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GEOLOGIC STUDIES IN SOUTHWESTERN KANSAS

By H. T. U. SMITH

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RAYMOND C. MOORE, Ph. D., Sc. D.,
State Geologist and Director
KENNETH K. LANDES, Ph. D.,
State Geologist and Assistant Director

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GEOLOGIC STUDIES IN SOUTHWESTERN KANSAS

By H. T. U. Smith

INTRODUCTION

LOCATION AND EXTENT OF THE AREA

The area described in this report comprises a block of fourteen counties in the southwestern corner of Kansas: Clark, Ford, Finney, Grant, Gray, Hamilton, Haskell, Hodgeman, Kearny, Meade, Morton, Seward, Stanton, and Stevens (fig. 1). It extends southward from the north line of T. 21 S. to the Oklahoma boundary and westward from the east line of R. 21 W. to the Colorado boundary. The total area is about 12,000 square miles, or about one-seventh that of the state of Kansas.

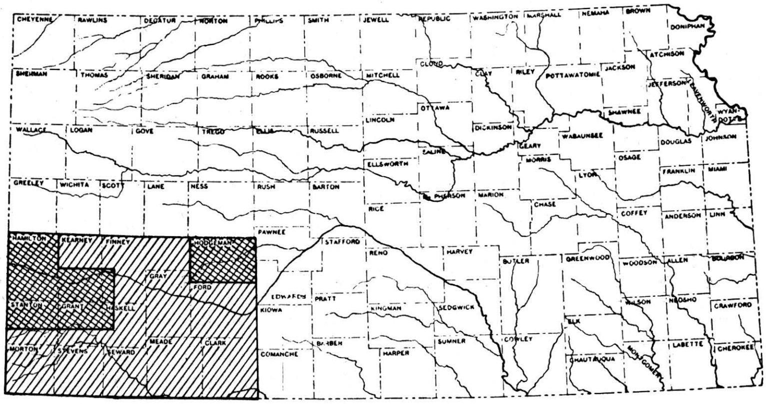

Fig. 1. Map showing the area described in this report. Areas in which detailed studies have been made previously are indicated by double cross-hatching.

PURPOSE OF THE REPORT

It is the purpose of this report to outline the broad features of Cenozoic geology in southwestern Kansas, and to consider their relations to the natural resources of the region, particularly to the underground waters. No detailed geologic mapping or areal description is undertaken. Rather it is endeavored to provide a foundation for future studies of detailed character in more restricted areas, and to anticipate some of the problems that must arise in the course of such studies. Working hypotheses are suggested for application to questions that cannot be answered satisfactorily now, with the expectation that they will be subjected to the test of future intensive work in critical areas.

PREVIOUS GEOLOGIC STUDIES

The important studies dealing specifically with the Cenozoic geology of southwestern Kansas are listed below. Others of more general character or less direct application to this area are cited at pertinent points in the text.

One of the first, if not the first, geologists to comment on the Tertiary of southwestern Kansas was Newberry (1861),* who traversed a part of the area on returning from an expedition to the far west in 1858. The first detailed study, however, was published by St. John in 1887, and in 1890 Hay published a reconnaissance geologic map and general description of the stratigraphy. In 1894, Case presented additional observations on the Mesozoic and Cenozoic formations. Hay, in 1896, assembled a comprehensive bibliography of Kansas geology prior to 1893. The reader is referred to this bibliography for reference to numerous obscure and relatively inaccessible works touching casually on the geology of the area here discussed. In 1897, Haworth contributed three important papers, one (1897) on underground waters, another (1897a) on areal physiography, and a third (1897b) on the nature and origin of the Tertiary deposits. In 1898, a topographic map of the state, on a contour interval of 100 feet, was compiled by Gannett. A report by Johnson (1901), regarded by many geologists as a classic in its field, presents a detailed analysis of the deposition of the Tertiary strata in western Kansas and contributes much valuable information on physiography, underground waters, and land utilization in parts of the area, particularly in Meade county. In 1905, Darton published a general report on the geology of the central Great Plains, outlining the stratigraphy of the region, and summarizing available data on underground waters, particularly with respect to deep wells. In the following year, Slichter (1906) presented the results of some detailed studies on underground waters along the Arkansas valley. Haworth, in 1913, published a general report on well waters, includ-

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* All citations of geological literature refer to the bibliography at the end of this report. The references are arranged alphabetically by authors, and chronologically under individual authors. The citations are made by giving author's name and date, either enclosed in parentheses or not, depending upon the context.

ing those in southwestern Kansas. In 1916, Darton published a semipopular account of the geology along the route of the Santa Fe Railroad. In 1920, the same author gave a detailed account of the geology of the Syracuse and Lakin quadrangles, embracing large sections of Hamilton, Kearny, Grant, and Stanton counties. In 1926, Bass contributed further to the geology of Hamilton county. In 1928, Landes published a detailed account of volcanic ash deposits and their utilization. Moss, in 1932, described in detail the areal geology of Hodgeman county. In 1934, some general features of regional geology were summarized by Ver Wiebe. In 1935, a preliminary announcement on results of ground-water studies by Theis and others was released. In 1937, the areal geology was delineated on a geologic map of Kansas (Moore and Landes, 1937) having a scale of about 8 miles to the inch (1:500000), issued by the State Geological Survey. In the same year, a summary of the mineral resources of individual counties was prepared by Landes (1937). A short preliminary paper on ground waters in a part of Ford county was published by Lohman in 1938. Also in that year, a summary of the oil and gas resources of western Kansas was compiled by Ver Wiebe (1938), and a preliminary paper on Pleistocene gravels was published by the present writer (Smith, 1938). Detailed studies of the underground waters in Ford, Morton, and Stanton counties have now been completed by H. A. Waite, T. G. McLaughlin, and B. F. Latta, respectively, and manuscripts are being prepared. Similar studies are progressing in Meade, Hamilton, Kearny, Finney, and Gray counties.

FIELD WORK FOR THIS REPORT

Field work for the present report was started in 1936 and essentially completed in 1938. It was of reconnaissance character, a total of three months and one week being devoted to the area here described. Some additional time, however, was devoted to studying the eastward extension of Cenozoic formations in the Great Bend area, and also the westward extension along the Arkansas valley in Colorado. Most of the time was spent in those parts of the area that had not yet been mapped in detail, and in these parts attention was concentrated on the more dissected sections where the rocks are best exposed.

Base maps used for field work were county road maps and U. S. Geological Survey topographic sheets. The latter cover about two-thirds of the area, and comprise the following quadrangles: Ashland, Dodge, Garden City, Lakin, Meade, Ness, Spearville, and Syracuse. The scale of these maps is 1:125000 and the contour interval is 20 feet. The degree of accuracy differs somewhat from map to map, and although some details of topography are considerably generalized, the maps, on the whole, are satisfactory for reconnaissance work. Morton, Stevens, and Seward counties, however, together with western Meade county, the southern portion of Stanton, Grant, and Haskell counties, and the northern portion of Hamilton, Kearny, and Finney counties, have not yet been mapped topographically. In these areas the County Engineers' road maps were used. The scale of these maps ranges from 1 inch = 2 miles to 1 inch = 4 miles. Also useful were the outline county maps prepared by the State Highway Department, on a scale of 1 inch = 4 miles.

A part of the field work was directed toward the making of a generalized topographic map (pl. 2), of 100-foot contour interval, for those parts of the area not included in standard topographic sheets, owing to the discovery of gross errors in the Gannett map of 1898. Data for the new map were collected by making speedometer traverses, using the Paulin Altimeter. U. S. Geological Survey and U. S. Coast and Geodetic Survey bench marks were used as controls. In some places, the results of State Highway surveys were available also, and were very helpful. The map thus prepared, although wanting in detail, gives a much more accurate picture of the relief of the area than does the Gannett map, which represents only an office compilation.

The rest of the field work was devoted to the study of surface and subsurface geology. Surface geology was studied by examining typical exposed sections in as many representative localities as time permitted. Particular care was given to the search for and collection of fossils, especially vertebrates. Subsurface data and information on underground waters were obtained from the records of deep water wells, supplied by well drillers, city and railway engineers, and landowners.

OTHER SOURCES OF GEOLOGIC INFORMATION

Field work was facilitated and the preparation of this report was aided by information obtained from many sources, both governmental and private. For the guidance of future workers in the area, the more important of these sources are listed below.

Departments of the Federal Government—Geological Survey: The annual reports, professional papers, bulletins, water-supply papers, and folios of this organization provide a fundamental background for all geological work in the area. Specific references to these publications are given elsewhere in this report.

Coast and Geodetic Survey: Precise elevations are available for bench marks spaced 1 to 2 miles apart along the following lines of leveling: Santa Fe Railroad route along the Arkansas valley from Dodge City to Colorado line; Rock Island route from Bucklin to Dodge City and from Bucklin to Liberal; Santa Fe route from Dodge City through Gray, Haskell, Grant, and Stanton counties; U. S. highway 83 from Liberal through Garden City; Kansas highway 27 north from Syracuse, and between Richfield and Johnson; and along Kansas highways 12 and 45 in parts of Seward, Stevens, and Morton counties.

Bureau of Soils: The results of a reconnaissance soil survey of the entire area, and of a more detailed survey for one part of the area are of geologic interest, and are discussed in a later section of this report.

Soil Conservation Service: A reconnaissance soil-erosion survey of the "Dust Bowl" counties has been published, and aerial photographs for these counties are available. These were not obtained in time to be used in the course of field work for the present report, but were extremely helpful in the office, and should be invaluable to future field workers.

Agricultural Adjustment Administration: Aerial photographs for all counties exclusive of those in the "Dust Bowl" are available, and many of these may be consulted in the local offices of the organization.

Departments of the Kansas State Government—Geological Survey: Much valuable information on southwestern Kansas, particularly on the economic aspects of the geology, is to be found in the many publications of the State Geological Survey. References to these are made in following sections of this report.

Board of Health: Chemical analyses of municipal well waters, together with partial records of the wells themselves, are on file in the offices of the State Board of Health.

Board of Agriculture: Data on stream-flow measurements, irrigation, and related matters are recorded in publications of the Division of Water Resources of this department.

Highway Department: Accurate elevations along many stretches of the state highways are available at the district offices. Generally, however, these start from assumed datum points, and must therefore be tied-in with standard bench marks before they are usable. Information on deposits of sand, gravel, volcanic ash, and other construction materials is also on file at the offices of the highway department.

City and County Departments.—Much valuable information on water wells, location of sand and gravel pits, etc., was obtained from city and county engineers.

Other sources.—Records of many deep water wells and general information on subsurface conditions were obtained from well drillers. Additional well logs were obtained from landowners, railway engineers, and from the Well Log Bureau of the Kansas Geological Society, in Wichita.

ACKNOWLEDGMENTS

The interest and encouragement of R. C. Moore and K. K. Landes throughout the progress of the work is gratefully acknowledged. To Claude W. Hibbard, of the Dyche Museum of Natural History, University of Kansas, sincere thanks are due for close coöperation both in the field and in the laboratory. Such progress as has been made in unraveling the Late Tertiary and Pleistocene stratigraphy in southwestern Kansas is to be credited largely to Mr. Hibbard's studies of the vetebrate faunas. Much unpublished information on this topic was placed at my disposal, and several days were spent with Mr. Hibbard in the field, studying faunal localities and stratigraphic relations. Also, portions of this manuscript relating to the age of Cenozoic deposits have been critically read by Mr. Hibbard. To Kenneth McCall, of the State Division of Water Resources at Garden City, I am indebted for helpful discussions on the hydrology of the area. In summarizing the geology of Meade and Ford counties, I have had the benefit of stimulating discussion with John Frye and H. A. Waite, of the U. S. Geological Survey, who have been engaged in more recent and more detailed studies in these areas as part of a program of ground-water investigations conducted in coöperation with the State Geological Survey. To many well drillers, and particularly to Dennis Doty, of Garden City, thanks are due for numerous water-well logs and for other information. Logs of wells operated by the Santa Fe Railroad were obtained through the courtesy of W. W. Kelly, Chief Engineer. Finally, it is a pleasure to acknowledge the helpful coöperation and friendly interest of city and county engineers and many other individuals, too numerous to mention by name.

A Paulin altimeter used in the field work and numerous aerial photographs used in studying the sand-dune areas were purchased with grants from the Graduate Research Fund of the University of Kansas. Mechanical analyses of sediments, compilation of well logs, and some general map studies were made with the help of student assistants provided by the National Youth Administration.

TOPOGRAPHY

General Features

Southwestern Kansas lies in the central High Plains region, and forms part of the broad treeless plain that, with some minor irregularities, slopes gently eastward from the Rocky Mountain front toward the Mississippi valley. The prevailing slope of this Plains surface is so slight as to seem almost perfectly flat, although actually the slopes average about 10 feet to the mile. Crossing the Plains in this area are two major streams: the Arkansas in the north, and the Cimarron in the south. These streams derive the greater part of their water from areas west of Kansas, and here receive the surface drainage only of relatively narrow belts bordering their own valleys and their widely separated tributary valleys. Large portions of the interstream areas have no outside surface drainage whatever. The total relief of the area considered in this report is slightly less than 2,100 feet. Altitudes range from 1,725 feet above sea level in the southeastern corner to nearly 3,800 feet in the northwestern corner. Local relief is slight on the Plains surface, but is as much as 300 feet along the larger stream valleys.

