly, and that the margin of the ice did not pause at its outermost position, but very quickly shrank back to or east of the position of the Missouri. This reconstruction is consistent with the fact that, west of the Missouri, drift is very scanty, consisting chiefly of scattered boulders, and that elsewhere, as noted earlier, the Iowan drift is thin and is not characterized by end moraines. But the reconstruction seems to be required by the absence of diversion channels and transected interfluves west of the river. If the ice had remained west of the river for a long period, such features would have been formed by the runoff that would inevitably have had to escape. On the other hand, if glaciation west of the river was very short lived, the accumulating runoff possibly could have been held in the wide valleys, and released via the Missouri River route before the ponded waters rose high enough to overflow at any point farther west. Hence it is suggested that glacial expansion and subsequent shrinkage across the plateau west of the Missouri required less time than the filling of the blocked valleys to the stage of overflow. An attempt to calculate the elapsed time in years would have little meaning because the contemporary river discharges are not known. However, the matter is simplified by the existence of the Missouri River trench, already established during the Illinoian glaciation. Therefore the Iowan ice probably crossed the Missouri with no ponded water accumulated in the blocked valleys, and hence with maximum storage capacity available to outlast the glacial occupation of the country west of the river.

The only alternatives to this hypothesis seem to be either a subglacial or a superglacial escape route along the Missouri trench, or an outlet by percolation through alluvium on the floor of the trench beneath the ice. Neither alternative has great appeal, because there is no record that the trench contained much permeable alluvium at the time in question, and because of the physical obstacles to so long a subglacial or superglacial escape route. However, any leakage that may have occurred through either of these means would have operated to extend the time available for retreat of the glacier margin to the line of the trench.

Farther north, in eastern Montana, the Iowan glacier ponded the Yellowstone River, and in North Dakota forced the cutting of temporary stream channels along the ice margin in the country southwest of the Missouri River (Alden, 1932; A. G. Leonard, 1916). In South Dakota, however, the conclusion seems unavoidable that glacier shrinkage was rapid enough to permit the escape of water down the Missouri trench before any one of the temporary lakes could fill its basin, overflow, and transect an east-west divide.

If the Iowan glacier ponded the western tributaries to the Missouri only temporarily, very little lacustrine sediment should have accumulated, and on the prevailing steep slopes underlain by Pierre shale, postglacial flushing away of sediment should have been effective, promoting the removal of such lacustrine sediment as was present.

Very little material that could be attributed to glacial ponding has been seen. The most convincing section reported is in the SE¼ sec. 16, T. 103 N., R. 73 W., Lyman County, in a draw tributary to the White River. Here C. L. Baker (written communication) of the South Dakota Geological Survey measured 135 feet of deposits consisting of 12 feet of sand and gravel, chiefly of western origin, conformably overlain by parallel-bedded sand, silt, and clay, becoming generally finer toward the top.

Detailed mapping of the glaciated region west of the Missouri can be expected to yield at least some additional remnants of lacustrine fills of similar character.

MISSOURI RIVER TRENCH

During Pleistocene time the Mississippi River repeatedly carried outwash sediments southward, away

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[40] Simpson, H. E., 1952, Geology of an area about Yankton, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, p. 262–271.

from a very broad sector of the ice sheet. The record of these events is present in outwash fills, having some continuity even though now considerably dissected.

The Missouri River in South Dakota has no such record, because the regional bedrock is chiefly very weak shale, outwash sediments are generally thin, and terrace remnants are generally very discontinuous. Furthermore outwash sediments entered the Missouri River trench through a number of tributaries spaced rather far apart, and the glacier itself repeatedly invaded the trench. Thus the hydraulic long profiles assumed by the Missouri at various times were greatly complicated. Finally, the extensive slumping that has occurred throughout that trench ever since it was cut, has further obscured the terrace relationships.

Reconnaissance of the trench in 1946 made it clear that mapping and correlation of the terraces would require very detailed study. In 1947 and 1948 the Geological Survey began detailed geologic mapping of quadrangles cut by the trench in three districts: the Yankton district by H. E. Simpson, the Chamberlain district by C. R. Warren, and the Pierre district by D. R. Crandell. Among the many results of these studies was an understanding of the character and probable correlation of the terraces.

Neither outwash nor cut terraces of Illinoian age have yet been identified. This is not surprising in view of the inference, already stated, that the trench itself did not come into existence until Illinoian time. Excavation of the trench was accomplished by overflow waters that should have had very small bed loads and that were flowing on generally steep initial gradients. Under such circumstances neither terracing nor outwash sediments are to be expected.

The Wisconsin terrace relationships in the Chamberlain area are represented in figure 34. According to C. R. Warren[41] the earliest outwash fill includes a considerable proportion of gravel. As this fill is overlain in places by Cary till, it is believed to date from the Iowan and Tazewell subages (undifferentiated). The Cary ice left a record of kame terraces as well as till, and well down in the trench a fill terrace consisting of a variety of sediments, ranging from cobble gravel to clay, is believed to be Cary outwash. A lower and still younger fill terrace, consisting mainly of sand and silt, is tentatively considered to be outwash derived from Mankato ice that did not enter this part of the trench.

The Wisconsin relationships in the Pierre area are shown in figure 35. In that area the Cary ice did not enter the trench, and, because the Iowan and Tazewell drifts are not easily differentiated from each other, dating of the terraces and fills is difficult. According to Crandell,[42] various bodies of outwash and ice-contact stratified drift, mostly coarse textured, at high and medium altitudes are tentatively separated into Iowan and Tazewell categories. At low altitudes a thick fill of finer textured sediments is interpreted provisionally as Cary and Mankato outwash. As far as is now known, the nearest source of Cary outwash at Pierre was the major sublobe in eastern Sully County. This sublobe contributed melt water to the Missouri via Okobojo Creek, along which are remnants of a Cary outwash body. However, as the distance from the end

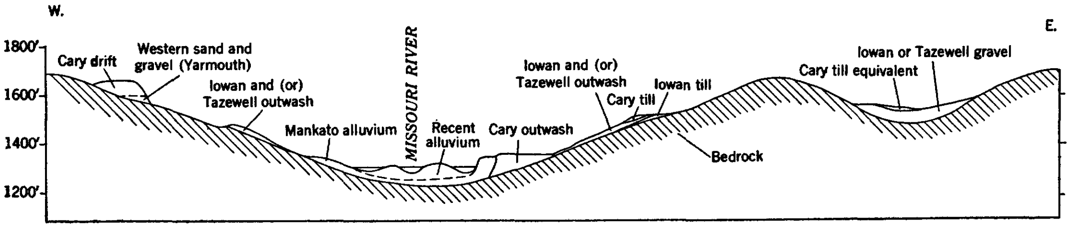

FIGURE 34.—Idealized profile and section, about 5 miles long, showing the relations of deposits occurring in the Missouri River trench near Chamberlain, S. Dak. Bodies of loess not shown. After C. R. Warren.

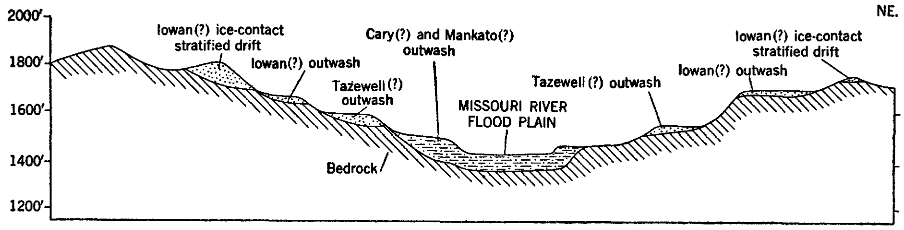

FIGURE 35.—Idealized profile and section about 3 miles long, through the Missouri River trench in the vicinity of Pierre. (D. R. Crandell.)

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[41] Warren, C. R., 1950, Preliminary report on the geology of part of the Chamberlain, S. Dak., quadrangle: U. S. Geol. Survey, manuscript on open file.

[42] Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, p. 170–188, 201–210.

of the sublobe to Pierre, via Okobojo Creek and the Missouri River, is more than 35 miles, outwash at Pierre from that source alone could hardly be either coarse or abundant. Other sources, such as the Cary ice that drained into the Missouri via Swan Creek in Walworth County, and the Cary ice that presumably entered the Missouri River trench itself somewhere to the north, can be invoked.

The earliest outwash fill in the Chamberlain area has distinctive characteristics that have been recognized in reconnaissance of the gravel remnants along the Missouri River between Chamberlain and Pierre. These remnants correspond essentially with those described and shown on a useful map by Rothrock (1944). What is apparently the same fill is dated by Crandell [43] as Tazewell(?) on the basis of its relationship to end moraines near Pierre. Other high-level fill remnants farther north up the Missouri may well be of this same date. A broad outwash mass at the mouth of Spring Creek, Campbell County, derived from nearby Mankato ice, stands 95 feet above the Missouri River. This presumably marks the vertical position of a former Mankato fill in the trench in that vicinity.

The fill and terrace relationships in the Yankton area yield a less complete record of Wisconsin events than those farther up the river, in part, perhaps, because both Cary ice and Mankato ice invaded the Yankton segment of the trench and, together with their melt waters, doubtless destroyed much of the record of earlier events. The features recognized are shown in figure 36. They are constructed from data assembled from a belt of country 8 miles wide, and supplied by H. E. Simpson.

Yankton Ridge is the bedrock interfluve that separated the Ancient Niobrara valley from that of one of its minor tributaries, now much deepened and occupied by the Missouri River. At some time before the Illinoian age, the Niobrara filled its then shallow valley with western sand and gravel, which spread over Yankton Ridge.

Later, after much erosion had occurred, Illinoian till and glacial gravel were deposited on the southern slope of Yankton Ridge, and the Missouri River came into existence. Thereafter the Loveland loess was deposited, presumably from the reworking of Illinoian outwash that was later entirely removed, and was weathered during the Sangamon age.

Iowan till was then laid down by ice that crossed the Missouri River into Nebraska, and the till was covered with thick loess. Cary ice then invaded the trench, depositing till on its northern slopes, and loess succeeded the till. Mankato ice entered the trench, and for a time probably confined the Missouri to a narrow channel between the glacier terminus and the chalk bluffs of the Niobrara formation on the Nebraska side of the trench. As this glacier melted, fine-grained sediments, chiefly outwash, filled the lower part of the trench cross section. The fill was later dissected to form terraces as the Missouri reduced its profile. The highest terrace labeled "Post-Mankato" in figure 36 corresponds with the alluvial floor of the James trench, and is believed to have been completed at the time when the James River ceased to discharge glacial melt water from North Dakota.

Between Chamberlain and Yankton, terrace remnants are not numerous, and bedrock crops out prominently through considerable distances on both sides of the trench. Beginning at Running Water and extending at least as far upstream as the Fort Randall damsite are many exposures of laminated silt and clay, locally with pebbles, extending as much as 60 feet above the river. These deposits, evidently lacustrine, are not clearly related to terraces, and their date is uncertain. It seems likely that they represent the partial filling of a temporary lake created by an ice dam when the James glacial lobe blocked the trench near Yankton, probably in Makato time.

Between Yankton and the southeastern corner of the State, terrace remnants are few. The geologic map of the Elk Point quadrangle (Todd, 1908) is representative of the conditions in that part of the trench.