The true Plains surface, although extensive, is by no means continuous over the entire area, for well below the general level lie stream valleys ranging from less than 1 mile to more than 10 miles in width. For the most part, these valleys trend parallel to the regional slope, but locally there are notable exceptions, as in Meade county, where the valley of Crooked creek lies transverse to the slope of the Plains for about 30 miles. Cutting across the upland in many directions, these valleys divide it into separate sections, and in places leave only narrow, dissected remnants. At the southeast, dissection is so extensive as to mark the border of the Plains. There the upland surface terminates at an irregular escarpment, dropping 500 feet over the Red Hills to the greatly broadened valley of Cimarron river.

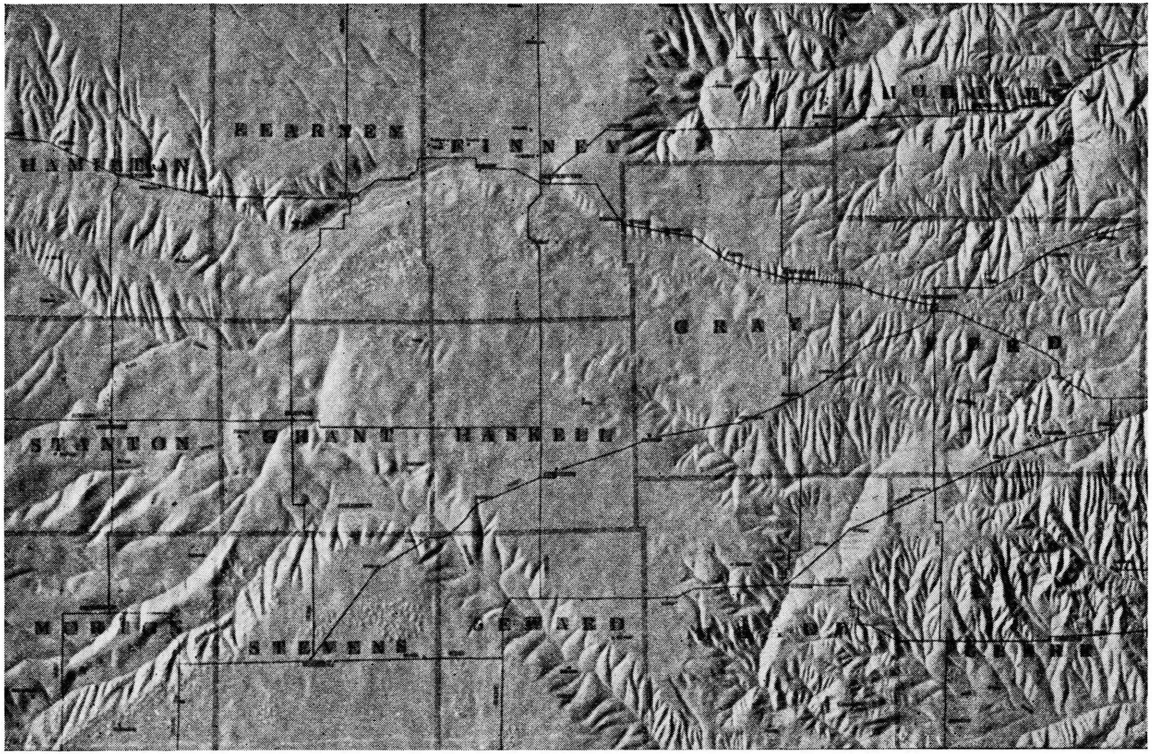


PLATE 1. Relief map of southwestern Kansas. Photograph of a part of the relief model of the state prepared under direction of R. C. Moore. Photograph by Bingham.

A more detailed discussion of topography is given in the following pages. This discussion is confined to description, whereas interpretations and explanations are reserved for a later section on physiography. Plates 1 and 2 show the regional topography pictorially and graphically.

THE PLAINS

The greater part of southwestern Kansas is characterized by the plains type of topography. Entering the area at the west at altitudes of 3600 to more than 3700 feet, the plains slope down to about 2400 feet at the eastern edge of the area. Although the regional declivity is to the east, locally there are important departures from this direction, as well as variations in the rate of slope, which generally is steeper in the western part than in the eastern part of the area. These may best be considered in connection with the separate sections into which the plains are divided by stream valleys.

North of Arkansas river the plains are divided into an eastern and a western area by a broad, shallow depression extending north from Garden City. The western or Kearny area has a general slope south of east, toward the depression, but also slopes somewhat toward the Arkansas along its southern margin. The average slope from west to east is about 15 feet per mile. East of the Garden City depression, in the Kalvesta area, the slope is almost uniformly eastward, and is gentler, averaging about 10 feet per mile. The eastern and northern portions of this area are much dissected by Pawnee river, Buckner creek, and Sawlog creek, and their tributaries, leaving narrow and irregularly branching remnants of upland in the interstream areas.

Between the Arkansas and Cimarron valleys there are three divisions of the plains: one of major extent in the central and eastern part of the area, and two of lesser extent in the west. (1) The smallest is the Syracuse upland in southern Hamilton county, constituting a long, narrow upland between the Arkansas and the northern tributary of Bear creek. (2) South of this, between Bear creek and the Cimarron, lies the broader Stanton area, bounded on the east by the southeastern stretch of North Fork of the Cimarron, and a north-south tributary valley. From west to east, it is trenched by North Fork and its nearly parallel tributaries. To the north it grades almost imperceptibly into the lowland of the Bear creek drainage basin. The general slope here is slightly north of east, and averages about 15 feet per mile. (3) Extending from central Grant county to the eastern edge of the area is the Haskell area, the largest area of typical plains country. Its slope is southeast to east-southeast, and the grade is as low as 7 feet per mile. Its eastern extension, the Minneola area, is bounded by the Red Hills escarpment, is almost completely cut off by the broad, transverse valley of Crooked creek, and is deeply indented also by Mulberry creek, Bluff creek, and the headwaters of Rattlesnake creek.

South of Cimarron river lies the other division of the plains, the Cimarron Bend area. At the west, this area is essentially continuous with the area north of the river, but at the east there is a distinct difference, for the slope here, in contrast to that northeast of the river, is easterly. The topography of this area is more irregular than that of the others, having many uneven low hills and hummocks and intervening depressions, owing partly to the presence of sand dunes, some ancient and some modern. There is no outside drainage, except in a narrow belt bordering the river, where short gulches cut into the upland.

Everywhere on the plains surface, broad shallow undrained depressions are a common feature. These range in shape from subcircular to elongate, and in size from less than a hundred feet to a few miles in their longest dimension. For the most part, their sides slope very gently toward the center, and in some places short tributary valleys drain into them. After heavy rainfall they commonly hold temporary ponds or lakes.

VALLEYS OF THE ARKANSAS DRAINAGE

Arkansas river rises in the mountains of central Colorado, and, leaving the mountains through the Royal Gorge, flows in a nearly straight line across southeastern Colorado into Kansas. At a point in southern Kearny county it swings toward the northeast, continues in this direction for nearly 20 miles, then turns south of east once more, and continues thence in a nearly straight line again to a point in eastern Ford county, where it curves northeast toward Great Bend. In the southwestern Kansas region, the river has an average gradient of about 6 feet per mile. Its open channel narrows from nearly 600 feet in width at the west (pl. 3A) to 200 or 300 feet at the east (pl. 3B). The channel is shallow and sandy, and contains many bars and islands. Much of the time there is little or no flow, the water being diverted for irrigation. Bordering and in fact crowding the channel at many places are heavy stands of cottonwood and tamarisk.

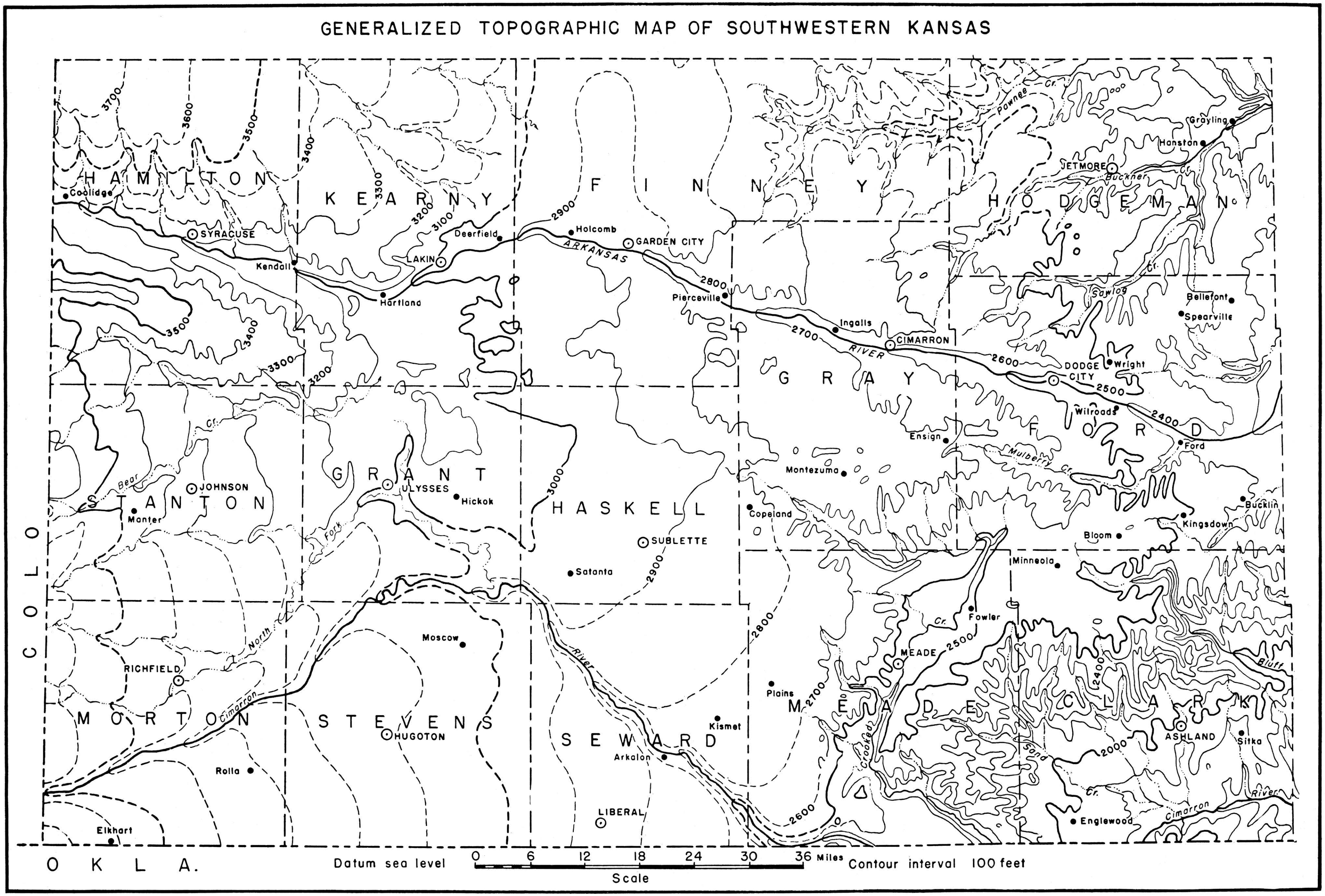


Plate 2. Generalized contour map of southwestern Kansas. Compiled from topographic sheets of the U. S. Geological Survey, level lines of the U. S. Coast and Geodetic Survey, State Highway surveys, and aneroid reconnaissance by the writer.

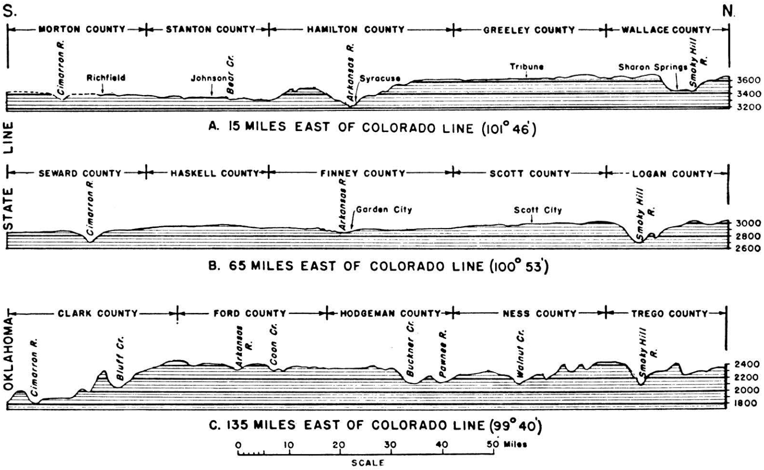
The valley bottom or inner valley of the Arkansas ranges in width from less than 1 mile to about 4 miles. It is narrowest near Hartland, in western Kearny county, and widest in eastern Kearny county, in the Lakin-Deerfield district. Bordering the valley plain on the north is an almost continuous line of bluffs as much as 100 feet high. These bluffs are extensively notched by short tributary valleys. South of the river, slopes are less abrupt, and the topography is dominated by a persistent belt of sand hills. This belt ranges in width from less than 1 mile to about 18 miles, being broadest in southwestern Finney county and adjoining districts, where the river bends to the north.