In summary, it seems likely that few if any individual fills can be traced as terrace remnants throughout the segment of the Missouri River that traverses South Dakota. Probably fills originated, or were conspicuously augmented, in sectors where they were fed directly from glacier ice, and their long profiles sloped

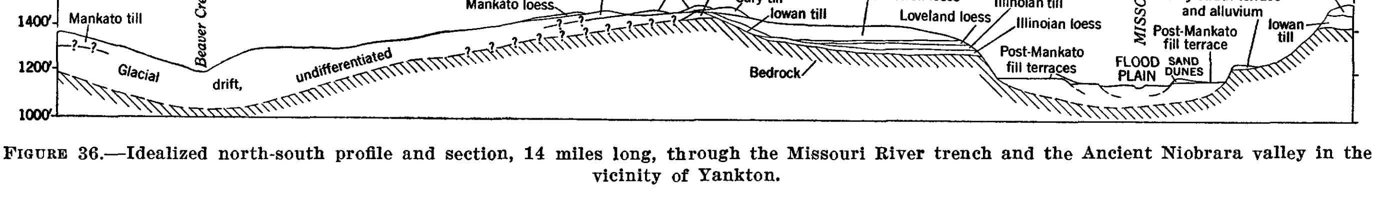

FIGURE 36.—Idealized north-south profile and section, 14 miles long, through the Missouri River trench and the Ancient Niobrara valley in the vicinity of Yankton.

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[43] Op. cit.

so much more steeply than the slope of the present trench floor, that correlation from one segment to another without detailed work between them can be only very tentative. The field worker must be prepared to expect a fill on a high terrace at one point to be represented by a low terrace farther downstream, and possibly still farther on, to be buried beneath a younger fill.

The Missouri River is now flowing on a flood plain of variable width, underlain by silt and sand. At no point in South Dakota is the river flowing on bedrock. However, the position of the lowest part of the bedrock floor beneath the Missouri River alluvium is known at only a few places. The data are assembled in the following table:

Probable depths to lowest part of bedrock floor of Missouri trench beneath alluvial fill

[Measured from mean low water]

Locality	Depth (feet)	Authority
Garrison damsite, N. Dak	175	Corps of Engineers, U. S. A.
Bismarck, N. Dak	70-80	A. G. Leonard (1916, p. 297).
Mobridge, S. Dak	119	Corps of Engineers, U. S. A.
Forest City	134	Do.
Little Bend damsite, near mouth of Cheyenne River.	143	Do.
Oahe damsite, 6 miles upstream from Pierre	79	Do.
Chamberlain	87	Do.
Mulehead damsite, 8 miles upstream from the Rosebud Bridge at Wheeler.	85	Do.
Fort Randall, 14 miles downstream from the Rosebud Bridge at Wheeler.	189	Do.
Gavin's Point, 8 miles upstream from Yankton.	139	Do.
Gavin's Point damsite, 4 miles upstream from Yankton.	135	Do.
Near Elk Point	*100	Todd (1908, p. 8).

*Greatest depth known; maximum depth not reported. Value represents depth below flood plain; depth below mean low water 10 to 15 feet less.

The data indicate that the depth is variable, but the cause of the variations is obscure. Concievably the differences could have been produced by variations in the erosive ability of the Missouri at different points on its bed profile under a single regimen. The date of deepest scour likewise is unknown. Todd (1923, p. 474) stated that the bed of the Missouri had been known to be deepened, within a few hours of flood dischrage, as much as 75 or 85 feet below its depth at mean low water. If this is so, then possibly most or all of the depth to bedrock beneath the Missouri trench may be the result of scour during exceptional floods under the present regimen. On the other hand the bedrock floor may have been cut at the time the trench was created, and the river may have been flowing on a fill or fills of outwash and alluvium ever since that time. C. R. Warren[44] found inconclusive evidence suggesting that during the Tazewell-Cary interval the profile of the Missouri River in the Chamberlain area was somewhat lower than the present one.

EAST OF THE MISSOURI RIVER

PREDIVERSION DRAINAGE SYSTEM

The radical diversion of the drainage of the eastern part of the State from an east-flowing system to a generally south-flowing system was an event of such wide importance that it constitutes a time marker from which both earlier and later events are dated. Believed to have occurred in Illinoian time, the diversion therefore separates Sangamon and Wisconsin history from pre-Illinoian history.

A belt of country about 10 miles wide, lying immediately east of the Missouri River trench, includes, at relatively high altitudes, vestiges of subflat surfaces that probably are continuations of the erosion surfaces west of the trench. They seem to have been preserved only where the drift is thin and where, by inference, glacial erosion was not very effective. Aside from these remnants, and aside from the segments of prediversion valleys preserved beneath the drift, probably no erosion surfaces are preserved east of the Missouri.

An attempt to reconstruct elements of the prediversion drainage system is shown on the map, plate 7. The streams there reconstructed have been restored mainly from four kinds of evidence: abandoned-valley segments still topographically distinct, linear areas of collapsed drift from which the presence of underlying valleys is inferred, anomalous divides still topographically distinct, and bedrock outcrops and records of borings showing depths to bedrock. The evidence is of varying reliability, and no accuracy is claimed for the reconstruction. Plate 7 represents simply the most reasonable synthesis the writer has been able to make from the spotty data available. The accumulation of additional subsurface data would certainly change the pattern in detail, and might change some of its major elements.

The inferred buried valleys are traced with least difficulty in the two coteaus and with much more difficulty and less detail in the James River lowland. Undoubtedly this difference arises from the greater glacial erosion of the lowland than of the coteaus; in places valleys in the lowland seem to have been obliterated by that process. The fact that linear depressions, apparently segments of valleys, are present beneath the Mankato drift in the lowland, can be explained in two ways. The first is that the valleys constitute parts of the prediversion system, and that subsequent glacial erosion did not go deep enough to obliterate them. Very likely this is true in the district immediately south of the Ancient Redfield divide, where glacial erosion should have been less effective than in other parts of the lowland, and it may be true elsewhere.

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[44] Op. cit.

The second explanation is that the buried valleys may have been cut by streams during the intervals between the Wisconsin glacial subages, following partial or complete obliteration of the prediversion valleys by glacial erosion. The data available are inadequate to make possible the elimination of either explanation. In view of the evidence, set forth hereafter, of general effective glacial erosion of the lowland, the second explanation may be more widely applicable than the first, but the matter remains unsettled.

In amplification of plate 7, a brief description of the prediversion stream pattern seems necessary. The pattern reveals two former river systems, that of the Cheyenne, which flowed northeastward out of the State, and that of the White, which left the State by a southeasterly path.

ANCIENT CHEYENNE SYSTEM

CHEYENNE RIVER

East of the Missouri trench the Ancient Cheyenne River is represented by a large abandoned valley, in places nearly 5 miles wide, partly filled with drift. The western end of the valley, opening out of the Missouri trench, is occupied and incised by Little Cheyenne Creek, a small tributary to the Missouri. The towns of Hoven (Potter County) and Loyalton (Edmunds County) stand within it. Between these towns the valley is obscured by thick bodies of Cary and Mankato drift that lie across it nearly at right angles. With a visible length of about 50 miles, the abandoned valley is collinear with the existing Cheyenne River west of the Missouri River, and with a 30-mile intervening segment of the Missouri itself.

East of Loyalton the abandoned valley is no longer visible as such, having been obliterated partly by glacial erosion but even more by the deposition of thick drift over it. In the vicinity of the junction of Edmunds, Brown, Spink, and Faulk Counties its presence beneath the surface is inferred from an elongate area of collapsed drift, with many deep depressions of which Scatterwood Lake is a conspicuous example. From this point onward the course of the Ancient Cheyenne is very uncertain. Meager subsurface data suggest that it flowed northward through east-central Brown County. The area of collapsed drift in Dickey County, N. Dak., described by Hard (1929, p. 28) possibly marks its continuation. Still farther northeast, as was long ago suggested by Upham (1894, p. 244), this river probably followed a route approximately coincident with that of the Red River, and, via the Lake Winnipeg and Hudson Bay lowlands, eventually emptied into the Arctic Ocean. Upham interpreted the prowlike northern point of the Coteau des Prairies as the headland between two large confluent stream valleys, the Ancient Minnesota, which then drained northward, and the valley here called the Ancient Cheyenne. Although the "prow" has been considerably modified by glacial erosion, Upham's interpretation is believed sound. The James River lowland north of Redfield is, then, the northeastern continuation of the Ancient Cheyenne, very greatly widened by glacial erosion.

MOREAU AND GRAND RIVERS

The Ancient Cheyenne River was joined by the Ancient Moreau in the vicinity of Hoven, Potter County. Hoven lies at the east end of a capacious valley 25 miles long, collinear with the valley of the existing Moreau, and drained by Swan Creek, which flows westward into the Missouri.

The Ancient Grand River flowed across the site of the Missouri at Mobridge and flowed eastward through the deep and wide valley, now abandoned, in which the town of Glenham, Walworth County, lies. This valley, 400 feet below the upland, extends through the southeastern part of Campbell County and turns southeastward past Bowdle, to join the Ancient Cheyenne valley in Edmunds County. The abandoned valley is obscured by thick Mankato drift in the Bowdle sector, but emerges distinctly in T. 122 N., R. 72 W., near its mouth.

The Ancient Grand, in turn, was joined north of Selby, Walworth County, by an important tributary that originated in North Dakota and that entered South Dakota along the line of the Missouri River. Turning easterly, it followed a wide valley past Herreid and Mound City, Campbell County, to join the Ancient Grand River. The former valley is now incised and drained in the reverse direction, between Herreid and Pollock, by Spring Creek. South of Herreid it is not occupied by a stream.

WESTWARD-FLOWING TRIBUTARIES

Some of the elements in the Ancient Cheyenne River system reflect the southeastward orientation that is common in the territory west of the Missouri. Several large tributaries, however, are remarkable in that they flowed westward, entering the master streams with an acutely barbed pattern. The valley of one of them, Spring Creek, in McPherson and Campbell Counties, is still occupied by a stream flowing westward. The explanation lies in the fact that the west-flowing streams drained a high part of the Coteau du Missouri that is capped with Fox Hills sandstone, apparently having a gentle westward dip. Evidently the streams developed as consequents on the gently sloping plateau surface. The inferred floor of the Ancient Cheyenne River valley in Edmunds and Faulk Counties lies well below the base of the Fox Hills sandstone to the north. This fact implies that the Cheyenne had already breached the sandstone, and was trenching the underlying Pierre shale, before the great diversion took place.

Undoubtedly the Ancient Cheyenne was joined in Brown County by a series of small subparallel streams that descended the western flank of the Coteau des Prairies. Truncated segments of those valleys are seen in the nearly flat summit of the coteau, but are not apparent on its steep flank, probably because the Pierre shale, into which they were cut, has been severely planed back by glacial erosion. The valleys farther south, on the west flank of the coteau, are in strong contrast, for the larger ones among them are still preserved, probably because the trend of the coteau flank there was favorably oriented to escape deep glacial erosion.

MINOR DIVIDES

Within the area of the Ancient Cheyenne River system the Missouri River transects four former divides. The positions of these are shown on plate 7. At the crossings the plateau surface is slightly higher than elsewhere along the Missouri, and at three of them the Missouri trench is narrower than elsewhere. As the bedrock is uniformly weak throughout this area, the narrows testify to the relative recency of the diversion.

Another divide within the Ancient Cheyenne system trends east of north through eastern McPherson County and continues into North Dakota. It coincides with the crest of the eastern scarp of the Coteau du Missouri, and was determined originally by the eastern limit of outcrop of the west-dipping Fox Hills sandstone. Its transverse trend, therefore, is the consequence of structural control.