The outer valley of the Arkansas, comprising all land sloping toward the river and lying below the level of the upland plains, is 5 to 20 miles wide. Its southern boundary is roughly coextensive with that of the sand-hills belt, but its northern boundary lies much closer to the river, the position being determined by the rim of the bordering bluffs. The depth of this outer valley ranges from about 300 feet at the west to about 100 feet at the east.

An unusual feature of the Arkansas is the elevation of its channel in comparison with those of the Cimarron to the south and the Smoky Hill to the north. Although it enters the state at a much lower altitude than either of those streams, the Arkansas descends less rapidly, and, eastward, becomes higher and higher above the channels of its sister streams. At the eastern edge of the area it is more than 500 feet above the Cimarron and more than 200 feet above the Smoky Hill (fig. 2).

Topographically continuous with the Arkansas valley, although having no surface drainage into it, is the broad, irregular, Scott-Finney depression, which extends northward from Garden City to Scott City. This depression is asymmetrical, being bounded on the east in many places by a definite escarpment that is as much as 50 feet high, but at the west sloping upward gradually and merging with the plains surface. It has no throughgoing drainage, and its floor is very uneven, having numerous depressions of various sizes and shapes, and many marshy areas. East-southeastward-flowing streams from Kearny county are "lost" as they enter the depression.

Arkansas river has comparatively few tributaries of appreciable size in this area and the distribution of these few is far from uniform. On the north side, the only tributaries of any consequence are found in Hamilton county. These streams are 10 miles or more in length, and have valleys more than 50 feet deep. The larger tributaries of the Arkansas in the northeastern part of the area join the main river at some distance beyond the area. The principal drainage lines are Pawnee river, Buckner creek, Sawlog creek, and Coon creek. These streams flow in a general easterly direction, and in part are parallel to the Arkansas. It is surprising to find that, except in headward stretches, the tributaries have gradients that are flatter than the gradient of the main river. The tributaries head within a very few miles of the Arkansas valley and for some distance flow away from the main stream, so that the drainage divide between the two is crowded against the latter. The tributary streams, for the most part, have some permanent flow, even though slight. Their channels are narrow grooves that flare upward into broader grooves, which cut downward about 20 feet below the general level of the valley plain. The total width of the inner and outer channels generally does not exceed 50 yards.


A. 15 MILES EAST OF COLORADO LINE (101° 46′)

B. 65 MILES EAST OF COLORADO LINE (100° 53′)

C. 135 MILES EAST OF COLORADO LINE (99° 40′)

FIG 2. Topographic profiles of southwestern Kansas. These profiles are based on data from topographic maps of the U. S. Geological Survey and level lines of the U. S. Coast and Geodetic Survey, supplemented by aneroid reconnaissance.

South of the Arkansas in this area there are only two significant tributaries, Bear creek at the west and Mulberry creek at the east, and the very headward portion of a third, Rattlesnake creek, which flows into the main stream far to the east. Bear creek heads in southwestern Colorado nearly 50 miles west of the Kansas line. Together with its tributaries, it drains a broad lowland in southern

Hamilton and northern Stanton counties, and, swinging to the north across southern Kearny county, approaches the Arkansas, only to end in a depressed basin amid the sand hills south of Hartland. In time of flood this basin is filled, and the water spreads out around the sand hills forming irregular ponds and lakes (pl. 4A), which persist for many days, until depleted by evaporation and infiltration. Although coming within about 4 miles of the Arkansas, the flood waters of Bear creek rarely if ever reach that stream. (Haworth, 1897a, pp. 23-24; Darton, 1920, p. 3.) From west to east the valley of Bear creek becomes shallower, the depth decreasing from about 60 feet to less than 20 feet. By means of a trench 20 feet deep and a few miles long, at a point near the Grant-Kearny county line, the waters of Bear creek could be diverted to the Cimarron drainage.

Mulberry creek heads in east-central Gray county, flows parallel to the Arkansas for about 20 miles through Ford county, and then swings northeast to join the main stream at the town of Ford. Its channel is narrow, and is incised below the valley flat to a depth ranging from less than 10 feet at the west to about 25 feet at the east. Although the valley bottom is comparatively narrow—generally less than a quarter of a mile in width—the valley as a whole, including the slopes of small, closely spaced tributaries, is 1 to 4 miles wide, and forms a deep embayment in the upland. Although shallow near its source, the valley becomes rapidly deeper, and through much of its course has a depth of about 100 feet. The bordering slopes are gentle at the west, but fairly steep farther east.

VALLEYS OF THE CIMARRON DRAINAGE

Cimarron river heads in northeastern New Mexico, in the lava-capped mesas east of Raton. It flows east into the panhandle of Oklahoma, turns northeast across the southeastern corner of Colorado, and continues northeastward in Kansas from southwestern Morton county to southern Grant county, where it curves east for a short distance, then swings abruptly southeastward across Seward county and southwestern Meade county, almost at right angles to its previous course. In southern Meade county it grazes the Oklahoma line, curves gently north for a short distance, and leaves the state in the south-central part of the county. In Oklahoma it continues eastward near and almost parallel to the Kansas line, and reenters Kansas in south-central Clark county, flowing north of east into Comanche county.

From the Colorado line to southwestern Meade county, the Cimarron has an average gradient of about 10 feet per mile. In southeastern Clark county, however, it flattens to less than 8 feet per mile. The channel is shallow, and of variable width. It narrows steadily from about 800 feet in southwestern Morton county to 65 feet in southwestern Haskell county (pl. 5) and then gradually broadens downstream to several hundred feet. The channel is sandy, and has no throughgoing permanent flow, although to the east and to the west of the narrowest part there is some water at nearly all times. The valley bottom in most places is considerably less than a mile in width, but broadens somewhat in southwestern Meade county and southern Clark county. The entire valley, from rim to rim, is only a few miles wide along the greater part of the stream's course. In southern Clark county, however, it broadens somewhat abruptly into a wide basin. From Morton county to southwestern Haskell county the valley averages about 100 feet in depth, but to the southeast it deepens to more than 200 feet in southeastern Seward county, where also the valley slopes are steepest and most abrupt (pl. 4B). In Clark county the valley again becomes somewhat shallower.

Until it reaches Meade county, the Cimarron has only one important tributary in this area, North Fork of the Cimarron. This stream heads in southeastern Colorado about 30 miles west of the Kansas line, and enters Morton county about 12 miles north of the main Cimarron. It flows northeast nearly parallel to the Cimarron as far as central Grant county, then turns abruptly to the southeast and joins the main stream in the southeastern corner of the county. It has two widely separated tributaries in northern Morton county and southern Stanton county. Its valley is shallower and slightly narrower than that of the Cimarron.

The most important—and most unusual—of the Cimarron's tributaries in this area is Crooked creek. This stream heads at the eastern edge of Haskell county, flows southeast through Gray county across the Meade county line, swings north of east into southwestern Ford county, and there doubles back on itself to flow south-southwest through Meade county. In south-central Meade county, it turns again to the southeast, leaves the state in the southeastern corner of the county, and joins the Cimarron in Oklahoma. In Meade county the valley of Crooked creek is strongly asymmetrical; north of the town of Meade the western side slopes more steeply, but south of Meade the eastern side is the steeper. North of Meade, also, the valley is a broad, shallow basin, and the stream's gradient is comparatively flat. South of Meade, the valley becomes narrower and deeper, and the stream's gradient is steeper. In both sections numerous short tributary valleys enter from the west. The actual channel of Crooked creek is inconspicuous and easily may be crossed on foot during dry periods. In times of heavy rainfall, however, the sluggish stream quickly overflows its banks and floods wide areas of bottom land, damaging crops and washing out roads and bridges.

In northern Clark county, another important tributary is Bluff creek. This stream rises just across the Ford county line, curves east south of the county line, flows east about 12 miles, and then bends abruptly south. After flowing south for several miles, it veers to the southeast and crosses into Comanche county, then turns south again and enters the Cimarron a few miles east of the Clark county line. Along its upper stretches, the valley of Bluff creek is comparatively narrow, and has a maximum depth of about 200 feet. It is enclosed between steep, varicolored bluffs, which give the stream its name (pl. 6). Toward its mouth, the valley becomes shallow and broad.

Between Bluff creek and Crooked creek there are many small tributaries, but no very large ones. These streams are mostly mere sandy arroyos. They are comparatively close-spaced, and ramify headward into innumerable small branches.

RED HILLS AND ASHLAND BASIN

The Red Hills (Adams, 1903) constitute a jagged, irregular escarpment leading down from the upland plain to the Ashland basin. They begin in eastern Meade county, cross northern Clark county, and extend for a long distance to the east. Fenneman (1931, p. 28) notes that "this escarpment is not a single abrupt descent, but a deeply eroded belt 10 to 20 miles wide." Cutting across Permian redbeds and the gray to brown Cretaceous rocks, and displaying innumerable mesas, buttes, and small canyons, this feature is one of the most colorful and picturesque in Kansas. Its total relief is about 500 feet, and local relief is as much as 300 feet.

The Ashland basin is a broad lowland lying between the Cimarron bluffs to the south and the Red Hills to the north. It is trenched by the valleys of many small streams, and is by no means a flat surface, although its relief is low in comparison with the rugged hills to the north. Bordering the Cimarron and certain of its tributaries there are belts of sand dunes, which in places cover areas of many square miles.

CLIMATE

GENERAL FEATURES

The climate of southwestern Kansas is the subhumid to semiarid type. The following description, from the U. S. Weather Bureau Climatic Summary of Western Kansas (Flora, 1932a, p. 1), outlines the general conditions:

> The western half of Kansas is characterized by a rather dry climate, abundant sunshine, warm summer days that are alleviated by a good wind movement and low relative humidity, pleasantly cool summer nights, and by winters that, while cold, are commonly free from excessive snowfall and the damp, cloudy days that occur so often over most parts of the country farther east. Hot winds occasionally blow during a dry, heated period and are the cause of great crop damage and much discomfort while they are occurring.
>
> Winter months, as a rule, are slightly colder and windier than in eastern Kansas, but are drier. Cold waves occasionally bring pronounced drops in temperature and are often accompanied by driving snow.

A more detailed discussion of climatic factors, summarized from U. S. Weather Bureau publications (chiefly Flora, 1932-1939) is given below. For additional data, the reader is referred to the works of Johnson (1901), Ward (1925), and Bates (1935).

PRECIPITATION

The average annual precipitation of southwestern Kansas decreases from about 22 inches at the east to about 17 inches at the west. Departures from the average, however, are frequent and extreme, resulting in irregular alternations from periods of excessive moisture to periods of notably deficient moisture or drought (fig. 3). In wet years precipitation reaches 30 inches or more, and in dry years it declines to 10 inches or less. On the whole, the number of years in which the rainfall is below average is considerably greater than the number in which it is above average. In general, yearly totals for different recording stations rise or fall together, but the amount of rise and fall is not always proportionate, and, owing to the local or "spotty" nature of the rainfall, minor reversals between different stations are common.

The recent drought, beginning in 1931, is the most severe on record, but is not without precedent. Other notably dry periods occurred in 1892-'94, and in 1910-'14. If longer records were available, others of equal or greater duration and severity would undoubtedly be shown, and their recurrence in the future is to be expected. This variability in rainfall has been the governing factor in the agricultural history of the region. Wet years brought "boom" times, immigration, and agricultural expansion. Dry years led to crop failure, bankruptcy, and emigration. This cycle has been repeated several times, and it remains to be seen whether lessons have been learned.

FIG. 3. Annual variations in southwestern Kansas rainfall. Based on data tabulated by the U. S. Weather Bureau (Flora, 1932-'39). Blank spaces in the records for Richfield and Syracuse indicate gaps in the period of observation. The dashed lines indicate averages for the years up to and including 1930.

Of the total annual precipitation, by far the greater part falls during the summer months (fig. 4), thus allowing maximum utilization by growing crops. July is the wettest month and January the driest. In detail, however, precipitation is generally local and sporadic. Torrential downpours, or "cloudbursts", are common, and, although fairly wide areas may be affected by a single storm, the intensity of rainfall varies markedly from one locality to another. Records at Dodge City show many falls of 2 to 3 inches in 1 hour, and of 6 inches in 24 hours.

During the winter months, from November to April, a part of the precipitation takes the form of snowfall, which may total as much as 20 inches. Generally the snow drifts considerably, and rarely does it cover the ground for longer than a week at a time. February is the month of maximum snowfall.

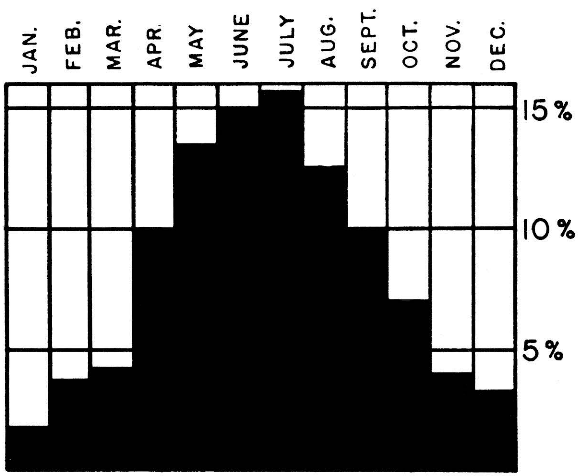


FIG. 4. Average monthly distribution of precipitation in southwestern Kansas.