ANCIENT REDFIELD DIVIDE

The principal divide in the prediversion drainage network had an eastward trend and separated the Ancient Cheyenne River system from the Ancient White River system. West of the James River lowland it is still a divide; within the lowland it is no longer so, for it has been breached, not only by the James River in Mankato time, but also very likely by outflowing melt water before that time. This former divide, here referred to as the Ancient Redfield divide because the town of Redfield, Spink County, is situated on it, is believed to have constituted part of the continental divide, separating the watershed of the Gulf of Mexico from that of the Arctic Ocean. Today, at the longitude of Redfield, the continental divide lies in North Dakota, 300 miles north of its former position.

The Ancient Redfield divide lies across the Missouri River about 10 miles downstream from the mouth of the present Cheyenne, and trends northeastward across Sully and Potter Counties as a conspicuous broad, swell-like ridge surmounted by a row of buttes, the Sully Buttes. Continuing eastward across Faulk County, it includes the high Orient Hills and extends across the James River lowland at latitude 44°50′ to 45°00′. At this latitude, bedrock crops out in two series of low hills, south and west of Redfield and in the vicinity of Doland and Turton, Spink County. Bedrock is also found beneath the drift at depths of only a few feet to a few tens of feet along that part of the divide between Frankfort and Doland. The bedrock surface, found in well borings, slopes gently northward and southward away from the divide, to depths of more than 100 feet.

Through a distance of about 12 miles along the divide eastward from Rockham, Faulk County, bedrock does not crop out, and subsurface data are lacking. It is possible that the divide may have been breached in this place, the breach having been filled with drift. Immediately east of Redfield the bedrock surface drops abruptly to a depth of 145 feet, as indicated by the log of a well in sec. 3, T. 116 N., R. 64 W. Lake Dakota sediments account for only the uppermost 10 feet of this depth, and outwash for only 15 feet more; the remainder of the log shows till. The log therefore suggests a breach in the divide antedating the Lake Dakota outflow. The breach can be attributed in part to glacial erosion, and in part to melt-water erosion antedating Lake Dakota. The map, plate 1, shows that the dam that retained the southern end of Lake Dakota was not the Ancient Redfield divide, but a mass of drift south of the divide. This indicates that the divide had already been breached (perhaps repeatedly) before Lake Dakota came into existence.

Persistence of the ancient divide, despite repeated glacial erosion, is hardly surprising, because apparently this feature was broad and had rather gentle slopes and hence did not constitute a steep, localized obstacle to the flowing ice sheet.

ANCIENT WHITE SYSTEM

WHITE RIVER

South of the Ancient Redfield divide the master stream was the Ancient White River, with large and important tributaries. Collinear with the existing White River valley west of the Missouri, the valley of the Ancient White is exposed in cross section in the eastern wall of the Missouri River trench 10 miles south of Chamberlain (fig. 11). The deepest part of its floor lies 115 feet above the mean water surface of the Missouri River. The ancient valley, as much as 2.5 miles wide and as much as 150 feet deep, trends northeastward across the Coteau du Missouri as a distinct topographic feature. It is delineated by the contours on the Iona, Pukwana, Kimball North, and Crow Lake topographic quadrangles. At two points in Brule County the position of the bedrock surface beneath the drift-covered valley floor, as shown by well logs (C. L. Baker, written communication), indicates a gentle gradient toward the northeast.

Where exposed in the Missouri trench the ancient valley contains western sand and gravel, not only on its floor but capping a terrace on its northwestern slope. All the sand and gravel is now covered with drift. Western pebbles like those in the gravel are incorporated in the drift at many places in Brule County (C. R. Warren, written communication), and in the western part of Aurora County.

In its course across the coteau the Ancient White is joined by three principal tributaries. One, entering at Pukwana, is a combination of American Crow Creek, a segment of the Missouri itself, and American Creek, now reversed. The second is a similar combination of Medicine Creek in Lyman County, a segment of the Missouri itself, and parts of Crow and Smith Creeks, now reversed, in Buffalo and Brule Counties. The third tributary consists of two branches, Elm Creek and Crow Creek, both heading well to the north in Hand County.

The two streams last named have remained essentially unchanged since before the diversion. Lying in the lee of a major topographic barrier, they received comparatively little drift, and were so oriented as to have been kept open by melt water discharging through them into the Missouri River trench.

Upon leaving the coteau and entering the James River lowland the Ancient White, like the Ancient Cheyenne, is traced by means of discontinuous linear areas of collapsed drift aligned across Aurora, Sanborn, Miner, and McCook Counties. Throughout this segment it is joined by numerous tributaries, some long, entering it from both sides. Although, as stated earlier, buried valley segments in the James River lowland may postdate the diversion, the prediversion streams must have had an essentially similar pattern.

Maps showing the surface of the Sioux quartzite beneath the drift in the southeastern part of the State (Darton, 1909, pl. 10, p. 32; Todd and Hall, 1903, artesian water sheet) strongly suggest that the Ancient White was superposed across a low ridge of quartzite at a point about 2 miles east of Spencer, McCook County. The maps show the quartzite ridge to be much narrower at that place than elsewhere, and to have a general altitude of slightly more than 1,300 feet. The control points on these maps are inadequate to show whether or not the quartzite surface is actually trenched, but the data assembled suggest that the altitude of the valley floor may be considerably less than 1,300 feet. It is very probable that at the time of diversion the Ancient White was flowing on quartzite at this place. If so, it descended at least 130 feet, in the 115 miles between the Missouri trench and Spencer, and thus would have possessed a valley-floor gradient, exclusive of irregularities in its channel, of a little more than 1 foot per mile, a gradient comparable with that of the Missouri today. If the quartzite ridge acted as a local base level, the gradient downstream from the ridge was probably steeper than that upstream from it.

Downstream from the inferred quartzite crossing, the Ancient White River valley can be traced by means of well logs and is evident also in the existing topography. In McCook County the former stream received a major tributary from the west, which also seems to have crossed the Sioux quartzite (Todd and Hall, 1903). This tributary is evident in the present surface from its source in the Bijou Hills to the southeastern corner of Aurora County, where, in sec. 13, T. 101 N., R. 63 W., it is obliterated by the margin of the Mankato drift. From that point eastward it is evidenced only by subsurface data and by areas of collapsed drift.

In the northern part of Turner County the presence of the broad Ancient White River valley, widened by glacial erosion, induced conspicuous lobations in both Cary and Mankato end moraines. Near Hooker, in Turner County, a large tributary enters the valley of the Ancient White from the northeast. The large size of the tributary is indicated by the width of a broad, shallow sag that extends obliquely across Lincoln County. The branches of this tributary headed in South Dakota; others entered the State from southwestern Minnesota. A "preglacial" stream in approximately this position was inferred by Todd (1899, p. 109).

Continuing into Clay County, the Ancient White is entered by a northeastern tributary, about 10 miles north of Vermillion. From Vermillion downstream, the ancient valley is essentially coincident with the existing Missouri River trench. Near Elk Point it is believed to have received a tributary that occupied the position of the present lower Big Sioux River.

Almost certainly the Ancient White flowed southeastward to the Mississippi. Whether it flowed southeastward across Iowa immediately prior to the diversion, or whether one of the earlier ice sheets had already diverted it southward from near Sioux City, Iowa, to the Platte in southeastern Nebraska, is not known.

At any rate the James River lowland south of the Ancient Redfield divide is the southeastern continuation of the Ancient White and of its tributary the Ancient Bad. It has been very greatly modified by glacial erosion, which was greater on the western convex side of the arcuate James glacial lobe than on the better-protected eastern concave side. This difference may explain why the present James River, flowing along the long axis of the former lobe, has reoccupied the prediversion drainage system only locally, being otherwise well to the west of it.

BAD RIVER

The principal tributary to the Ancient White flowed in the Ancient Bad River valley. Crossing the Missouri River trench at Pierre, at an altitude of more than 200 feet above the present Missouri River, this ancient valley[45] traverses Hughes County and the southeastern part of Sully County. North of Harrold it is obliterated by a massive Mankato end moraine. Across Hyde County its position is uncertain, but it becomes visible again in Hand County, and continues across southern Spink County, turning south through Beadle County to join the Ancient White in Sanborn County. It received a number of tributaries, notably the extended Chantier and Antelope Creeks in the Pierre district, an extended and reversed Okobojo Creek in Sully County, Turtle Creek in Hand and Spink Counties, and streams entering from both west and east in Beadle and Sanborn Counties.

RELATION OF DIVIDES TO STREAM PATTERN

Divides in the Ancient Bad River drainage basin, breached during the creation of the Missouri River, are distinct even today. One, a broad high swell, extends across the Missouri in the northwestern corner of Hughes County and trends northeastward to Eakin in Sully County. Another lies across the Missouri 3 miles north of Pierre, and including Snake Butte, continues eastward to near Blunt. A third is 7 miles southeast of Pierre. The most conspicuous, however, is the ancient divide that separated the Bad River from the White. Extending across the Missouri near De Grey, Hughes County, it crosses Hyde and Hand Counties and swings southward into Jerauld County. The divide is high and conspicuous today because its higher parts, the Ree Hills and Wessington Hills, are capped with resistant rocks of the Ogallala(?) formation. The eastern and northern scarp of this divide, and the southward trend of the Ancient White River tributaries that drain it, suggest that the cap rock had the form of a very shallow syncline plunging slightly toward the south.

In their courses across the Coteau du Missouri the Ancient Bad and the Ancient Cheyenne paralleled each other, scarcely more than 35 miles apart, across the intervening Continental Divide; yet having reached the longitude of the present James River lowland they diverged from each other. Even if the valleys buried beneath the lowland were cut after the diversion, the courses of the major prediversion rivers must still have followed the lowland and therefore could not have been very far from the valleys shown on plate 7

Probably the explanation of the divergence lies in the distribution and attitude of the strong cap rocks: the Fox Hills sandstone in McPherson County and the sedimentary rocks of the Ogallala(?) formation south of the Ancient Bad. The intervening country, in which high residuals capped with resistant rocks do not exist today (except possibly in the Orient Hills), provided conditions for more rapid downcutting than did the terrain to the north and south. Indeed both ancient major valleys make their respective turns through the James River lowland in remarkable parallelism with the eastern faces of the highlands capped with resistant strata (pl. 7). From the fact that these ancient valleys do not continue eastward across the Coteau des Prairies it may be inferred that a resistant cap was once widely present on that highland also. Furthermore the component strata revealed by well logs dip very gently westward. The dip is reflected further in the pattern of the prediversion drainage, shown in plate 7, in which the principal valleys drain southwest. These considerations combine to frame a reasonable explanation of the pattern formed by the Ancient Bad and Cheyenne Rivers.

Farther south another ancient divide, separating the Ancient White from the Ancient Niobrara and other tributaries, is outstanding. This divide is marked by hills capped with Ogallala quartzite, the Iona Hills in Gregory County and their continuation in Brule County, the Bijou Hills. The divide is transected by the Missouri River trench at the junction of Brule, Gregory, and Charles Mix Counties, where the trench, conspicuously narrow, is incised more than 800 feet below the tops of the buttes on the divide. Inconspicuous in Aurora County, this divide reappears in Davison and Hanson Counties as a discontinuous group of hills exposing bedrock (chiefly Carlile shale and the Codell sandstone member) in many places. In Davison and Hanson Counties, it crosses the western part of the James River lowland, its crest near the city of Mitchell. For that reason it is here termed the Ancient Mitchell divide.