During the summer months, especially June and July, hail storms are not uncommon, and some are very destructive to crops.

TEMPERATURE

Average monthly temperature ranges from about 30° in January to about 78° in July. Average monthly maxima, however, range from about 43° to 93° for the same months, and average monthly minima from about 17° to 65°. Detailed monthly variations for Lakin, most nearly representative of the few stations for which complete temperature records are available, are given in figure 5.

Daily temperature ranges during the summer months are commonly as great as 30°, thus making for relatively cool nights after even the hottest days. Daily ranges sometimes reach 50°.

The highest recorded temperature in the area was 116°, at Hugoton, Stevens county. The lowest recorded temperature was —28°, at Ulysses, Grant county.

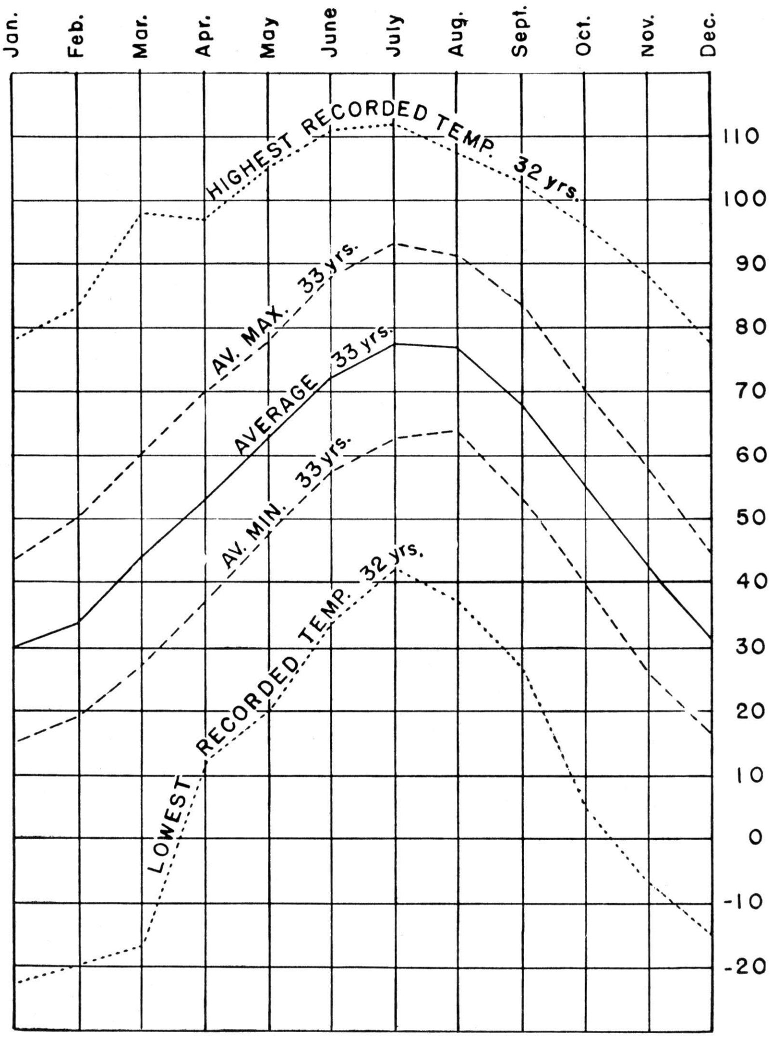


FIG. 5. Monthly temperature ranges at Lakin.

Wind

The only station in this area at which complete wind observations have been made is the one at Dodge City. There the prevailing wind direction is northwest for 5 months of the year—November to March, inclusive—and southeast for the remaining 7 months, except September, when it is south. At Johnson, in Stanton county, prevailing wind directions are essentially the same. At Liberal, partial records kept by the Soil Conservation Service from March, 1936, to November, 1939, inclusive, show that the prevailing winds were northerly for the 4 months November through February, and southerly for the 6 months, May through October. During March northerly and southerly winds were about equally important, but in April the northerly winds were again prevalent. Southerly winds are significant during every month of the year, and reach the peak of their activity in July and August, when their strength and constancy considerably exceed those of the northerly winds at their best.

The average hourly wind velocity at Dodge City ranges from 9.1 miles per hour in August to 11.8 in April. Maximum wind velocities, however, reach 58 miles per hour, and are greatest in the winter and spring months. Winds of maximum velocity blow from the northern quadrant for 8 months of the year—January to March, and July to November.

Tornadoes, although infrequent, have occurred in the area in every month of the year except December and January. They are more common in May and June.

Sunshine and Cloudiness

Records at Dodge City show an average of 178 days of the year to be clear, 65 to be cloudy, and 122 to be partly cloudy. The number of clear days is relatively greater during the summer and early fall months.

Humidity and Evaporation

On the whole, the air is very dry in southwestern Kansas, and the relative humidity is low. Thirty-year records at Garden City Experimental Farm show the following average rates of free surface evaporation for the months of the growing season: April, 6.68 in.; May, 8.46 in.; June, 10.25 in.; July, 11.90 in.; August, 10.42 in.; September, 8.10 in. It may be noted that maximum evaporation occurs during the month of maximum rainfall, and that the rate of evaporation greatly exceeds the rate of precipitation.

DUST STORMS

Local dust storms have been known in western Kansas since the country was first settled. (Throckmorton and Compton, 1938, pp. 7-8.) It was not until the recent drought, however, that dust storms became so frequent, so severe, and extended over so wide an area as to attract national attention. After several dry years, dust blowing became severe in 1934, and reached a climax in 1935. During some of the storms of that year—

> dust became so thick in the southwestern part of the state as to cause total darkness early in the afternoon and chickens went to roost as early as 3 p.m. In some localities schools in the western counties were closed on account of the danger to children in going and coming through the dust. In several of them all forms of travel, including trains and busses, were stopped in the vicinity of Dodge City and highways were closed. (Flora, 1935, p. 104.)

At several times, these dust storms extended beyond the eastern border of the state. Dust blowing continued during 1936 and 1937, but, although locally severe, generally did not extend eastward nearly so far. In 1938, increased rainfall brought considerable alleviation in many places. Table 1 shows the frequency of dust storms of different intensities at Garden City from early in 1935 through 1937, and table 2 presents similar data for Liberal.

Dust storms occurred most frequently in the late winter and early spring months, but began as early as January and continued until summer. In the extreme southwestern counties, sporadic dust "blows" of varying intensity occurred in every month of the year. Dust-bearing winds came from all points of the compass, and not infrequently shifted their direction 180° or more during a single storm. Records at Garden City show dust storms of all intensities occurring at all wind velocities from 5 to more than 30 miles per hour. Obviously, decreasing wind velocity favors settling of dust already in suspension, so that, away from the source of the dust, no definite relation between wind velocity and dust intensity can be expected.

Minor dust storms that I observed in the summer of 1937 were of two types. The first type involved a gradually increasing haziness of the air as more and more dust was stirred up by strong, steady winds (pl. 7A). This type lasted hours or days, until the strength of the wind declined. The second type came more abruptly, after the fashion of a thunder-shower. It progressed in wavelike manner and showed a steeply inclined and sharply defined front, resembling an irregularly lobate dark cloud rolling over the ground (pl. 7B). With this cloud came strong, gusty currents of air and temporary darkness,

TABLE 1—Number of days per month on which dust storms were recorded at Garden City Experimental Farm. (Data from Susan Hadley, Secretary.)

Intensity of dust storms: (A) Dusty, but visibility greater than ¼ mile; (B) very dusty, visibility 100 feet to ¼ mile; (C) extremely dusty, visibility less than 100 feet.

DATE OF STORMS.	Intensity.			DATE OF STORMS.	Intensity.		
	A.	B.	C.		A.	B.	C.
1935—March	1	1	1	1937—January	1	1	......
April	6	16	1	February	1	6	1
May	3	2	......	March	4	4	2
June	......	......	1	April	8	3	2
1936—February	1	1	......	May	7	7	1
March	3	2	......	June	3	1	1
April	1	2	1	July	5	......	......
May	......	6	1				

TABLE 2—Number of dusty days recorded at the U. S. Soil Conservation Service office at Liberal. (Data from M. M. Taylor and E. O. Hill of that office.)

Intensity of dust storms: (A) Dusty but visibility greater than 0.2 mile; (B) very dusty, visibility less than 0.2 mile.

MONTH.	A.	B.	MONTH.	A.	B.	MONTH.	A.	B.
1936—Mar.	11	11	1937—June	1	1	1938—Sept.	6	......
April	14	......	July	......	1	Oct.	9	......
May	12	2	Aug.	6	......	Nov.	6	......
June	5	......	Sept.	2	......	Dec.	5	......
July	......	......	Oct.	......	......	1939—Jan.	5	......
Aug.	1	......	Nov.	1	......	Feb.	8	......
Sept.	1	......	Dec.	1	......	Mar.	6	......
Oct.	2	......	1938—Jan.	6	3	April	10	......
Nov.	2	......	Feb.	6	3	May	11	......
Dec.	......	......	Mar.	13	3	June	10	......
1937—Jan.	1	......	April	12	2	July	8	......
Feb.	8	1	May	10	2	Aug.	7	......
Mar.	2	2	June	16	1	Sept.	8	1
April	5	2	July	8	......	Oct.	12	......
May	......	......	Aug.	17	......	Nov.	5	......

and in its wake were lingering swirls and streamers of dust and a gradually decreasing haziness. This type of dust storm generally came late in the afternoon, and sometimes was followed immediately by a slight amount of rainfall, though more commonly by nothing more than a somewhat clouded sky. Preceding such storms, dust whirls or "dust devils" were usually conspicuous (pl. 8A).

STRATIGRAPHY

EXPOSED PRE-TERTIARY ROCKS

The pre-Tertiary rocks outcropping in southwestern Kansas range in age from Upper Permian to Upper Cretaceous. They are widely exposed along Pawnee river, Buckner creek, and Sawlog creek at the northeast, and in the Red Hills and Ashland basin at the southeast. At the west, their outcrop areas are fewer and smaller, being limited to scattered areas along the larger stream valleys. Only casual observations on these rocks were made, and the following summary, included for completeness, is compiled from the literature.

Permian Rocks

Redbeds and associated rocks of Permian age are widely exposed in Clark county and in southeastern Meade county. These rocks have been collectively known as Cimarron, but are now classified by the State Geological Survey according to series that are based on the Permian succession of western Texas. Subdivisions represented in the area here discussed are indicated in the following table, mainly from Norton (1939).

Permian rocks of Clark and Meade counties, Kansas

Series.	Formation.	Member.	Thickness in feet.
Guadalupe	Taloga		65
	Day Creek dolomite		2
	Whitehorse	Upper shale member Even-bedded member Relay Creek dolomite Marlow member	38 100 22 110

The following descriptions are from Norton (1939).

The Whitehorse formation crops out in southern Clark county. Its lower member, the Marlow—

> is a unit of poorly bedded, soft, ordinarily fine-grained, commonly cross-bedded sandstone, very difficult to subdivide into its individual layers. It weathers into deep canyons and massive bluffs. Locally some of its more resistant beds are composed of masses of "sandballs." . . . Many of the basal beds are prominently cross-bedded. In places they are more shaly or silty and some are veined. . . . The Relay Creek dolomite member is a variable member of sandstone 22 feet thick, with a dolomite bed, ranging from a few inches to a foot in thickness, at top and bottom. . . . In central and northern Clark county these beds are recognizable only as white streaks in the redbeds above a mass of featureless red sandstones, and below the next evenly bedded sandstone member. . . . Overlying the horizon of the Relay Creek dolomites and related beds is 100 feet of well bedded sandstones with thin intervening shaly siltstone partings, which also weather into canyons and promontories, but unlike the Marlow below, the individual beds of this member can be followed and correlated from place to place. . . . One of the more prominent and thicker sandstone beds has a deeper maroon color than the average and makes a good correlative marker. "Sand-balls" are present in these strata also, and the "sand-crystals" from which they developed were found in the lower beds of the member. Probably the best exposure of this member is in the Morrison oil field of Clark county. . . . The 38 feet of shale intervening between the even-bedded member and the Day Creek dolomite is a very distinctive unit of the Whitehorse. . . . Close to the base is a dolomitic horizon of two to three members, each about ½ foot thick, bedded in maroon clay shale. Calcite crystals of good size are present in an interlocking mass in the intervening shale. Above are some brick-red sandy clays, another calcareous sandy lentil near the middle of the member, a thin, hard red sandstone, more soft red sandstones, a last thin maroon shale, and above that 4-7 feet of gray-green sandy shale, more buff-colored immediately beneath the contact with the Day Creek dolomite.
>
> The Day Creek dolomite is a single bed, typically about 2 feet thick, of fine-grained, dense dolomite, overlain and ordinarily underlain by gray shales. . . . In local areas, the dolomite has been partly altered to a siliceous rock which Cragin dignified by the name of "faresite".

This formation crops out in the area north and west of Ashland in Clark county. It makes an excellent horizon marker, and its outcrop has been mapped in detail by Putnam (in Suffel, 1930, pl. 17). This rock is being used as rip-rap on the dam at Clark County State Lake.

The Taloga ("Big Basin") formation crops out in Big Basin and in other parts of west-central Clark county.

> The basal 7 feet of the lower shaly member of the formation, immediately overlying the Day Creek dolomite, is gray-green in color at some localities. . . . The upper and more prominent part of the Big Basin sandstone consists of 40 feet of sandstones and sandy shales, both locally lithified to a varying extent. The massive sandstones are normally cross-bedded, red and hard, with a crystalline sheen along a freshly broken face as if bonded with gypsum or some form of calcium carbonate. Three principal beds make bold cliffs, the

lower 5 feet thick, the top one 8 feet thick, and an intermediate bed 2 feet thick. . . . Between these principal sandstone beds, the shales become more or less sandy from place to place (Norton, 1939).

TRIASSIC (?) ROCKS

Triassic rocks are widespread in northeastern New Mexico, and extend into the Texas panhandle and Cimarron county, Oklahoma (Stovall, 1938, pp. 585-587). Their occurrence farther east in the Oklahoma panhandle and in southwestern Kansas is debatable. In Texas county, Oklahoma, a small area of red rocks along Beaver creek west of Guymon is mapped by Gould and Lonsdale (1926, pp. 25-26) as very questionable Triassic. More detailed descriptions of these rocks are given by Schoff (1939, pp. 49-54), and the suggestion is made that both Triassic and Jurassic beds may be present. In Morton county, Kansas, near the boundary between sec. 12, T. 34 S., R. 43 W., and sec. 7, T. 34 S., R. 42 W., just east of Point Rock, a few small exposures are represented on the state geologic map (Moore and Landes, 1937) as possibly of Triassic age. These exposures occur along a small gully just north of the river, and in a bedrock ledge on the river bank. The rock consists of red chippy shale, and the exposed thickness is about 20 feet. It is overlain by fine-grained cross-bedded yellowish to buff sandstone containing some red bands, and having a minimum thickness of slightly more than 40 feet. No fossils of any kind were found in either division. The upper sandstone differs in appearance from typical Dakota, and may possibly be of Jurassic or Early Cretaceous age.

LOWER CRETACEOUS ROCKS

In this area, rocks of Early Cretaceous age are virtually restricted to the upper slopes of the Red Hills in Clark county. They are grouped in two divisions, the Cheyenne sandstone and the Kiowa shale. The following descriptions are drawn from discussions by Twenhofel (1924) and Bullard (1928).

CHEYENNE SANDSTONE

The Cheyenne sandstone is best exposed at the type locality near Belvidere, in southeastern Kiowa county, where it reaches a thickness of 55 feet. In Clark county, where present at all, it is very much thinner. It lies unconformably on the Permian redbeds, and consists of strongly cross-bedded gray to yellowish sandstone, locally streaked or mottled with red and other colors, and containing some interbedded gray to yellowish and black shale. Bedding is discontinuous, and grain size, cementation, and other lithologic features are variable from place to place. Locally the rock is gypsiferous. Fossils of land plants are common. The sandstone exposed between the Permian redbeds and the Tertiary sand and gravel on the east side of Big Basin in western Clark county may belong to this formation, as may also the sandstone overlying redbeds at the Point Rock section in Morton county.

KIOWA SHALE

The Kiowa shale is well exposed at Clark County State Lake, along the valley of Bluff creek about 13 miles north of Ashland (pl. 6). The thickness here is about 100 feet. According to Bullard (1928, p. 56), the rock—

> consists typically of thinly laminated black shale grading into a yellowish clay in the upper part. The black shale of the lower portion of the Kiowa is especially characteristic, consisting of very thinly laminated, paper-like shale. . . . The upper portion contains more lime and has a distinctly yellow color. . . . There are numerous thin layers of soft yellowish sandstone, particularly in the upper part. The formation contains throughout thin limestone layers, almost a fossil coquina, consisting of fragments of oyster shells. Fossils are exceptionally abundant, occurring in the limy and sandy layers throughout the formation. The black shale rarely contains fossils.

Vertebrate as well as invertebrate fossils have been found in the formation. Selenite is common throughout.

UPPER CRETACEOUS ROCKS

Upper Cretaceous rocks are far more widely exposed in southwestern Kansas than are those of Early Cretaceous age. The exposures are broad and continuous in the northeastern part of the area, but scattered and discontinuous at the west. The following formations, in upward order, are present: Dakota sandstone, Graneros shale, Greenhorn limestone, Carlile shale, and Niobrara formation. These have been described and mapped in detail in Hodgeman county by Moss (1932), and in Hamilton county and adjoining areas by Darton (1920) and Bass (1926), from whose reports the following descriptions are mainly summarized.

DAKOTA SANDSTONE

The Dakota crops out along Bluff creek and other streams in northern Clark county, at a few places on the north side of the Arkansas in Ford county, and along Sawlog creek and Buckner creek in Hodgeman county. At the west, there are scattered outcrops on the south bank of the Arkansas just west of Hartland in Kearny county, along Bear creek and its northern tributary in Hamilton and Stanton counties, and along tributaries of North Fork of the Cimarron in northern Morton county and southern Stanton county. The maximum exposed thickness of the formation in this area is about 80 feet. The complete section is nowhere exposed, however, and its thickness may reach or even exceed 350 feet. No detailed studies of the formation have yet been made in this area.

Typical exposures of the Dakota show a fine-grained thin-bedded to massive sandstone, which commonly exhibits cross-bedding. The color ranges from gray through the characteristic buff to rusty brown. The cement is calcium carbonate in some places, iron oxide in others, and silica in a few others. The last forms a very hard, quartzitic rock. All the sandstone beds are more or less lenticular, and are interbedded with variegated clay or shale or both. The formation as a whole is distinctly ferruginous, and ironstone concretions are common in many places.

GRANEROS SHALE

The Graneros shale crops out along Sawlog creek, Buckner creek, and Pawnee river in Hodgeman county, along the north side of Arkansas river in Hamilton county and in western Kearny county, and at several scattered localities south of the river in Hamilton county. Its thickness is variable, the maximum being 65 feet. The formation consists mainly of bluish-gray to gray-black fissile argillaceous shale. In places it contains beds and lenses of sandstone, sandy shale, and sandy limestone, and locally there are a few thin layers of fossil oysters. In Hamilton county a thin band of bentonitic clay is reported. Selenite crystals are present in many outcrops.

GREENHORN LIMESTONE

The distribution of the Greenhorn limestone is similar to that of the Graneros shale. Its thickness ranges from 122 to 132 feet. The formation consists of a series of thin chalky and crystalline limestones separated by thicker beds of chalky shale, which contain thin bentonite beds (Moss, 1932, p. 26). From bottom to top, the following members are distinguished: Lincoln limestone, Hartland shale, Jetmore chalk, and Pfeifer shale. In Hodgeman county the lower two of these are not satisfactorily differentiated, and in Hamilton county the upper two are not distinctly separable, being grouped together as the Bridge Creek limestone. Subdivisions, as their names imply, are distinguished on the basis of relative proportions of limestone and shale. The Fencepost limestone bed, widely quarried for the use indicated by its name, lies at the top of the formation.

CARLILE SHALE

The Carlile shale crops out along Pawnee river and Buckner creek in the northeastern part of the area, and along tributaries of the Arkansas in northern Hamilton county. Its maximum thickness is about 260 feet. The formation consists of bluish-black noncalcareous fissile shale above, grading downward into lighter-colored calcareous shale containing thin beds of chalky limestone. The lower part is designated as the Fairport chalky shale member, and the upper part as the Blue Hill shale member. The latter has a sandy zone at the top, and contains large calcareous concretions, in part septarian, in the upper part.

NIOBRARA FORMATION

This formation crops out along Pawnee river in northeastern Finney county, and along a few tributaries of the Arkansas in northern Hamilton county. Only the lower part of the formation is exposed in this area, and in Hamilton county this has a thickness of 73 feet. Two members are recognized: the Fort Hays limestone member below, and the Smoky Hill chalk member above. The Fort Hays member consists of massive beds of chalky limestone separated by thin beds of clayey to chalky shale. The limestone tends to be gray on fresh surfaces, but buff on weathered surfaces. This member has a thickness of 61 to 80 feet. The Smoky Hill chalk is composed of soft beds of chalk alternating with chalky shale, and containing numerous thin layers of bentonite.

TERTIARY FORMATIONS

The Tertiary section in southwestern Kansas is by no means complete. The Eocene, Oligocene, and Miocene are nowhere known to be exposed at the surface, although possibly deposits representing these epochs may be concealed beneath younger deposits. The Pliocene is represented by the widespread Ogallala formation, which covers by far the greater part of the area, and by other deposits of less extensive distribution. Vertebrate faunas and grass seeds from the Ogallala in southwestern Kansas indicate a middle Pliocene age. Beds of possible early Pliocene age lie uncomformably beneath the Ogallala at a single locality. The upper Pliocene is represented by the Rexroad formation, which is almost restricted to Meade county. This formation lies unconformably on the Ogallala.

LOWER PLIOCENE (?) BEDS

Rock of possible early Pliocene age occurs in one small area in southeastern Seward county (fig. 6), on both sides of Cimarron river in contiguous portions of sections 23, 24, 25, and 26, T. 34 S., R. 31 W. The total outcrop area is slightly more than 1 square mile.

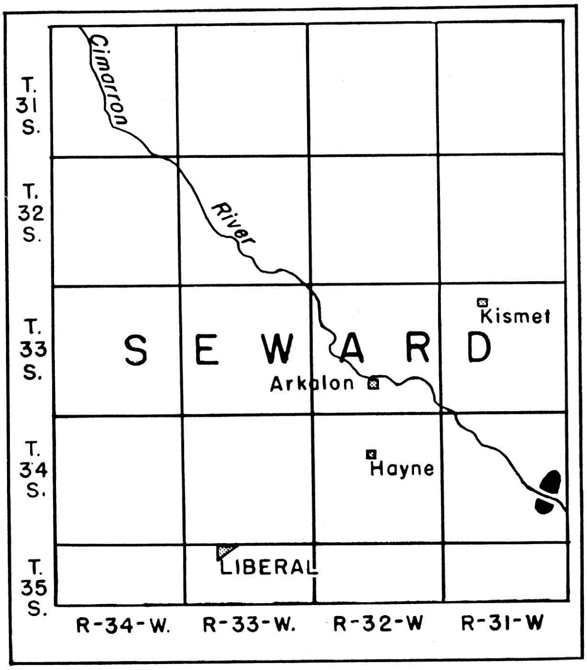


FIG. 6. Map showing location of lower Pliocene (?) beds in southeastern Seward county.

The lithology of the rock is unique, and entirely dissimilar to anything else exposed in the region. The beds show irregular easterly dips of 10° or more, and underlie essentially flat beds of the Ogallala with angular unconformity. This rock was observed and described by Adams in 1902, but seemingly has been unnoticed by later geologists.

No complete section of these beds was found. The following partial section, however, was measured on the northeast side of the river at the site of a small old quarry:

Section of Lower Pliocene (?) beds in sec. 24, T. 31 S., R. 34 W., Seward County

	Thickness in feet
8. Limestone, hard, somewhat porous, white to light sandy	1
7. Sand, very rusty, coarse and gritty below and somewhat clayey above	7
6. Sandstone, soft, massive, coarse-grained, gritty, gray to yellowish, including some grains of limestone	1
5. Chalk, soft, porous, friable, gray to yellowish-gray in color, but weathers gray-buff; shows fine banding but weathers massive. Weathered surface somewhat "case-hardened" by solution and redeposition. Quarried zone	5.5
4. Covered interval	6
3. Chalk, soft, porous, friable, very fine-grained, thinly laminated, somewhat argillaceous, gray to light-chocolate-colored, and somewhat variegated. Some dark fragmentary carbonaceous material on bedding planes	5
2. Covered interval	5
1. Chalk, soft, porous, friable, thin-bedded, light-brownish, clayey, weathers massive; contains some plant remains in lower part, and abundant ostracodes throughout	7 to 12

The base of the section is about 40 feet above river level, the underlying material being concealed. Overlying the section is about 130 feet of Ogallala beds. A few hundred yards to the south, beds of chalk and of limy sandstone, totaling about 5 feet in thickness, are exposed, and seem to be lower in the section. The chalk constitutes the most distinctive part of all the outcrops. It was formerly quarried and sawed into blocks with wood saws for local use in building. It is easily worked, and on exposure becomes superficially hardened by solution and redeposition of calcium carbonate.

Rock similar to that described above was reported by Claude Hibbard, in 1939, from the valley of a tributary to the Cimarron in southwestern Meade county. Similar rock was described also by Cragin (1891) and by Case (1894) from the south side of Beaver river near Beaver, Okla.

The fine banding (pl. 8B) and uniform lithology of the chalk beds, together with the presence of fresh-water ostracodes and of a fossil fish, reported by residents of the locality, suggest a lacustrine origin. Exact data as to age, however, are wanting. Turtle tracks and bone fragments were found by Adams, and additional fragments were collected by Hibbard and me, but none of these are diagnostic. The ostracodes, now being studied by John R. Embich, may be helpful. If these beds correlate with those near Beaver, Okla., as suggested by Adams, an early Pliocene age would be indicated by the recent studies of Chaney and Elias (1936). In the absence of definite information they are tentatively assigned to that age. It may be mentioned, however, that Adams noted the lithologic similarity of the Seward county beds to the White River Oligocene.