NIOBRARA RIVER

The Ancient Niobrara River valley, as recognized by Todd (1912), followed the route of the existing Missouri River trench from the present mouth of the Niobrara opposite Running Water, Bon Homme County, to a point about 4 miles east of Springfield. Thence it continued northeastward through Tabor and Utica, around the northern flank of Yankton Ridge (fig. 36), continu-

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[45] Described in detail within the Pierre area by Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation.

ing again along the existing Missouri River trench to Vermillion, where it emptied into the Ancient White. Tributaries to the Ancient Niobrara are shown in plate 7. The longest of them headed in northwestern Charles Mix County, and with its lesser tributaries has the southeastward orientation that is common west of the Missouri. This tributary is marked by a broad, shallow sag in the topography, contains the southern part of the basin of Lake Andes, and is clearly traceable eastward as far as Delmont, Douglas County. At that place it is transected obliquely by thick Mankato drift, which narrows it for several miles and, farther east, obliterates it entirely. In Hutchinson and Yankton Counties the valley reappears as a topographic feature, having been reexcavated by the James River and its predecessors.

Two minor tributary valleys, those of the ancient extended Whetstone and Randall Creeks in Charles Mix County, are conspicuous as deep, empty, high-level valley segments lying respectively south and west of Lake Andes.

Other tributaries to the Ancient Niobrara include an abandoned valley, first recognized by Todd (1912), largely filled but still evident in the present topography, heading in Mosquito Creek in southeastern Charles Mix County. It includes a short segment of the present Missouri River, and continues through southwestern Bon Homme County as a high-level valley filled with western sand and gravel and capped by till.

The Missouri River transects several high areas that were divides in the Ancient Niobrara drainage system. One trends eastward about 6 miles upstream from the bridge at Wheeler. Another trends northeastward about 10 miles downstream from the same bridge. A third lies athwart the Missouri about midway between the mouth of Randall Creek and the Indian settlement of Greenwood. Another ancient divide forms narrows in the Missouri River trench, 5 miles upstream from Running Water. Finally Yankton Ridge and its high counterpart on the Nebraska side, locally known as The Devil's Nest, constitute a transected ancient divide.

ANOMALIES IN THE PATTERN

Inspection of plate 7 shows not only disconnected valley segments but irregularities, divergences, and other anomalies in a pattern whose general aspect is systematic. Such features are noteworthy, for example, in western Minnehaha County and in western Faulk County. Their origin is not clear, but it may lie in the repeated blocking of minor valleys and the cutting of new ones either before or after the main diversion of the drainage. It is natural to expect that a valley may have been blocked repeatedly, but the evidence at hand is insufficient to prove it.

BIG SIOUX RIVER SYSTEM

INTERLOBATE ORIGIN

The contoured map (pl. 2) shows clearly the anomalous position of the Big Sioux River, virtually bisecting the conspicuous highland of the Coteau des Prairies. furthermore the Big Sioux transects a series of subparallel ancient valleys, all of which drain toward the southwest (pl. 7). The relation of the Big Sioux to the borders of the Wisconsin drift sheets (pl. 1) leaves little doubt that this river is interlobate—that it came into existence at a time when the Des Moines lobe and the James lobe covered opposite sides of the coteau, leaving a long narrow strip of ice-free country along which melt water could escape. The ancient northeast-trending valleys were blocked by ice and drift and the new stream, consequent on the interlobate area, became incised sufficiently so that it remained in its glacially imposed course after deglaciation had occurred.

Although the Big Sioux transects elements of the previous drainage system, in one place it follows such an element. That is the segment between Flandreau and Sioux Falls Junction in Moody County. There the escaping interlobate waters evidently found their most efficient route along the ancient valley partly filled with drift.

The relation of Tazewell outwash to the drainage indicates that the Big Sioux came into existence not later than Tazewell time. No clear evidence for or against the hypothesis that this river antedates the Tazewell has been discovered. Whether or not the southwest-draining, earlier valley system on the Coteau des Prairies is of the same age as the prediversion drainage farther west is not known either; tentatively it can be assumed that it is.

GLACIER-MARGINAL SEGMENT

The interlobate character of the Big Sioux is evident only as far downstream as Sioux Falls. There the river turns abruptly eastward for 10 miles, and then continues south past Canton, Fairview, and Hudson in Lincoln County to join the Missouri at the southeastern corner of the State. From Sioux Falls to Hudson the trench cut by the Big Sioux River is narrower than in the segments north of Sioux Falls and south of Hudson. Furthermore, between Sioux Falls and Fairview the river is nearly coincident with the eastern limit of the Cary drift sheet (pl. 3).

These facts suggest that before Cary time the Big Sioux followed a course from Sioux Falls to Fairview somewhat west of its present course, that the advancing margin of the Cary glacier obliterated the old route and established a new drainage line along the toe of the ice, and that the stream became so deeply incised in its new course that it has continued to follow it. If, as is possible, the Tazewell glacier margin was coincident, or nearly coincident, with the Cary margin in this sector, the event suggested may have occurred in Tazewell rather than Cary time.

Corroboration of the inference that pre-Cary glacial drainage between Sioux Falls and Brandon flowed southwest, rather than northeast as at present, lies in the fact, first noted by Rothrock (Rothrock and Newcomb, 1926, p. 17, 34), that Iowan (?) ice-contact sand and gravel in that segment are foreset toward the southwest.

An isolated hill 100 feet high, in secs. 7 and 8, T. 98 N., R. 48 W., 1 mile west of the Big Sioux, probably represents a west-facing spur that formed a part of the eastern side of the inferred pre-Cary valley. When the river assumed its course along the glacier margin, this spur was transected, so that a part of it became isolated on the west side of the river. Less distinct hills, a small one in the SE¼ sec. 17, T. 99 N., R 48 W., and a broad ridge in secs. 10, 11, 15 and 16, T. 99 N., R. 49 W., may have had a similar origin.

From Hudson to the Missouri trench the wide Big Sioux valley, as seen on plate 2, is believed to be a reoccupied element of the earlier system that drained toward the southwest, tributary to the Ancient White.

SUPERPOSITION ON QUARTZITE

The interlobate Big Sioux River, the details of its course consequent on the local topography of the glacial drift, became superposed on the underlying Sioux quartzite at two places, Dell Rapids and Sioux Falls, both in Minnehaha County. At both places series of falls and gorges have been formed, which have been described by Rothrock (Rothrock and Newcomb, 1926, p. 33–34).

The falls in the city of Sioux Falls are peculiar in that they occur in a part of an intricate S-bend in the Big Sioux trench. The explanation given by Rothrock (Rothrock and Newcomb, 1926, p. 34–35) is believed to be essentially correct. According to his interpretation, slightly modified, outwash here assigned to the Cary substage was built by melt water flowing southeastward down the valley of Skunk Creek. The water could not escape along the inferred southeastern continuation of that valley because it was blocked, immediately south of Sioux Falls, by the Cary glacier. Accordingly the escaping water found an outlet northeastward down a short tributary (pl. 7) to another parallel valley, and thence detoured the margin of the Cary ice. As it crossed the divide, the water quickly became superposed across a mass of quartzite. Meanwhile, the flow was greatly augmented by melt-water discharge coming down the interlobate Big Sioux River. This discharge continued long after shrinkage of the Cary ice had ceased to contribute melt water to the valley of Skunk Creek. Probably it was the Big Sioux melt-water discharge that eroded the quartzite at the falls by hydraulic plucking and excavated the capacious trench that now exists downstream from the falls.

Other melt-water streams likewise became superposed across quartzite. A notable example is Split Rock Creek in eastern Minnehaha County, which flows on quartzite through a distance of 8 miles downstream from the town of Sherman. At one point the gorge cut into the quartzite by the stream is more than 50 feet deep.

TRANSECTION OF DIVIDE

The north-trending divide between the Big Sioux drainage basin and that of the Minnesota River is transected in several places by deep narrow trenches cut by melt-water streams flowing southwestward from the Des Moines glacial lobe, toward the Big Sioux, during both the Cary and the Mankato subages. These trenches, draining through Deer Creek in Brookings County, Hidewood Creek in Deuel County, and Stray Horse, Willow, and Gravel Creeks in Codington County, have extended eastward the drainage basin of the Big Sioux.

BRULE CREEK

Brule Creek, tributary to the Big Sioux in Union County, shows interesting features of glacial history. Its east fork, in northwestern Union County, reoccupies a tributary member of the Ancient White system. Its main stem, from the junction of the two forks to near its mouth, coincides approximately with the eastern edge of the Cary drift sheet. It originated as a melt-water stream flowing between the glacier margin and the much higher ground on the east. While in that position, it transected five pre-Cary spurs, isolating them from the highland of which they were once parts. These spurs are well shown on the Elk Point topographic quadrangle.

Of these spurs the conspicuous group centering near the intersection of T. 93 and 94 N., R. 50 and 51 W., are a part of the former headland between the Ancient White River valley and one of its eastern tributaries. One of the spurs is doubly transected. An abandoned gap in secs. 30 and 31, T. 94 N., R. 50 W., lies 1 mile west of the gap still occupied by Brule Creek. Undoubtedly the abandoned gap was cut by a glacier-marginal Brule Creek, but whether the cutting took place just prior to the Cary maximum, or during the Iowan or some other pre-Cary glaciation, is not known.

MINNESOTA RIVER SYSTEM

The present Minnesota River, flowing southeastward, does not touch South Dakota, but its trench, containing the shallow basins of Big Stone Lake and Lake Traverse and the head of the Bois de Sioux River, forms the northeastern boundary of the State. The trench was cut by the water spilling southward from Lake Agassiz, in a direction opposite to that of the former drainage, which was northward via the Red River basin toward the Arctic Ocean. Owing to erosion by the successive ice sheets and by their melt waters, the present trench may not coincide with the course of the earlier northward-flowing stream, but may lie somewhat southwest of it.

The streams that drain the northeastern flank of the Coteau des Prairies in Roberts, Grant, and Deuel Counties are in part consequent on Wisconsin drift, and are therefore comparatively recent in origin. Some of them undoubtedly have reoccupied pre-Wisconsin valleys not entirely obliterated by Wisconsin glaciation. On the other hand former minor valleys, parallel with the present streams, have been largely filled with drift but still persist as faint, slightly sinuous sags in the surface. One such former valley trends through secs. 32, 33, and 34, T. 118 N., R. 49 W., Grant County, and is clearly shown in U. S. Department of Agriculture air photographs, numbers CBO 3–128 and 129. Quite evidently valleys here and elsewhere in eastern South Dakota have been blocked repeatedly; the drainage history is actually far more complex than that which it has been possible to reconstruct during the present study.

JAMES RIVER SYSTEM

GLACIAL EROSION AS A FACTOR IN LOCALIZING THE JAMES RIVER

Comparison of plates 1, 2, and 7 makes it clear that although the James River flows down the axis of the James River lowland, it is coincident only locally (chiefly in Beadle County) with important elements of the prediversion drainage system. In view of the opinion expressed earlier in this paper (p. 9), that the lowland owes its origin to valley cutting by two major prediversion rivers, one flowing north and the other flowing southeast, the lack of coincidence between the existing James and the ancient rivers is an anomaly that requires special explanation.

The anomaly is believed to be the result of substantial alteration of the prediversion valleys by glacial erosion, first suggested by C. R. Warren in oral discussion. Great widening and at least some deepening of the Ancient Cheyenne, Bad, and White river valleys seem to have occurred, together with planing down of the Ancient Redfield divide. The result was the conversion of these major valleys into a broad shallow trough-like lowland, an accomplishment that must have been made easy by the weakness and softness of the Pierre shale, the principal bedrock.