Ogallala Formation

GENERAL RELATIONS

The Ogallala formation is a widespread mantle consisting mainly of stream-laid sand, gravel, silt, and minor amounts of clay, all derived principally from the Rocky Mountain region. In places the formation contains small deposits of volcanic ash, and locally there are important limestone beds and some erratic deposits of chert. This mantle is essentially continuous from the Platte valley in Nebraska to the panhandle of Texas, and covers a belt 100 to more than 250 miles wide from west to east. The top of the formation is essentially the surface of the High Plains throughout this region. The formation rests with angular unconformity on older rocks, which, in southwestern Kansas, range from Permian at the east to Upper Cretaceous at the west. The angular discordance is so slight, however, that in many exposures the older and younger rocks seem to be parallel. The thickness of the Ogallala varies with the relief of the underlying topography, and in this area ranges from less than 50 feet to possibly more than 500 feet. In general, the formation is thinner at the east than at the west, but there are also significant differences in thickness from north to south.

PREVIOUS STUDIES

The Ogallala formation, comprising beds previously called "Loup Fork", was named by Darton in 1899 (pp. 734-735, 741-742, pl. 84) from a locality* in southwestern Nebraska and its distribution in that state was shown on a generalized map. In 1903 the formation in the Scotts Bluff and Camp Clarke quadrangles in Nebraska was described (Darton 1903, 1903a), and in 1905 its extension across western Kansas and eastern Colorado was mapped and described by Darton (1905, pp. 178-179, pl. 44). In 1935 the vertebrate fauna of the type locality was described by Hesse, and in 1939 recent detailed areal studies in Nebraska were reported by Lugn in a preliminary paper.

Prior to Darton's naming of the formation, beds in southwestern Kansas now classed as Ogallala were described briefly by Hay (1890) and beds in parts of northwestern Kansas were described by the same writer (Hay, 1895). Hay recognized two divisions in these

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* See footnote, p. 73.

deposits: the "Tertiary grit" below, and "Tertiary marl" above. Two years later, Haworth (1897b) described the general lithology of the Tertiary in western Kansas, and showed that its origin was fluviatile rather than lacustrine as had been assumed by Hay and other previous writers, excepting Gilbert (1896). Johnson (1901) elaborated on Haworth's interpretation, presenting an extended analysis of Tertiary fluviatile deposition, and questioning the validity of Hay's two divisions. After Darton's reconnaissance report of 1905, introducing the name "Ogallala", little further study of this formation was made in Kansas until 1920, when Darton mapped and described in some detail the formation as exposed in the Syracuse and Lakin quadrangles. Later, the Ogallala of Russell county was described by Rubey and Bass (1925), of Ellis and Hamilton counties by Bass (1926), of Osborn county by Landes (1930), of Wallace county by Elias (1931), and of Ness and Hodgeman counties by Moss (1932). The studies of Elias, beginning in 1931, were by far the most detailed, and led to the recognition both of definite horizon markers, and of the value of grass seeds as index fossils (1932, 1935). More recent studies by Theis have as yet been published only in preliminary form (1935).

In eastern Colorado, Tertiary beds now regarded as equivalent to the Ogallala were recognized as fluviatile deposits, and were designated simply as upland sands and gravels by Gilbert in 1896. In 1897, they were given the name Nussbaum formation in a more detailed study of the Pueblo quadrangle. This name was used also by Hills (1899) in describing the geology of the Elmoro quadrangle. Darton (1905) pointed out that this formation corresponded to his Ogallala formation, but he retained Nussbaum in describing the geology of the Arkansas valley in Colorado (Darton, 1906, pp. 34-35). This name was subsequently employed also in the description of the Tertiary strata of the Nepesta quadrangle (Fisher, 1906, pp. 2-3), Apishapa quadrangle (Stose, 1912, p. 7) and several counties in the southeastern part of the state (Coffin, 1921, p. 3; Duce, 1924, p. 91; Patton, 1924, pp. 22-23; Tieje, 1921, pp. 10-11; Toepelman, 1924, p. 12, 1924a, pp. 62-63). On the state geologic map of Colorado (Burbank and others, 1935), however, the greater part of the Tertiary in the Plains region was mapped as Ogallala, and only a few outliers at the west were designated as Nussbaum. The separation of the latter was apparently based on Gilbert's priority for the type locality, but was made arbitrarily, without explanation, and consequently is confusing to the user of the map.

Tertiary beds in the panhandle of Oklahoma corresponding to the Ogallala were described without use of a formation name by Rothrock (1925) and by Gould and Lonsdale (1926). More recently Schoff (1939, p. 57) has definitely referred these beds to the Ogallala.

Beds in the panhandle of Texas equivalent to the Ogallala formation are grouped in the Panhandle formation, a usage to which Hesse (1936, p. 49) objects. A summary of the studies on this formation was made by Plummer in 1932 (pp. 763-776).

Widespread deposits of Ogallala in eastern New Mexico have been mapped and briefly described by Darton (1928, pp. 58, 300; 1928a). Additional data for Curry and Roosevelt counties are given by Theis (1932).

Paleontological studies, as distinguished from the areal studies listed above, are cited in a later section dealing with the age of the formation.

LITHOLOGY

General statement.—The lithology of the Ogallala formation is notably variable, both laterally and vertically. With the single exception of a limestone member at the very top of the formation, individual beds are characteristically lenticular, and few can be traced very far. Gravel, sand, clayey silt, and calcium carbonate are the principal materials, but their proportions and degree of induration are typically irregular, and they occur in variable sequence. Beds of one type of material commonly grade into those of another so gradually that no sharp dividing line can be drawn.

Gravel and conglomerate occur throughout the greater part of the formation, but, in many of the thicker sections, they seem to be coarser, thicker, and more persistent at the base. In many relatively thin sections, no basal gravel is present. The gravel generally is admixed with more or less grit and coarse sand, and commonly grades upward into sand. Channeling (pl. 9A) and cross-bedding are characteristically prominent. The material is generally at least moderately well sorted, and, unless thoroughly cemented, has a relatively great porosity. All gradations are found from loose, uncemented gravel to hard, compact conglomerate, resembling concrete. The former is well represented by the basal beds in Meade and Clark counties, the latter by rock in exposures along Bear creek in western Stanton county. Beds showing an intermediate degree of cementation are perhaps the most common, and constitute the typical "mortar-bed" conglomerate, which generally is easily broken by the hammer. These beds commonly weather in relief, and form prominent ledges along the valley sides. The cementing material is generally calcium carbonate, which in some places is seen to be megascopically crystalline. Limonite is locally conspicuous also. In many outcrops gradation from slight cementation to strong cementation is found, governed seemingly by minor differences in the permeability of beds or cross-laminae. The color of the gravel ranges from dirty gray to rusty brown, the latter being perhaps the more common. In some beds the rusty stain is streaked or spotty, and locally a sooty-black staining is found. The conglomerate beds are generally somewhat dark gray on the weathered surface.

Facies variations.—On the basis of the lithology of the pebbles, two distinct facies of gravel are recognizable: one composed dominantly of sandstone, ironstone, and quartzite, and the other of crystalline igneous and metamorphic rocks. The former occurs only at the base of the formation, and is exposed only in Meade and Clark counties. The latter is widespread along the Arkansas valley, and crops out also at scattered localities along the Cimarron valley, above the base of the formation.

The sandstone-ironstone-quartzite facies is composed mainly of material similar to that found in the Dakota sandstone and other Cretaceous formations. Most of the ironstone pebbles are flat, and are probably concretionary. The sandstone is fine-grained, light buff in color, and more or less saccharoidal in texture. The quartzite is dominantly gray, but weathers rusty brown; it is of the type formed by secondary cementation rather than by metamorphism and recrystallization. Locally some pebbles of gypsum, dolomite, and red sandstone from the Permian are present, and a few mudballs are found. Pebbles of quartz are common, but volcanic rocks are rare and not a single pebble of granite was observed, although some feldspar grains occur in the coarse sand associated with the gravel. In shape, the pebbles range from rounded through subrounded to subangular, the last being almost exclusively quartzite. In size, most of the pebbles do not exceed 3 inches in their longest dimension, but some reach a length of 8 inches, and some sandstone blocks more than a foot long are found. The latter are probably of local derivation. A few ventifacts (pl. 10A) are found among the quartzite pebbles, and are distinguished by their well-smoothed, fine matte surface and shallow, irregular pitting.

The granitic facies of the gravel and conglomerate is composed of reddish granite, graphic granite, pink feldspar, quartzite, quartz, several varieties of felsite, and other crystalline igneous and metamorphic rocks. The quartzite ranges from light gray through brown and reddish to black, brown being the most common. The felsite ranges from almost white to reddish and purple. Texturally, it ranges from very fine-grained to aphanitic, and from porphyritic to nonporphyritic. A conspicuous, though by no means abundant variety consists of sparse white feldspar phenocrysts in a very fine-grained reddish-pink matrix. Petrographically, the felsites include varieties of rhyolite, quartz porphyry, syenite, andesite, and probably other rock types. Pebbles of sandstone, ironstone, and chert are also found. The pebbles in this facies are generally well rounded, and few exceed 3 inches in length.

Possibly other facies or subfacies of the gravel and conglomerate may be represented by the deeper, buried portions of the formation, particularly along the Arkansas valley, but few samples of this material have been seen. One, obtained from a water well in Dodge City, at a depth of about 100 feet below river level, is composed mainly of chalky limestone pebbles, but contains a few pebbles of granite and ferruginous sandstone, and coarse grains of quartz and feldspar.

Basalt pebbles were found in very few places, and of these the least equivocal is at Point Rock in western Morton county. There, pebbles of reddish, scoriaceous basalt as much as 5 inches in length occur scattered sparsely through gritty sand in the upper part of the formation. Cobbles of similar material as much as 10 inches in length were found in a gravel bed about 50 feet above stream level on the north side of Crooked creek south of Meade, but it is possible that this bed is post-Ogallala.

Sand and silt.—Sand is the principal material of the Ogallala formation, and occurs at all horizons. It grades into gravel on the one hand, and into sandy, clayey silt and sandy limestone on the other. The sand is composed dominantly of quartz, but contains a subordinate amount of feldspar and minor amounts of the heavier dark minerals. Texturally, the sand ranges from coarse to very fine grained. The degree of sorting varies. Some beds are clean, uniform, and well sorted (pl. 9B), whereas others are "dirty" and poorly sorted, containing silt and some clay (pl. 11A). Structurally, the sandy deposits range from even-bedded to irregularly cross-bedded, and many layers may be classed as structureless, showing no bedding whatever through a thickness of several feet. The last, in fact, are very common, and are typical of the middle and upper parts of the formation. The structureless layers, in general, tend to be fine grained and poorly sorted, containing admixed silt and minor amounts of clay, and some calcium carbonate. Irregular nodular, knobby, and tubular calcareous concretions are abundant in these layers. The coarser sand, on the other hand, is commonly better sorted, and shows more distinct bedding, but this is not an invariable rule. The cementation of the sand is similar to that of the conglomerate. Calcium carbonate is the principal cementing agent, and as the proportion of lime increases the sand grades from a calcareous sandstone to a sandy limestone. The color of the clean sand is generally gray buff to rusty buff where uncemented, and light gray where the cement is calcareous. Where considerable silt and clay are present in the sand, as in the structureless layers, the color ranges from gray to reddish pink. In a very few places, particularly in the bluff east of Clark County State Lake, a gray-green color was observed in impure sand layers.

Silt is an important constituent in some of the poorly sorted sandy beds, but was not found to occur in very pure form. Clay likewise occurs principally in mixtures with sand and silt, no beds of true clay being found in the Ogallala formation in this area.

Limestone.—Limestone occurs in the Ogallala at many places, but is of subordinate quantitative importance. It is commonest in the upper part of the formation, particularly at the very top, but occurs also at the bottom of some relatively thin sections, as at Point Rock, in Morton county. Exposures are most numerous in Clark county, eastern Meade county, southern Hamilton county, and western Morton county. Limestone beds are medium bedded to massive, and range from about 2 feet to slightly more than 5 feet in thickness. Texturally, they range from soft and chalky to hard, compact, and crystalline, gradations from one extreme to the other being found in a single bed or in closely associated beds. In fresh cuts the limestone is commonly softer than on long-exposed surfaces, suggesting that some "case-hardening" takes place by superficial solution and redeposition. Everywhere it contains scattered grains of sand, sparse in some places, abundant in others. The color on fresh surfaces ranges from light gray buff to reddish buff, the former being the more common. The weathered surface exhibits various shades of gray. More common than limestone proper are beds or zones of "caliche", which characteristically show a very irregular bottom (pl. 11B).

The most persistent and distinctive limestone layer is one that occurs at the top of the formation, and is here referred to as the capping limestone. This limestone has a maximum thickness of about 5 feet, and the upper part generally erodes in relief, forming a prominent ledge. It is commonly massive, and weathers to a knobby, cavernous, or irregular surface. It differs from underlying calcareous beds in degree rather than in kind—in greater thickness and hardness, in superior compactness and purity, and in the occurrence, locally, of conspicuous concentric structures. These are made up of concentric, wavy bands differing slightly from the enclosing rock in color or texture, or both (pl. 12B). These structures are etched in relief by weathering. In some the appearance is pisolitic, and in others it suggests algal structure. In a single locality (in the northwestern corner of Harper county, Oklahoma) the concentric structure was found to conform to the outline of a pebble of ferruginous Dakota(?) sandstone (pl. 12A). These structures were observed only in the uppermost part of the capping limestone, and, although common at that level, are locally obscure or absent, and seem to be spotty in their distribution. Inasmuch as these structures have been found only at the very top of those sections of Ogallala in which they occur, they are believed to be diagnostic of the top of the formation. Limestone beds lacking the concentric structures, but otherwise similar to those displaying them, cap exposures of Ogallala in some localities, and are inferred also to mark the original top of the formation.

The lithology of the capping limestone is remarkably persistent, although wide gaps occur between known exposures. It constitutes the only satisfactory horizon marker in the formation. In southwestern Kansas, outcrops were found in Clark, Meade, Hamilton, and Morton counties. In northwestern Kansas, algal structure is seemingly more prominent in the equivalent horizon, which is referred to by Elias (1931, pp. 136-141) as algal limestone. Beyond the Kansas state line, rock similar to the capping limestone was found by me at the following localities: (1) in the northwest corner of Harper county, Oklahoma, in bluffs east of U. S. highway 283, about 4 miles south of the Oklahoma line, resting directly on Permian redbeds; (2) in Cimarron county, Oklahoma, in a railroad cut north of Boise City, separated from underlying Cretaceous rock only by thin beds of gravel; and (3) along U. S. highway 160 in western Baca county, Colorado, about 4 miles east of the Las Animas county line.

Chert.—Some small, irregular bodies of chert, generally of milk-white color, are found in the calcareous beds of the Ogallala, and a single thick bed of chert was discovered in western Clark county, on the south side of U. S. highway 160 in the E½ sec. 9, T. 32 S., R. 25 W. There the chert is about 5 feet thick and seems to be a local variant in the capping limestone, perhaps formed by replacement of the limestone. It forms a prominent white ledge, visible for a considerable distance. The chert is very brittle and easily shattered by the hammer, forming irregular, hackly fragments; seemingly it is thoroughly traversed by incipient fractures. The color ranges from white on the weathered surface to light gray on a fresh surface, and shows some dark mottlings. The rock is megascopically opaque, but contains scattered and irregular clots and veinlets of translucent, opaline silica. The veinlets are locally so prominent as to give the rock a brecciated appearance. Although most of the chert is dense and compact, there are numerous small, irregular tubular openings, marginal to which there are some indications of solution.

Volcanic ash.—The Ogallala seems to contain volcanic ash in only one southwestern Kansas locality, in southern Hamilton county (sec. 18, T. 26 S., R. 40 W.). The ash at that place differs from typical Pleistocene ash in its calcareous nature and in a considerably more advanced degree of induration. It is overlain by calcareous sand indistinguishable from that common in the Ogallala.

AREAL DESCRIPTION

The bedrock floor.—Although lithologic variations are common, indeed characteristic, throughout the Ogallala, they are unsystematic for the most part, and lack any broad regional significance. Of greater interest and importance are the variations in the thickness of the formation, and in the configuration of its bedrock floor, as shown in the cross sections and map, figures 7 and 8. Surface elevations used in preparing these figures were obtained from topographic maps, and my field measurements by altimeter. They are obviously of a lower order of accuracy in parts of the area that are covered only by my reconnaissance contouring than in those for which standard topographic sheets are available. Delineation of the bottom of the Ogallala is based on actual exposures of the contact, as shown on published geologic maps, and on well records. In the greater part of the area the latter provide the only source of information. The degree of confidence with which the bottom of the Ogallala can be recognized in such records depends on two factors: the lithologic contrast between the Ogallala and the underlying beds, and the accuracy and adequacy of the record itself.

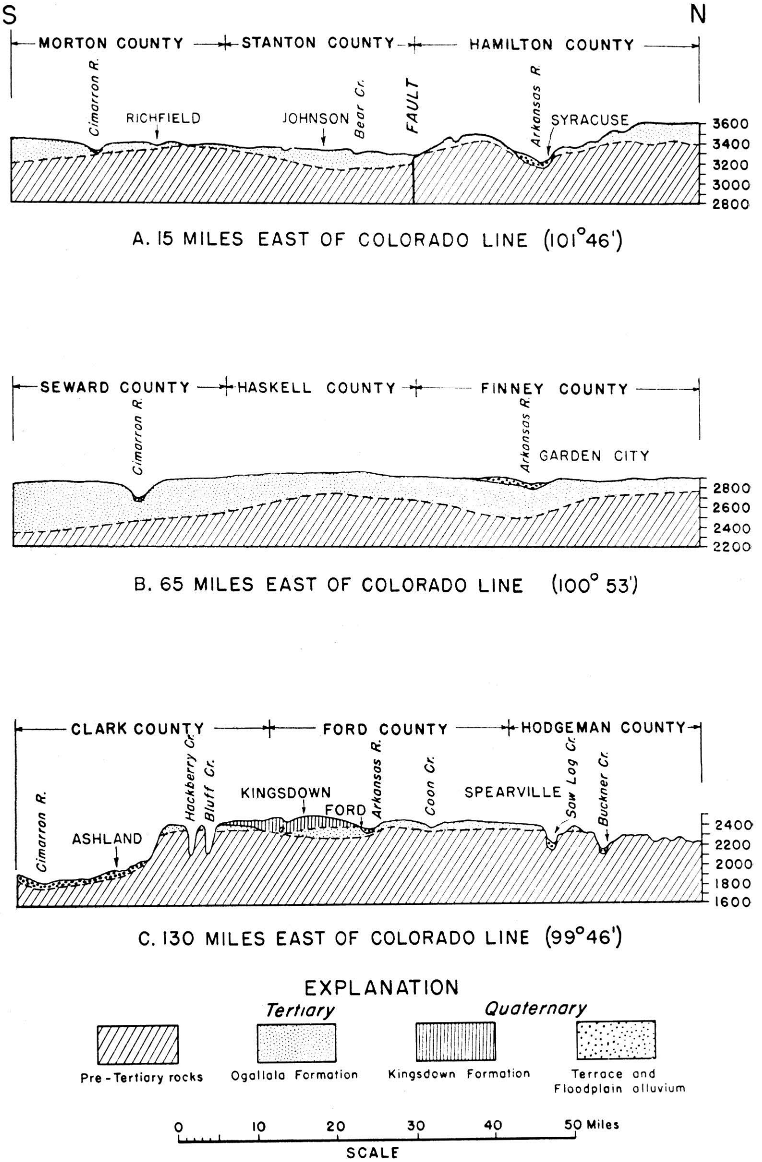

FIG. 7. Geologic cross-section of the Ogallala formation and associated rocks in southwestern Kansas. Earlier Tertiary beds possibly may be included in sections A and B. Undifferentiated Rexroad beds are included with the Ogallala in section C.

The accuracy of the well log depends first on the type of record that it represents, whether the driller's original log, or a log based on the study of actual samples or cuttings taken from the well. Logs of the latter type are greatly to be preferred, but very few were available in the area studied; these few served to check interpretations resting solely on driller's logs, which are based on the "feel" of the drill, on the rate of penetration, and on inspection of cuttings, sometimes somewhat cursory. The reliability of this type of log varies with the method of drilling, with the purpose of the well, and with the care and experience of the individual driller. Other things being equal, the logs of wells drilled with cable tools are more satisfactory than logs of wells drilled by the rotary method, but the former are in a minority. Water-well logs, on the whole, show far more detail than those of oil and gas wells, particularly with respect to sand and gravel zones, which are of interest as aquifers. Logs of municipal water wells and of deep irrigation wells were found most helpful, but most of these wells failed to reach the base of the Tertiary, and thus gave only a minimum figure for its thickness; unfortunately, no records were available for many wells of this type. Logs of oil and gas wells, although more numerous in some parts of the area, are far less satisfactory. Most of these wells are rotary-drilled, and owing to the speed of drilling and to lack of interest in Tertiary deposits on the part of oil operators, the upper 600 feet is logged only in a very casual fashion. Commonly there are glaring inconsistencies between the logs of near-by wells. Compromises, averages, and approximations are necessary in the interpretation of such records, and the margin of error in estimating the thickness of the Ogallala reaches 100 feet. Finally, it may be noted that the terminology used by drillers is different, and almost never is it the same as that of the geologist. Calcareous beds, for example, are variously referred to as "gyp", "magnesia", or "shells".

The confidence with which the base of the Tertiary may be recognized in well records depends also on the character of the underlying rock. Where this is the shale, limestone, or chalk of post-Dakota formations, the lithologic contrast on entering it is generally well enough marked to attract the driller's attention. This condition prevails over large areas north of Arkansas river. There the Cretaceous beds are commonly logged as blue shale, blue clay, lime, or chalk, as the case may be. Where the color of the "clay" is not indicated, the Ogallala may be inferred to extend to such depth as

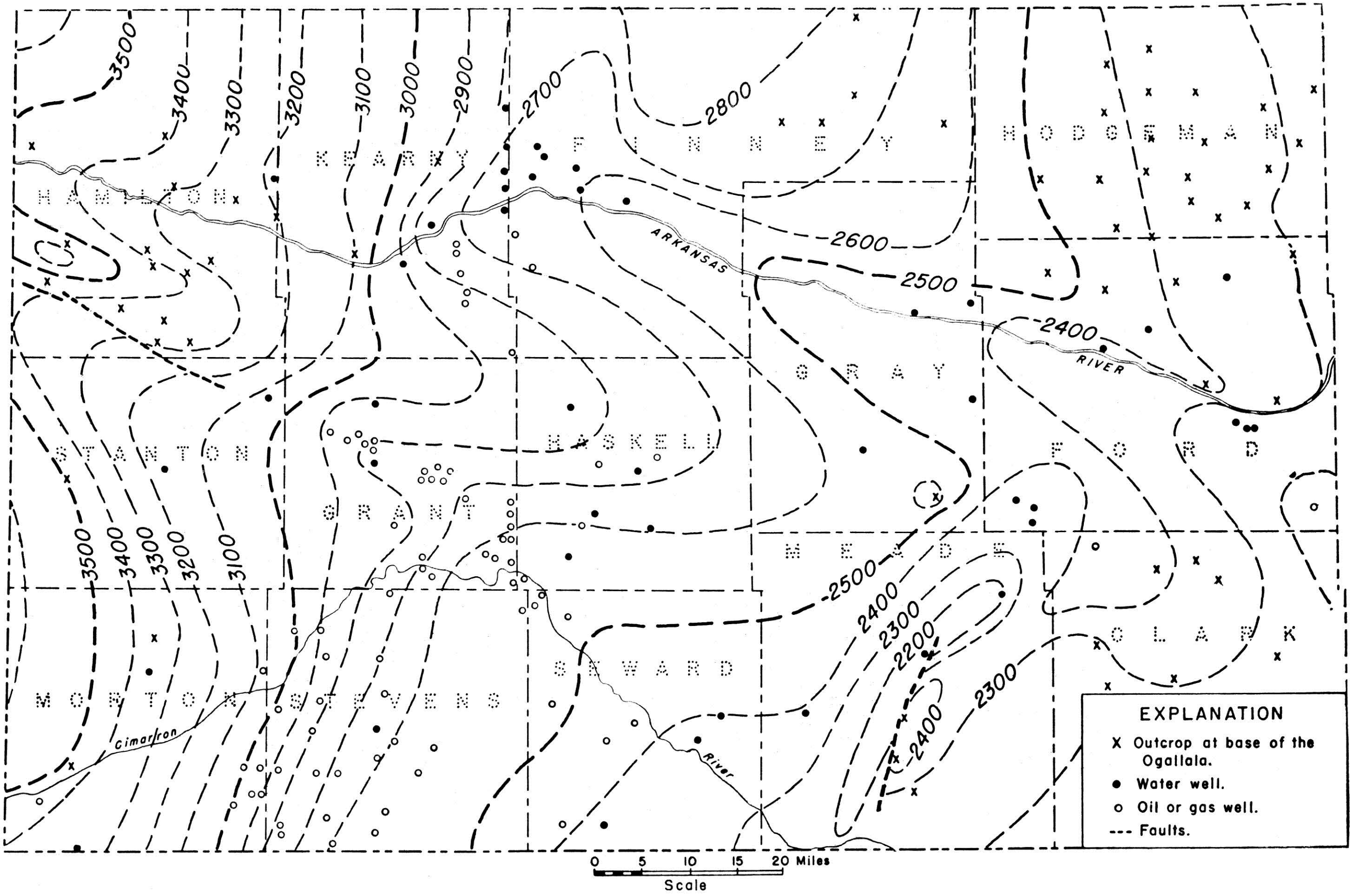

FIG. 8.—Preliminary contour map of the base of the Tertiary formations in southwestern Kansas. Contour interval 100 feet.

gravel or coarse sand is reported, and probably to such depth as much sand of any type is interbedded with the clay or shale.