Important lateral erosion by glacier ice is implied by the steep, smooth character of the northeastern and northwestern flanks of the Coteau des Prairies, and by the eastern flank of the Coteau du Missouri wherever it is capped by resistant rock. These flanks lack the spurs that characterize stream-dissected plateaus, and this fact suggests grinding away of the spurs by glacial erosion, coupled no doubt with the packing of drift into the intervening tributary valleys. In northern Brown County and in the western parts of Marshall and Day Counties bedrock crops out in many places in the beds of streams draining the lower slopes of the two coteaus. The irregular contact between bedrock and overlying drift indicates that the streams are flowing on a drift-covered irregular bedrock topography and that they are not adjusted to the irregularities.

Lateral glacial erosion is further suggested by the fact that the west flank of the Coteau des Prairies has a much gentler slope south of the latitude of the Ancient Redfield divide than north of it. The orientation of the major prediversion river valleys produces a bend in the axis of the James River lowland at that divide, so that the plan of the lowland as a whole is concave eastward. A glacier lobe flowing southward through the lowland should have created just such a difference as that described, whereas if widening of the lowland is ascribed solely to stream dissection, the difference is unexplained.

Glacial deepening of the lowland is suggested by the inferred profile of the Ancient White River valley. The valley floor sloped eastward from an altitude of 1,430 feet at the point where it is cut by the Missouri River trench, to 1,300 feet or less at the point in McCook County where it is believed to have crossed the ridge of Sioux quartzite described earlier. Yet in that part of the James River lowland traversed by the Ancient White between these two points, the surface of the bedrock (chiefly Pierre shale) lies generally at an altitude of 1,200 feet or less. The low altitude and discontinuous character of the Ancient Redfield divide (p. 149) further suggest that it was reduced by glacial erosion.

The fact that the James River follows the axis of the James glacial lobe of Mankato age, rather than the positions of the prediversion valleys, supports further the concept of glacial erosion of the lowland. The line of deepest glacial erosion in material of uniform resistance should have been down the center of the lobe, and the runoff of melt water should have been consequent on the lowest available path. The adherence of the James to the axis of the lobe is so close that it is difficult to escape the inference that erosion by Mankato and pre-Mankato James glacier lobes has been chiefly responsible for the location of the river.

Thus, whereas quantitative evaluation of the matter is beyond the reach of the present investigation, there is a very strong suggestion that glacial erosion may have been the chief agency that converted two river valleys separated by a major divide, into a wide and continuous lowland.

If great enlargement by glacial erosion is accepted as probable, then it is likely that the valleys buried beneath the lowland date in large part from pre-Mankato Wisconsin time, although they may occupy the sites of older, prediversion valleys.

If glacial erosion has been as effective as suggested in the foregoing discussion, it is very unlikely that much, if any, pre-Wisconsin drift remains in the James River lowland.

Certainly the buried valley system, whether as perfect as suggested in the crude reconstruction shown on plate 7, or much less so, is not reflected in the lobation of the Mankato drift except at the extreme margin of that drift sheet. From this it may be inferred that at the time when Mankato deglaciation began, the relief of the subglacial floor of the lowland was small.

ARCUATE TRIBUTARIES

Most of the tributaries to the James within South Dakota are both intermorainal and glacier marginal. The arcuate pattern they form as a group has been described. Most of them follow the broad shallow depressions between adjacent end moraines, and some indeed may be no more than postglacial streams consequent on glacially made depressions. Others, however, are fringed with remnants of thin outwash bodies, some clearly related to the younger of the two confining moraines. These streams must have originated along the margin of the James lobe while the moraines were being built.

WEST OF THE MISSOURI RIVER

FILLING, TRENCHING, AND EROSION SURFACES

Discussion of the nonglacial stream deposits, in a foregoing section of the present paper, brought out the fact that they occur principally on broad uplands and stream terraces. The results of studies in the vicinity of Pierre by Crandell[46] and in the vicinity of Chamberlain by Warren[47] agree in visualizing the Pleistocene history of the country immediately west of the Missouri River as consisting mainly of alternate cutting and filling by large eastward-flowing streams. Figure 10 shows three former erosion surfaces made by the Bad River, now represented only by buttes capped with sand and gravel. It shows also the inferred development of a tributary, Willow Creek, along the margin of an earlier fill. The Bad River is inferred to have assumed its present position in an analogous manner, along the opposite margin of a later fill.

Inherent in the example shown in figure 10 is the principle of topographic inversion, whereby areas formerly parts of valley floors have become high points because they were protected by sand and gravel against erosion. Inversion is favored by the very weak, very impermeable character of the Pierre shale, the regional bedrock, in contrast with very permeable, relatively durable overlying sand and gravel.

Another principle, represented in the district[48] although not shown in the figure, is that of the shifting of drainage, by capture, from a medial position to a marginal position with respect to a fill. A stream, growing headward along the contact between the lateral margin of a valley fill and the Pierre shale in the valley side slope, captures the drainage area formerly belonging to the main stream. Capture is favored by the fact that the main stream loses water by percolation into the fill on which it is flowing, whereas the marginal stream, flowing on shale, has no such losses. This process is a direct aid to topographic inversion.

These two principles are represented also in figure 11. Probably both have operated generally and repeatedly throughout the Pleistocene history (and for that matter throughout the whole Cenozoic history) of western South Dakota. The chain of buttes, capped with resistant strata of the Ogallala formation, that constitute the Iona and Bijou Hills, are oriented east-west, parallel with the White River. Their orientation suggests that they are the remnants of a valley floor of Ogallala time, a floor later inverted by differential erosion, so that it is now part of a high divide.

The vertical distance between the tops of the Iona Hills and the Missouri River is more than 800 feet. This is a minimum measure of the extent to which the country immediately west of the river has been incised since Ogallala time. And since the Iona Hills and Medicine Butte capped by the Ogallala formation stand some 300 feet above the general surface of the interfluves, a prism of rock about 300 feet thick must have been removed from that country completely.

Stream terraces and broad erosion surfaces, both cut into bedrock, have been observed in various parts of western South Dakota beyond the limits of glaciation

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[46] Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation.

[47] Warren, C. R., 1950, Preliminary report of the geology of part of the Chamberlain, S. Dak., quadrangle: U. S. Geol. Survey, manuscript on open file.

[48] Crandell, idem.

(Perisho and Visher, 1912, p. 15, 56–58; Wanless, 1923, p. 261–264; Baker, 1948, p. 1–5), as well as in western North Dakota (Alden, 1932), which seems to have had a comparable history. But as no attempt has been made at correlating them, they can only be mentioned in the present discussion, with the added statement that nothing in the available descriptions of them is inconsistent with the physical history suggested above.

The meager evidence from stratigraphic relationships and fossil vertebrates suggests that filling may have occurred in Holdrege (Nebraskan), Red Cloud (early Kansan), and Grand Island (late Kansan) times, and that during at least parts of the intervening times incision can be inferred. Evidence from fossils (again very meager) combined with glacial-stratigraphic data, suggests further that in the Chamberlain area filling in Crete (Illinoian) time succeeded at least 350 feet of post-Grand Island downcutting accompanied by lateral planation.

When the Missouri came into existence the White River, in the vicinity of its present mouth, had incised its valley to an altitude of about 200 feet above the bedrock floor of the Missouri River trench at the same locality. That time, with considerable probability, was the Illinoian glacial age. If the probability is accepted, then the last 200 feet of cutting by the White River date from Illinoian and post-Illinoian time, whereas all the earlier erosion recorded along that stream is post-Ogallala, pre-Illinoian. Although parallel data for western streams other than the White have not been obtained, it is likely that their erosional records, both qualitatively and quantitatively, are roughly comparable.

DRAINAGE PATTERN

MASTER STREAMS

The belt of glaciated country west of the Missouri River is drained by a series of nearly parallel, rather evenly spaced rivers. They flow eastward down the slope of the Missouri Plateau and occupy broad, deep, steep-sided valleys incised into the plateau surface. From north to south these rivers are the Grand, the Moreau, the Cheyenne, the Bad, and the White. South of the White two smaller streams, Ponca Creek and the Keya Paha River, flow southeastward into Nebraska. All have their headwaters in or slightly beyond the extreme western part of South Dakota, although there is reason to believe that in earlier Pleistocene time one or more of them reached even farther west. The gradients of their valley floors are of the order of 10 to 12 feet per mile, although the gradients of the stream channels themselves, measured along their meandering courses, are much less.

It has long been recognized that the various Cenozoic deposits of the Great Plains region were laid down by streams that flowed eastward from the region of the Rocky Mountains. In this respect the Pleistocene sediments are similar to those made in earlier Cenozoic times. There seems to be no reason to doubt that the existing rivers of western South Dakota are descendants of earlier streams, though their number and their latitudinal positions may have varied considerably from one time to another.

TRIBUTARIES

DESCRIPTION

Not only in the glaciated belt but throughout a much wider region west of it, the streams tributary to the rivers named show a strong tendency to trend about N. 50° W. Together the tributaries form a subparallel pattern that is striking on a map of almost any scale. The pattern is visible on plate 1; it is better shown on the Geological Survey Base Map of South Dakota, scale 1:1,000,000. These small-scale maps, however, depict only the larger tributaries. Large-scale representations, such as published quadrangle maps and air photographs, show that not only the larger tributaries, but very small ones as well, prefer a northwest-southeast orientation. The topographic "grain" appearing on maps such as those of the Pierre and Oahe quadrangles is very striking. (See also the Iona and Chamberlain quadrangles.)

Spacing of the parallel valleys is variable. In some places the valleys are less than a mile apart; in others they are separated by distances of several miles. In general close spacing and parallelism of alinement are somewhat less evident in the immediate vicinity of the master rivers than in areas somewhat removed from the rivers.

The stream alinement has created a pattern wherein tributaries enter the master rivers from the north in the normal way, making horizontal angles of junction that are acute on the upstream side. But streams entering from the south make angles of junction that are acute on the downstream side. This pattern is by no means universal. Many exceptions are clearly visible on small-scale maps, although the force of the exceptions is diminished by inspection of air photographs, many of which show alined minor tributaries even where major tributaries lack alinement.

There is no pronounced tendency for the tributaries entering a master river from opposite sides to be collinear. Offsets between the mouths of opposed tributaries are so common as to suggest that the collinear relationship, where it does occur, has only a random distribution.

Although the pattern described occurs primarily west of the Missouri, it is seen locally east of the river.

It is visible in northern Brule County (see the eastern part of the Chamberlain quadrangle, the Pukwana quadrangle, and the western part of the Kimball North quadrangle) and in northwestern Buffalo County. In the former area the drift is very thin, and in the latter it is absent altogether. The alined topography is distinct throughout a large area in northwestern Potter County, where the drift is also very thin. Traced eastward from these three areas into terrain where the drift is thicker, the parallel-oriented topography disappears, seemingly because glacial erosion and deposition have erased it.

Throughout the region examined, the northwest-trending valleys occur entirely in the Pierre shale, but casual observations farther west, in South Dakota and Nebraska, show that similar topography occurs also on more resistant rocks younger than the Pierre shale.

The anomalous drainage pattern was recognized by Russell (1929), who found that it occurs within an area of 125,000 square miles, extending from Montana southeastward through Nebraska. He rejected the hypothesis that the pattern is controlled by lithologic or structural features of the bedrock, because he could find no agreement between the positions of such features and the positions of the alined streams. The writer, likewise, has seen no such agreement, and is impressed by the lack of visible structures and by the remarkable parallelism of the drainage lines over wide areas. For the present, therefore, he shares Russell's view. However, if future detailed studies should reveal bedrock features now unknown, this position may have to be revised.

ORIGIN

Among those who have studied the matter the opinion has been reached repeatedly that the origin of the peculiar pattern described is related to eolian activity. As to the exact mode of origin opinions differ somewhat. Among them there are apparent two hypotheses, which can be termed the dune hypothesis and the deflation hypothesis.

The dune hypothesis was put forward by Russell (1929), who first found the parallel pattern in the area between the North Platte and South Platte Rivers in western Nebraska. There he found the interfluves composed of eolian fine sand, in places at least 50 feet thick. Topographic relations indicate that the sand is not accumulating now, and that deep dissection has occurred since deposition of the sand.

Russell concluded that the areas in which the pattern is found were once the sites of groups of longitudinal sand dunes built by northwest[49] winds, that small streams developed along the interdune depressions, and that these became superposed upon the underlying rock. He derived the eolian sand from "sandy Tertiary formations" that formerly covered the region.

A similar drainage pattern in Texas and New Mexico was ascribed to a similar cause (Price, 1944).

The deflation hypothesis is a concept first outlined by Baker (1948, p. 5-8) and later amplified by Crandell.[50] It embodies a combination of deflation and stream erosion. The interfluves on Pierre shale in the country west of the Missouri are pitted with deflation basins having maximum lengths exceeding half a mile and depths as much as 20 feet. The basins tend to be ovate with long axes trending southeastward, parallel with the general topographic lineation. According to Baker the basins may have developed by deflation of shale exposed in interdune troughs. Overflow of water from one basin to the next, during times of rain, may have integrated the basins and thereby may have helped to form the parallel minor valleys.

In the following paragraphs considerations favorable to the concept of general eolian origin of the alined tributaries are noted, and the merits of the two hypotheses are discussed briefly in the light of the facts available.

Favorable to eolian control are the apparent absence of any other factor capable of having alined the drainage and the directions of present strong winds in central South Dakota. A compilation of wind statistics for Huron, Beadle County, during the period 1897 to 1930 supplied by the U. S. Weather Bureau at Huron, and for Pierre during the period 1891 to 1930 shows that in this region the direction of prevailing winds in June, July, August, and September was southeast, whereas during the 8 other months it was northwest. The frequency of winds having velocities greater than 32 miles per hour is greatest in April and is far greater during the months October to May than during the summer months. Therefore, in this sample district both the prevailing winds and the strong winds effective for the transport of sand blow from the northwest.

The high frequency of strong winds in the spring season arises from the presence of snow on the ground in the plains region of Canada and its general absence farther south. The difference creates differences in surface temperatures that set up movements of air from north to south. It is quite likely that such differences were enhanced during glacial times when the country north of South Dakota was covered with ice. During interglacial times conditions for strong northwesterly winds during the spring season may have been about as favorable as they are at present.

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[49] Russell (1929, p. 255) wrote "southwest," but from the context it is evident that he meant northwest.

[50] Op. cit., p. 112-130.

Apparently, therefore, the winds today have a direction and force that should be capable of creating the needed dunes if a supply of sediment were available and also that should be able to create deflation basins.

Considerations favorable to the dune hypothesis are the existence elsewhere of longitudinal-dune fields, the presence of bare surfaces between existing longitudinal dunes, and the existence of probable sources of dune-building sediments.

Large fields of longitudinal dunes, similar to those inferred to have covered much of western South Dakota at a former time, exist elsewhere today. Among conspicuous fields are the Navajo Country, Ariz. (Hack, 1941), the Danubian plain in Hungary (Högbom, 1923), North Africa (Bagnold, 1942), India (Cornish, 1897), and central and western Australia (David, 1950, v. 1, p. 634). Students of longitudinal dunes generally agree that a dry climate, a moderately flat surface, a supply of sand that is only moderate in amount, and the operation of occasional strong winds rather than less-strong prevailing winds, are conditions important in the building of such dunes. Many descriptions of them state that the interdune troughs are bare of sand. Individual dune ridges extend unbroken through many tens of miles, and are remarkably straight, regardless of irregularities in the surface on which they are built. Many are quite evenly spaced, "giving the country an extraordinary aspect of geometrical order unseen elsewhere in nature except on a microscopic scale" (Bagnold, 1942, p. 232).

In Yuma and Washington Counties, northeastern Colorado, low longitudinal dunes, oriented southeastward, give the country a similar geometrical lineation. The writer has observed these features repeatedly from the air, and they are well shown on the detailed soil map of part of this district (Knobel and others, 1947). Back of the bluffs of the Arikaree River, draws oriented southeastward occur between the dunes (see U. S. Department of Agriculture, Agricultural Adjustment Administration, Western Division Laboratory, Air Photo no. CU–148–21), and presumably were localized by the dune ridges.

Similar longitudinal dunes occur in Lea County in extreme southeastern New Mexico, and in the adjacent part of Texas. The dunes, trending N. 40° W. to N. 50° W., have individual lengths as great as 10 miles; they are "a few hundred yards wide" (Harper and Smith, 1932). The swales are minor drainage lines, most of the streams ending within the swales in "miniature playas" that may have originated through deflation.

In the Sand Hills region in western Nebraska, H. T. U. Smith (written communication) has mapped extensive longitudinal dunes with southeasterly to easterly orientation. Longitudinal dunes that probably are northern outliers of this group have been noted by the writer in Todd County, S. Dak. and Keya Paha County, Nebr. A small area of southeast-trending longitudinal dunes overlies Iowan-Tazewell(?) outwash in southwestern Buffalo County, S. Dak.; these dunes are responsible for the topographic lineation visible in the northeast corner of the Chamberlain quadrangle.

Descriptions of present longitudinal dunes make it clear that quite generally the interdune areas are essentially bare of sand. Hence in those linear areas little impediment to surface runoff is to be expected. In the region of outcrop of the Pierre, ease of runoff is enhanced by the fact that the shale is nearly impermeable to water. Hence, whereas any sand ridges formerly present can be expected to have absorbed rainfall, intervening shale-floored troughs should have been subject to rapid erosion by runoff sharply concentrated in flash floods.

Potential sources of sediment from which longitudinal dunes could have been built may have been several. One source may have been the broad belts of sand and gravel deposited at various times during the Pleistocene epoch by streams flowing eastward across South Dakota, and inferred from small remnants still preserved. Such deposits, added to season by season throughout considerable periods of time, should have possessed surfaces essentially free of vegetation, much like those characteristic of outwash valley trains. The inferred great widths of individual fills—as much as 20 miles in the case of the White River—should have favored the deflation of large quantities of fine sediment. Another source may have been the fine-grained and easily disaggregated Fox Hills sandstone, still present overlying the Pierre shale in the northern part of the State, and presumably formerly extensive over the territory farther south. Still a third source may have been the Pierre shale itself. As stated on page 132, during the dry years in the 1930's this shale yielded sand-size aggregates of clay minerals which were heaped into dunes as much as 10 feet in height.

In contrast to the three factors favorable to the dune hypothesis, just set forth, two facts favorable to the deflation hypothesis are evident. One is the presence of large numbers of deflation basins, chiefly in the Pierre shale and chiefly in the country west of the Missouri River, as described on page 131. The other is the report by Crandell[51] of two instances in the Pierre district of control by such basins of the headward growth of small valleys.

During or after the Kansan deglaciation the Ancient Bad, White, and Niobrara Rivers, and perhaps others,

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[51] Crandell, D. R., 1951, Geology of parts of Hughes and Stanley Counties, S. Dak.: Yale Univ., unpublished Ph. D. dissertation, p. 123–124.

aggraded their courses with coarse alluvium brought from far to the west. This alluvium is recorded today by isolated remnants of fossil-bearing bodies of sand and gravel. Similar aggradation occurred in Nebraska, where the Grand Island formation rests against bluffs and overlies flat surfaces of eroded Kansan till (Condra, Reed, and Gordon, 1950, p. 21).

If the volcanic ash exposed in Minnehaha County (locality 17, p. 35–36) is in fact upper Kansan, then one or more volcanic eruptions in the country somewhere to the west, showering ash upon the surface as far east as eastern South Dakota, can be included in the history of Kansan events.

The assemblage of gastropods collected from Sappa deposits throughout the region extending from northern Texas to northeastern Nebraska forms the basis of ecologic inferences by A. B. Leonard (1950, p. 43–45), who reached these conclusions: In Sappa time the belt of country along the boundary between the Central Lowland and the Great Plains was moister and possibly a little cooler than now, with reduced seasonal extremes of temperature. Although trees were more plentiful than now along stream courses, there is no evidence of a forest cover. The climate seems to have been much the same throughout the broad belt of latitude represented. For this reason eastern South Dakota can be expected to have had a similar climate in late Kansan time.

At the time represented by the Grand Island formation the mammal fauna of Nebraska was abundant and varied, differing notably from the fauna of pre-Kansan time. That similar faunas inhabited South Dakota is established by fossils identified from the few localities at which they are known to occur.

It is true that longitudinal dunes are not present in most areas in western South Dakota in which the parallel drainage pattern occurs. However, this fact does not necessarily refute the dune concept, for the Pierre shale consists largely of one of the weakest rock types known, and those who have studied it are unanimous in testifying to the remarkable ease with which it yields to both mass wasting and stream erosion. Where the Pierre shale is protected by overlying resistant strata, as in the Platte River district cited by Russell and along the South Dakota-Nebraska State line west of the Missouri River (Wanless, 1923, p. 263), a capping of dune sand is still present (although many of the dunes there are not of the longitudinal type).

It is possible that the preservation of dunes on high surfaces underlain by Ogallala and other Cenozoic sandy deposits, and their absence from areas underlain by Pierre shale, is the result of differences in runoff characteristics of the two kinds of material. The sandy deposits absorb a considerable proportion of the precipitation and yield it to runoff indirectly, in regulated form throughout the year. In contrast, the Pierre shale absorbs almost no precipitation, with the result that rainfall runs off over the surface immediately, often in flash floods that have much larger capacity for erosion than have the smaller, steadier streams in the sandy areas.

It is possible also that some dunes were destroyed as a result of lateral planation of Pierre shale by major streams that filled their valleys with coarse alluvium and cut laterally as they flowed, with shifting channels, on the surfaces of their fills.

Finally, unfavorable to the deflation hypothesis is the apparently random distribution of existing deflation basins. It is not easy to derive the lineated topography, created by parallel-oriented stream valleys, by means of the headward extension of valleys through basins having a random pattern.

Although some form of eolian control seems the probable explanation of the lineated topography, the exact mechanism of stream development is not yet clear. Probably both longitudinal dunes (now largely destroyed) and deflation basins have played a part. Evaluation of the relative importance of these two factors must await more detailed study, not only in western South Dakota but in other parts of the Great Plains region.

No single date of inception of the parallel drainage pattern has been inferred from the facts accumulated thus far. In the opinion of Crandell[52] the inception of lineation in the Pierre district seems to date from Yarmouth time. A pre-Illinoian time of origin is consistent with the fact that along the Missouri River between Pierre and the mouth of the Niobrara River there are features suggestive of the lineation having guided the path of the Missouri as it was formed, apparently at the Illinoian maximum.

In Todd County, S. Dak., low longitudinal dunes overlie a plain formed by a high-level body of western sand and gravel referable to the Holdrege, Red Cloud, or Grand Island formations. Evidently in that district the dunes postdate, or are nearly contemporaneous with, the sand and gravel. It is believed that both alluvium and dune sand are preserved there because of the presence of a broad capping of resistant strata of the Ogallala, well exposed beneath the alluvium at a number of places.

The longitudinal dunes in southwestern Buffalo County apparently overlie Iowan-Tazewell (?) outwash and are therefore referable to the middle or later part of Wisconsin time. In the Sand Hills region in Nebraska the stratigraphic relations of the dunes suggest

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[52] Op. cit., p. 127.

that two distinct generations of dunes are present, one of which may date from early Wisconsin time and the other from the later Wisconsin (H. T. U. Smith, written communication).

Thus the scattered information available suggests that dunes and (or) parallel drainage have been instituted in South Dakota and Nebraska more than once during the Pleistocene epoch. It is very likely that these features may have originated not only in more than one way but at several times. It is unlikely, however, that large areas of longitudinal dunes have formed west of the Missouri River at any time since the Illinoian, because deep dissection, which would have created a surface unfavorable for dune building and which still persists, apparently dates from that time.

SYNTHESIS OF PLEISTOCENE REGIONAL HISTORY

TERRITORY WEST OF THE GLACIATED REGION

The Pleistocene history of western South Dakota is synonymous with post-Ogallala history, as the stratigraphy is now understood.[53] In that region the post-Ogallala record is one of predominant erosion interrupted repeatedly by episodes of at least partial filling of stream valleys with sediments, mostly coarse grained, derived in part from the Black Hills. During the course of erosion successive terracelike surfaces were cut, through lateral planation by the main streams and through other processes of erosion along tributaries and on interfluves. These surfaces represent times when the main streams were graded, but the cause or combination of causes responsible for the grading is unknown. The streams flowed eastward, down the slope of the plains, just as they do today. Although they did not change their general direction of flow they did occasionally become incised along the lateral margins of their own fills, intrenching themselves into the Pierre shale and thereby converting former gravel-filled valleys into gravel-capped interfluves. Topographic inversion of this kind probably occurred in many areas during the earlier part of Pleistocene time. Lateral displacement became increasingly difficult, however, for as time progressed valleys became deeper and narrower.

To judge from paleontologic evidence in western Nebraska, Nebraskan or Aftonian time was marked by a mammal fauna approximately equivalent to the Villafranchian fauna of southern Europe, whereas late Kansan or Yarmouth time was characterized by a fauna that lacked some of the earlier mammals and that included many new immigrants (Schultz and Stout, 1948).

The extent, if any, to which the regimens of the eastward-flowing streams were affected by the successive ice sheets, aside from the Illinoian diversion and the Iowan ponding, is not known.

THE GLACIATED REGION

NEBRASKAN GLACIAL AGE

The presence of Nebraskan drift in northwestern Iowa and eastern Nebraska makes it clear that an ice sheet entered South Dakota in Nebraskan time. The extent of ice within the State can be guessed at present only by extrapolating the Nebraskan drift border northward from Nebraska (pl. 4). In that State, and probably also in Kansas as well, the outer edge of the Nebraskan drift lies well inside that of the Kansan drift; for this reason it is nearly everywhere concealed.

In Nebraskan time the James River lowland of today did not exist, but the highlands capped with strata of the Ogallala(?), in the region of the present Coteau du Missouri, probably constituted low mesas standing higher than the country now drained by the present James River. Accordingly it can be conjectured that the Nebraskan glacier margin, guided by this topography, trended northwestward across eastern South Dakota, possibly in the vicinity of the James River of today, occupying a country of very low relief.

The Nebraskan glacier is known to have blocked eastward-flowing streams in Nebraska; it must have done so in South Dakota as well. The continental divide, wherever it stood then, must have been breached and all the ponded water must have been diverted southward. However, no record of these events remains, doubtless because the surface stood much higher at that time than it does today, so that all parts of it were destroyed in the sculpture of the James River lowland by streams and later glaciers. For the same reason any outwash, loess, and other sediments of Nebraskan date are likely to have vanished from the lowland region, although remnants of Nebraskan deposits might still exist in favorable situations on the Coteau des Prairies.

AFTONIAN INTERGLACIAL AGE

Like Nebraskan events, Aftonian events in South Dakota must be inferred by analogy with an adjacent region. Thorough weathering produced gumbotil on poorly drained uplands in Iowa as far west as Ida County,[54] and erosion occurred in valleys in eastern Nebraska. The rich and varied late Nebraskan or Aftonian mammal fauna of Nebraska probably was present in South Dakota as well.

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[53] This statement is made in analogy with the stratigraphic relations in western Nebraska (Schultz and Stout, 1948, p. 558, 560, 571).

[54] Ruhe, R. V., 1950, Reclassification and correlation of the glacial drifts of northwestern Iowa and adjacent areas: Iowa Univ., unpublished Ph. D. dissertation, p. 16.

KANSAN GLACIAL AGE

Kansan drift is widespread in Iowa, and in Nebraska it occurs as far west as the drift border shown on plate 3. It has a greater extent westward than has the Nebraskan drift. The till believed to antedate the Sappa formation at two localities in the extreme eastern part of South Dakota (localities 17, p. 35–36; 19, p. 36) is probably Kansan. The western margin of the Kansan glacier can be conjectured to have trended across eastern South Dakota from Bon Homme County in a northwesterly direction, perhaps in the vicinity of what is now the western border of the James River lowland. There was, however, no James glacial lobe, because the lowland had not yet come into existence. The region was one of low relief, with high ground over the site of the Coteau du Missouri, where probably a good many mesas capped by the Ogallala still existed, though most of them have since been destroyed.

Presumably the Kansan glacier blocked eastward-flowing rivers and diverted them toward the south, as it did in Nebraska. However, the high altitude of late Kansan or early Yarmouth alluvium near Chamberlain (locality 6, p. 38) indicates that diversion would have occurred at positions far above the surface of the present James River lowland; hence all trace of it could have been, and probably has been, removed. Kansan stratified drift and loesslike silt are known in eastern Nebraska; such sediments probably were deposited farther north as well, but have been extensively removed by post-Kansan erosion.

If the dune hypothesis of origin of the southeast-trending streams is accepted, then possibly the low-relief surface of late Kansan time, west of the Kansan drift sheet, should be pictured as a field of long narrow sand dunes, oriented northwestward, and trailing away southeastward from the plains of western alluvium deposited by eastward-flowing streams.

YARMOUTH INTERGLACIAL AGE

During the Yarmouth interglacial age, on uplands, in areas where drainage conditions were poor, gumbotil developed in western Iowa, and probably formed also in the adjacent part of South Dakota, where ground moisture was sufficient to bring about the necessary alteration. In eastern Nebraska and Iowa, reddish soils developed on uplands with better drainage, and these soils too probably existed in South Dakota in similar situations.

The deep and wide valley cut by the Ancient White River during late Kansan or Yarmouth time and recorded near Chamberlain (p. 51), shows that by then eastern South Dakota had become well dissected. The future James River lowland was in the making, for its site was occupied by the valleys of two major streams, the Ancient Cheyenne, and the Ancient White with its chief tributary the Bad. These valleys were separated by an east-west divide, but their trends determined the axis of the later lowland. The deep stream incision was greater than any subsequent stream cutting, and seems to have been greater than any earlier Pleistocene stream erosion as yet discovered in eastern South Dakota.

ILLINOIAN GLACIAL AGE

Although the greatest general change in the topography of the region seems to have been brought about by the deep dissection mentioned above, the greatest change in the drainage pattern, of which evidence still exists, was an Illinoian event. The Illinoian glacier flowed westward and southward, forming sublobes in the prediversion valleys, which had been greatly deepened during the long Yarmouth erosion. Near Chamberlain the White River had reduced its valley floor to 200 feet above the altitude of the bedrock floor of the present Missouri trench, and had covered its floor with western sand and gravel, constituting the Crete formation. No doubt other major valleys had been reduced by comparable amounts.

Ponding of these valleys must have begun well before the ice sheet reached its maximum extent; yet there is no distinct evidence that overflow occurred anywhere east of the line of the Missouri River. Hence the inference that in this sector the ice sheet expanded very rapidly and without fluctuation is almost compulsory. It seems likely also that the outer limit of expansion was determined by the time of overflow. Once the spillovers began, probably taking place in sequence from north to south, the discharge of water along the glacier margin would have melted the ice so effectively that its margin could not have advanced any farther. Thus, if the pre-Illinoian drainage of the region had been southward instead of eastward, the outer margin of the Illinoian ice sheet might have been very different in detail from the one actually inferred. Particularly in the northern part of the State, where overflow should have begun earlier than in the southern part, the glacier might have been more extensive.

The overflow itself, and the erosion that accompanied it, must have been spectacular. For erosion of the Pierre shale in the creation of the infant Missouri River trench must have been very rapid. Hence the diverted water quickly found itself flowing through a trench too deep to be abandoned in favor of the ancient valleys, as the latter reappeared from beneath the shrinking glacier.

As eastern South Dakota was deglaciated, the valleys of the Ancient Cheyenne, Bad, and White Rivers in what is now the James River lowland reappeared in greatly altered form. They had been deepened and much widened, had been smeared with drift, and were no longer occupied by their original streams. Melt water from the shrinking Illinoian glacier, however, probably created along their axes a prototype of the James River of Wisconsin time, following the general line of the ancient Bad and White Rivers from near Huron to the Missouri at Vermillion.

As the initial flood created by release of the ponded waters subsided, the Missouri acquired a more normal proglacial regimen and deposited outwash sediments along its valley floor. Little record of the outwash remains, but the extent and abundance of the Loveland loess downstream testifies to the former presence of an outwash source, as a supplement to the silt blown eastward from sources farther west. The Illinoian age came to a close in eastern South Dakota, at least, with much of the surface generally mantled with Loveland loess.

The fauna of the Loveland loess in Nebraska indicates an abundant and varied population of mammals, both large and small, many of which must also have inhabited South Dakota. The fauna included a mammoth, a tapir, a deer, a caribou, an elk, and a bison not recorded in older deposits in Nebraska.

SANGAMON INTERGLACIAL AGE

The climate of Sangamon time did not differ greatly from that of Yarmouth time, to judge from fossil plants occurring in eastern Iowa and Illinois. The surface of eastern South Dakota was mantled with drift more extensively than the Yarmouth surface had been, but both drift and overlying loess underwent marked dissection throughout a belt that fringed the deep, newly created Missouri River trench, so that there relatively few remnants of Illinoian till and Loveland loess persisted into the Wisconsin age.

Sangamon alteration of the deposits exposed at the surface developed conspicuous weathering profiles. In well-drained areas there took form the red soils now commonly seen in exposures of the Loveland loess and in the Crete formation. In poorly drained upland areas gumbotil is known to have formed in Iowa; probably it developed in extreme eastern South Dakota also, as suggested by the single exposure of gumbo silt recorded from Lincoln County. Lowland wet spots were characterized by dark Wiesenböden such as the one exposed at Sioux Falls (unit 4, section 22, p. 37). In general the Sangamon weathering profiles imply more thorough alteration than that implied by any post-Loveland profile yet discovered in central United States.

In Kansas, where Loveland weathering products have not been overrun by Wisconsin glaciers and have been less affected by dissection, a transition from a somewhat moist Sangamon climate in the east to a drier climate in the west is recorded by soil profiles. By analogy the moister climate of extreme eastern South Dakota probably gave way, in central South Dakota, to a subhumid climate, under which leaching of carbonates from the surface soil occurred while strong accumulations of caliche formed immediately below. As the implied transition from moist to dry in the Sangamon climate of Kansas is somewhat less abrupt than the corresponding transition in the existing climate, it can be suggested that the precipitation over central and west-central United States was slightly greater then than now, other climatic factors remaining much the same.

WISCONSIN GLACIAL AGE

IOWAN SUBAGE

At the close of the Sangamon interglacial age eastern South Dakota was again invaded by glacier ice. The Iowan ice sheet flowed into the State from the northeast, but now for the first time the James River lowland, and therefore the Coteau des Prairies, had begun to be defined. These features influenced the direction of flow of the ice to some extent, as recorded by striations made on the Sioux quartzite. The ice spread rapidly out to its maximum extent, which in this region was greater than that of any earlier or later glacier. The ice entered the Missouri River trench throughout the entire State and spread into northeastern Nebraska and into South Dakota west of the Missouri.

On the western side of the James lobe the bulk of the drift carried in the base of the ice was scraped off in the deep valleys of the Coteau du Missouri and in the Missouri trench itself; as a result most of the drift carried west of the Missouri consisted of far-travelled boulders that rode high within the ice. On the south the ice deposited clay-rich till in northeastern Nebraska; this may have been possible because the James River lowland offered a smoother path, with fewer and shallower valleys to act as traps for the drift in the base of the glacier, than did the more deeply dissected Coteau du Missouri.

Near the mouth of the Niobrara the glacier blocked the Missouri, ponded it, and forced the overflow to detour the ice margin and to drain southeastward across Nebraska to the Platte. Farther east in Nebraska other melt-water streams drained away from the Iowan ice sheet. The downstream parts of all the valleys west of the Missouri in South Dakota were ponded likewise, but as the ponds did not overflow, the ice margin must have begun to melt rapidly back as soon as it attained its extreme limit. The early stages of deglaciation involved marked thinning of the ice, which became stagnant or nearly so over Minnehaha and Moody Counties at least, and kamelike knolls were left over the upland as a record of the deglaciation. It may have been during the Iowan deglaciation that part or all of the Big Sioux River came into existence as an interlobate melt-water stream.

Residual parts of the Iowan ice continued to occupy the Missouri trench after the adjacent uplands had become ice free; in consequence, high-level channels were cut within the trench by streams forced to detour the relict ice. Two such channels exist south of Chamberlain. At that time the trench had much the same size and form as it has today. Outwash accumulated in it, but these sediments have not been differentiated with certainty from the outwash of Tazewell time.

As the Iowan ice sheet wasted, the climate was windy, and possibly also dry, especially in the extreme eastern part of the State. Clay, silt, and sand in the uppermost part of the drift were deflated, leaving an armorlike concentrate of pebbles at the surface. This was abraded and polished by the winds, which then gradually buried the stony surface beneath loess. While the loess was accumulating, corresponding parts of Iowa and Illinois were covered with cool, moist subarctic forest made up of spruce, fir, yew, pine, and hemlock. Presumably similar forests may have existed in eastern South Dakota, despite the fact that no direct evidence of their presence has been found.

The shrinking Iowan glacier uncovered eastern South Dakota at least as far north as Codington County. How much more extensive the retreat was is unknown, although it is probable that South Dakota was freed of ice. At any rate the deglaciation was short lived, for no appreciable weathering profile had altered the Iowan drift or loess before the region was once more overwhelmed, this time by the Tazewell ice sheet.

TAZEWELL SUBAGE

The new ice invasion took the form of better-defined lobes—the Des Moines lobe and the James lobe—than had the earlier one. The Tazewell glacier in this region failed to cover the Coteau des Prairies; it was thinner than its predecessor. However, it was able to flow through a James River lowland enlarged and smoothed by the Iowan ice. Climatic fluctuation brought the Tazewell advance to a halt before it had spread to the outer limits of the Iowan drift; in consequence the James glacial lobe, although broad, was relatively short.

The glacier margin stood long enough at its outermost position to build an end moraine, and the Big Sioux River now certainly functioned as an interlobate stream and carried abundant outwash sediments. Deflation again created a stone concentrate in some areas, and again the concentrate soon became buried beneath a blanket of loess, thicker than the loess deposited on the Iowan drift. Meanwhile a body of outwash sand and gravel partly filled at least some segments of the Missouri trench, the upper surface of the fill reaching nearly 150 feet above the existing bedrock floor of the trench in the Pierre segment, and possibly 300 feet in the Chamberlain segment.

TAZEWELL-CARY INTERVAL

The Tazewell ice sheet must have shrunk away entirely from South Dakota, for a time of weathering now set in, oxidizing the loess and allowing Chernozem soil to develop. The presence of the soil and the weathering profile implies that the ground was thawed, that a plant cover was present, and that the effective deposition of loess had ceased. Some modification of the Iowan-Tazewell drift by mass wasting and stream erosion occurred also.

Tazewell(?) loess in Hughes County, S. Dak., has yielded a pocket mouse (*Perognathus hispidus*) and an unidentified anurin. Whether these animals lived during the Tazewell deglaciation or during the Tazewell-Cary interval is not known. However, as the occurrence is at the northern limit of the present range of this mouse, it seems more likely that the fossil form dates from the Tazewell-Cary interval.

The fauna from this interval in Nebraska is not well known. It is found in the Brady soil of Schultz and Stout and in sediments of equivalent age. It includes two ground sloths, giant bear, American mastodon, elephant, woolly mammoth, horse, caribou, moose, two musk oxen, and bison. This collection suggests both glacial (woolly mammoth and musk oxen) and nonglacial (ground sloths) environments. Whether it represents a mixed fauna, or distinct faunas that inhabited the region at slightly different times, is not known.

Probably the fossil wood found in a well at Corsica dates from the Tazewell-Cary interval, suggesting, as do fossil pollens from contemporaneous deposits in Illinois, the presence of subarctic forest vegetation. It does not follow, however, that such vegetation existed in the region during the whole interval, for coniferous forest may have been replaced for a time by deciduous forest or by prairie vegetation.

CARY SUBAGE

The ice sheet again invaded South Dakota, plowing up the Tazewell loess and cutting down into the till and underlying rock. The Cary glacier, however, was a thinner body having a better-defined James lobe than its predecessor, partly because of the further conversion of the lowland into a glaciated trough by the Tazewell ice. The Cary glacier was cleanly split by the prow of the Coteau des Prairies, so that the two glacial lobes, the James lobe and the Des Moines lobe, lay opposite each other across a narrow wedge-shaped segment of ice-free terrain at the summit of the coteau. The Big Sioux River carried away the melt water from both lobes and deposited outwash along its course. Cary outwash near Sioux Falls contains fossils that record a subarctic assemblage of large mammals.

South of Sioux Falls the Cary glacier blocked the preexisting drainage and established the present course of the Big Sioux in that district. The Cary ice reached the Missouri trench on a broad front extending, with only local exceptions, from near the southeastern corner of the State upriver as far as Chamberlain. As no diversion channels of Cary date south and west of the trench have been identified (except locally in the vicinity of Yankton), it is likely that the Missouri River was not diverted widely, but continued to flow through the channel between the ice margin and the southwestern bluffs of the trench. This flow must have persisted for some time, because the outer margin of the Cary drift is marked nearly everywhere by a massive end moraine. The Cary maximum therefore was a long-drawn-out event. In the Chamberlain district kame terraces were built in the Missouri trench. Somewhat later outwash accumulated in the trench, filling it, in the vicinity of Chamberlain, to about 125 feet above its bedrock floor.

Cary ice flowed into many valleys on the coteaus, became covered with drift, and subsequently melted out, collapsing the overlying drift and thereby preserving segments of the valleys as chains of steep-sided basins. Through erosion and deposition each of the successive glaciers of Wisconsin time seems to have pushed the divide between the James and Missouri Rivers farther west.

The Cary retreat was slow, marked by many temporary readvances of the glacier margin. During the retreat loess accumulated over the entire surface of the Cary drift as a thin mantle derived from many separate outwash sources.

During the Cary retreat the fauna of the southeastern part of the State included reindeer and a small horse.

MANKATO SUBAGE

During the interval that separated the Cary retreat from the subsequent Mankato invasion, Chernozem soil apparently developed in places, and slight leaching of the Cary loess occurred. Likewise Cary outwash in the Missouri trench near Chamberlain was somewhat dissected before being partly covered by Mankato outwash. Glacier ice is believed to have melted away from South Dakota completely during the Cary-Mankato interval.

When the Mankato ice sheet entered South Dakota it was thinner than the Cary ice had been, and hence formed a relatively narrow James lobe, as well as a Des Moines lobe, with the Coteau des Prairies constituting a broad wedge between them. The Mankato glacier destroyed whatever Cary end moraines may have stood in its path along the James River lowland, although near its margin it was evidently unable to erode deeply, for it failed to remove completely the Cary loess beneath it. Despite its relative thinness, the Mankato ice reached almost as far south as the Cary glacier had done, possibly in part because Cary glacial erosion had converted the lowland into a more efficient trough as a pathway for glacial flow, and in part because advance of the Cary glacier terminus may have been inhibited by melting and erosion by the Missouri River as the stream flowed along the glacier margin.

The James glacial lobe seems to have dammed the Missouri at a point a few miles downstream from the mouth of the Niobrara. As the escaping water did not cross the upland in Nebraska it is believed to have found outlet within the Missouri trench, along the line of contact of the ice margin with the Nebraska bluffs. Lacustrine silt and clay accumulated upstream, in Charles Mix and Gregory Counties, and still farther upstream, in the Chamberlain district, an outwash fill of sand was deposited.

Like its predecessor, the Mankato ice bulged into each major depression, forming a series of sublobes. On the northern part of the Coteau des Prairies it overrode Cary end moraines, and on the Coteau du Missouri it overlapped the Cary drift sheet completely. In the northern part of the State, therefore, the Mankato ice seems to have been thick and vigorous. Along almost the entire length of its margin this glacier built a massive, composite end moraine that records repeated minor climatic fluctuation sustained over a considerable period of time. As the ice melted, water drained along and away from its margins, depositing outwash in relatively thin sheets and valley trains. Thin, localized spreads of windblown sand and loess accumulated on the Mankato drift upon and in the lee of these outwash bodies.

The Mankato deglaciation was marked by many re-advances of the ice margin; as a consequence many end moraines were built. The re-advances were of various orders of magnitude, indicating a complex sequence of climatic variations.

The ice, relatively thin over the northern part of the Coteau du Missouri, shrank eastward across it with rapidity, as indicated by the wide spacing of the end moraines there. In the James River lowland, however, the retreat was slow, for there end moraine is almost continuous, with successive crests crowding closely upon one another. The melt water from the central part of the James glacial lobe found escape, on a high profile, along the line of the James River, which lengthened headward as the glacier shrank.

In Beadle County the melt water was ponded against the proximal side of one of the end moraines. Therewith glacial Lake Dakota came into existence, beginning as a small body of water and lengthening northward as the ice that constituted its northern shore melted back. At some time during the history of the lake, ridges of sand and gravel were built by waves along its southeastern shore. The lake outflow spilled over the moraine and down the James valley, gradually trenching it. Deep trenching of the outlet eventually drained the lake, and the trench extended itself back through the former lake floor as melt water continued to pour down the James from melting ice in central and northern North Dakota. At the time the glacial discharge through the James ceased, the Missouri was flowing on a profile about 15 feet above its present flood plain at the mouth of the James.

At the close of the Lake Dakota episode, the vast Lake Agassiz began to form in the Red River basin in North Dakota and Minnesota, including the extreme northeastern corner of South Dakota. Discharge of its overflow through the Minnesota River valley continued throughout a large part of the time during which Lake Agassiz existed.

RECENT TIME

The record of events since the Mankato glacier abandoned South Dakota is meager. A Chernozem soil has developed over much of the eastern part of the State, and surface till and loess have been leached through very shallow depths. The Missouri River has continued to trench its outwash and lacustrine deposits. On the uplands very little erosion has occurred. Climatic variations induced fluctuations in the water table beneath the uplands and in the lakes that occupy depressions in the Mankato drift. These fluctuations have continued to the present time.

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