Where the Ogallala is underlain directly by Dakota or pre-Dakota beds, the contact is more difficult to identify, and in many well records can be estimated only very roughly. Where redbeds are first logged, in significant thickness, a post-Permian unconformity is of course indicated, but this may leave a questionable section of considerable thickness below undoubted Tertiary. If gravel or coarse sand is reported in any thickness, however, Tertiary beds are probably indicated to at least the depth at which it occurs, for such material is very rare in the pre-Tertiary beds of this area. This criterion, of course, presupposes that the well log is true to the facts, which in some instances is open to grave doubt, as indicated by conflicting records of different wells in the same locality. Sand or gravel being lacking, estimation of the basal Tertiary contact in any given well log can only be approximated by comparison with the nearest wells for which the records contain more distinctive features, on the assumption that major changes in the bedrock topography are reasonably gradual and orderly. A few wells for which the records seem to have been more carefully made serve as controls on the interpretation of other logs within a considerable radius, and those few wells from which actual samples are available provide the most definitive check of all. Even samples, however, particularly rotary samples, are by no means unequivocal, and must be interpreted with caution. Cuttings from the bottom of the hole may be contaminated with material dropped or carried down from higher levels. Pebbles derived from pre-Tertiary formations are included in Tertiary beds, and, when found in fragmental form mingled with cuttings of other material, easily may be confused with cuttings from the bedrock itself. Pebbles of Dakota ironstone, for example, occur well up in the Ogallala, so that the presence of ferruginous chips in cuttings does not necessarily indicate that the drill has reached the Dakota formation. Nor does the presence of red streaks necessarily indicate that redbeds have been reached, for some beds in the Ogallala are reddish, and probably contain material reworked from the Permian and Triassic.

All factors considered, the data available were hardly adequate, either in quality or in quantity, for accurate contouring of the Tertiary basement. The map is preliminary only, and is subject to such revision as the finding of additional data may require. On the whole, however, it is believed to present a true, though generalized picture of the major features of bedrock topography.

The bedrock floor, as mapped, is obviously not to be regarded as a normal erosional topography. Crustal deformation is believed to have played an important role, and to have taken place partly before or during the deposition of the Ogallala, and partly after the deposition of that formation. Evidence for this is discussed in the section on structural geology. It may be noted also that the bedrock surface does not necessarily represent the base of the Ogallala in all places. It is entirely possible that, where depth to the bedrock floor is considerably greater than the "normal" thickness of the Ogallala, the latter is underlain by older Tertiary formations, and that it is these that rest directly on the bedrock.

Variations in the western area.—A more detailed description of the Ogallala and its areal variations is given in following pages. This description is based on division of the area into three broad, north-south-trending belts, centering roughly about the three cross-sections (fig. 7); these are discussed in order from west to east.

At the western edge of the area, near the Colorado line, the base of the Ogallala (or of the Tertiary) has a relief of more than 250 feet, and the thickness of the formation ranges from 50 feet to more than 200 feet. The noteworthy features here are two buried valleys or basins separated by a ridge (fig. 7A). Evidence for these is found mainly in the areal maps of Darton (1920) and Bass (1926). The north valley corresponds in position to the present valley of Arkansas river. At the west, the bottom of the old valley, as reconstructed, lies above the modern valley level. Eastward it seems to become somewhat shallower and to converge with the present valley level, but toward the eastern border of Hamilton county data are inadequate and the relations are obscure, so that the old valley cannot be traced with certainty into Kearny county.

North of the Arkansas valley, data on the floor of the Ogallala are very meager. Beyond the evidence of several inliers of Cretaceous rocks along short tributary streams, and of a single well record, contours are drawn on the basis of interpolation to a few water-well logs in Greeley county. The record of the well, in Hamilton county, located about 6 miles north of Kendall, is of interest, and is quoted from Haworth (1897b, pp. 261-262):

Record of well 6 miles north of Kendall, Kansas

	Thickness in feet	Total depth
Soil and light-colored subsoil	8	8
Clay with large amount of calcareous cement	6	14
Sand and gravel	57	71
Sandy clay with much calcareous cement	28	99
Sand and coarse gravel	6	105
Sandy clay	25	130
Sand and gravel	12	142
Yellow sand	13	155
Sand and gravel	9	164
Clay	6	170
Water-bearing sand and gravel	22	192
Yellow clay and fine sand	4	196

A thickness of at least 192 feet is indicated for the Ogallala, placing the base of the formation at a lower level than in the river bluff at Kendall, due south.

South of the Arkansas valley, the bedrock surface rises abruptly to a ridge, which marks a structural dome in the Cretaceous beds. Here the Ogallala thins to 50 feet or less. An outcrop of the capping limestone was found along a road cut in the E½ sec. 8, T. 25 S., R. 42 W., and it seems probable that this limestone controls the present plateau. The bedrock ridge declines eastward, with the topographic surface, but adequate controls for its delineation toward and beyond the Kearny county line are wanting.

In southern Hamilton county and northern Stanton county, south of the ridge, the Ogallala seems to occupy a broad basin. According to Darton's interpretation of the log of a well at Johnson (1920, p. 9), the Ogallala there reaches a thickness exceeding 180 feet. To the southwest and south, the bedrock floor gradually rises, to crop out along shallow stream valleys in southwestern Stanton county and northern Morton county. In southern Morton county it declines again. At Point Rock, on the river bluff about 6 miles east of the Colorado line, the thickness of Ogallala beds is 80 feet, and the section is as follows:

Section of Ogallala beds at Point Rock on Cimarron river, 6 miles east of the Colorado state line

	Thickness in feet
Tertiary system, Ogallala formation:	
6. Calcareous beds, poorly exposed	8 to 10
5. Calcareous sandstone to sandy limestone, containing some sand lenses and numerous vertical, rod-like concretions	8
4. Calcareous sandstone, irregularly cemented and more or less massive	6

3. Calcareous sand, structureless, gray-buff, gritty, with scattered limy concretions and pebbles of reddish scoriaceous basalt as much as 5 inches in length	10
2. Poorly exposed interval, mostly soft sandy material	42
1. Gray limestone, weathering cavernous to platey	4
Unconformity	——
Sandstone of Mesozoic age	
Total thickness	78 to 80

The base of the section is 53 feet above river level; it is underlain by Mesozoic sandstone. The Ogallala beds are slightly warped.

Farther south, at Elkhart, the thickness of the Ogallala formation is at least 250 feet. A representative section is recorded in the log of Elkhart city well No. 5:

Record of well at Elkhart, Kansas, showing Ogallala beds

	Thickness in feet	Total depth
Dirt	3	3
[Tertiary system, Ogallala formation]		
Sandy clay	15	18
Sandy clay with "gyp"	22	40
"Gyppy" clay	5	45
Sand	9	54
"Gyppy" clay	16	70
Plain "gyp"	16	86
"Gyp" and clay	12	98
"Gyp"	24	122
"Gyp" and clay	14	136
Sandy clay	18	154
"Gyp"	4	158
"Gyp" and clay	5	163
Sandy clay	9	172
Red clay with little sand	16	188
Red joint clay	4	192
Pack sand with few boulders	33	225
Pack sand and clay, larger percent clay	20	245
Sand and gravel	5	250
[? *Unconformity*]		
[? Permian system or Mesozoic]		
Brown pack sand	7	257
Red sandy clay	8	265
Pink sand rock	12	277
Light-yellow sand rock	9	286
Red shale	1	287

The sand and gravel at a depth of 245 to 250 feet must be Tertiary, and the material below is probably pre-Tertiary. Examination of samples from depths of 246 to 277 feet in test hole No. 4

for Elkhart city well No. 7 confirmed the above interpretation, showing sand of typical Ogallala lithology to a depth of 258 feet. This sand is fine to medium grained, angular, buff, dominantly quartzose and subordinately feldspathic, and at a depth of 246 to 250 feet contains a few small pebbles. A distinct red color is first observed at a depth of 272 feet. The sand at a depth of 258 to 272 feet is somewhat finer and more nearly uniform than that above, and contains some silt. All or part of it may be of Mesozoic age. East of Elkhart, toward Stevens county, the bedrock floor declines and the thickness of the Tertiary strata increases rapidly.

Variations in the central area.—The Tertiary attains its maximum thickness in the central part of the area (fig. 7B). Here the bedrock topography shows two basins separated by a broad divide. The basin at the north reaches its maximum depth of 300 feet below the present Arkansas valley level in the vicinity of Garden City. Inasmuch as some previous workers have assumed that the deposits underlying the Arkansas valley are all Quaternary alluvium, it is desirable to review briefly the evidence for Tertiary age of the greater part of the fill. (1) The bedrock floor of the Ogallala plunges under the Arkansas valley near Hartland in Kearny county. (2) Just east of the point noted, the bedrock floor steepens too abruptly to be accounted for by normal stream erosion alone (fig. 8). (3) Well records in western Finney county and eastern Kearny county, at places some miles distant from the present valley, show Ogallala similar in composition and in thickness to the material under the Arkansas valley. (4) From central Kearny county to Ford county, two water-bearing zones separated by relatively impervious "clay" are reported along the Arkansas valley. The "first" water, in the upper 25 to 35 feet of fill, is distinctly harder than that at greater depth. This suggests two separate and independent aquifers having different intake areas. The upper of these is obviously Quaternary valley fill. The lower one can be only Ogallala.

Eastward, the bedrock depression—or Finney basin—becomes a buried valley coinciding approximately with the Arkansas valley as far as the town of Ford, gradually becoming shallower toward that point. Westward, between Deerfield and Hartland, it shallows abruptly, and, near the latter locality, emerges from the river alluvium. Typical are the following well records from Garden City and Lakin.

Record of Railroad Well No. 4 at Garden City, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Loam	8	8
"Arkansas river bed"	44	52
Yellow clay	7	59
Sand and gravel	29	88
Yellow clay	9	97
Red sand and gravel	25	122
Clay	1	123
Fine sand	8	131
Yellow clay	7	138
Black sand	7	145
Sand and water	10	155
Clay	1	156
Quicksand and water	29	185
Coarse sand and gravel	17	202

This well stops far short of bedrock, for Darton (1905, p. 298) reports that a deeper well encountered "quicksand" to a depth of 311 feet, and entered black shale below that depth.

Record of Railroad Well No. 4 at Lakin, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Loam	8	8
"Arkansas river bed"	24	32
Yellow clay	3	35
Blue sand	83	118
Blue clay	7	125
Coarse dark sand	8	133
Blue sand	5	138
Blue clay	8	146
Coarse red sand	4	150
Yellow sand and gravel	20	170
Yellow clay	7	177
Yellow sand and gravel	21	198
Red sand and gravel	16	214
Yellow sandy clay	3	217
Coarse sand and gravel	14	231
[*? Unconformity*]		
[? Pre-Tertiary]		
Rock		

The signficance of the "blue" sand and clay recorded in the Lakin well is not clear.

North of the Arkansas valley, the Finney basin extends into Scott county, and is continuous with the Shallow Water basin of that county. Evidence for this is based partly on well records and partly on the surface topography, which has the form of a broad, asymmetrical depression (pl. 2). This depression is traversed by no stream, has no surface drainage, and obviously could have been formed only by areal subsidence, which presumably affected the bedrock in equal degree. In southern Scott county, about 3 miles north of the county line, an oil-well log for the deeper part of the trough gives the following record:

Partial record of a well in sec. 14, T. 20 S., R. 33 W., Scott county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Surface clay	50	50
Sand	40	90
Gravel and sand	35	125
[*Unconformity*]		
[Cretaceous system]		
Shale and "shells"	65	190
Lime	35	225
Lime and shale	100	325

This suggests that the thickness of the Ogallala is 125 feet. Another well in the same section, however, gives the contact between sand and gravel and blue shale at 182 feet.

On the western flank of the Finney basin, in Kearny county about 9 miles north of Deerfield and just west of the Finney county line, a representative well log is as follows:

Partial record of a well in sec. 25, T. 22 S., R. 35 W., Kearny county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Soil	19	19
Fine sand	53	72
No. 10 sand	10	82
No. 9 sand	20	102
No. 8 sand	28	130
Clay	12	142
No. 8 sand	15	157
No. 9 sand	6	163
No. 8 sand	11	174
Clay	10	184
Coarse gravel	22	206
[*Unconformity*]		
[Cretaceous system]		
Clay	21	227
Blue shale	75	302

This indicates a thickness of 206 feet for the Ogallala.

In northeastern Finney county, the Cretaceous-Ogallala contact crops out along the valley of Pawnee creek. Here the Ogallala is generally less than 100 feet thick.

South of the Arkansas valley, the bedrock surface rises more than 200 feet to form a broad swell in northern Haskell county and adjoining counties at the east and west. The overlying sediments thin to 200 feet or less. Evidence for this bedrock divide is found partly in well records studied by Darton. At the now-abandoned town of Santa Fe, in central Haskell county, Darton (1920, pp. 5, 6) reports 226 feet of Ogallala on the basis of a well log not quoted in full. The surface elevation here is about 120 feet higher than at Garden City. Ten miles northwest of Santa Fe, however, only 42 feet of Ogallala is reported (Darton, 1905, p. 303); the log is as follows:

Record of a well 10 miles northwest of Santa Fe, Haskell county, Kansas

	Thickness in feet	Total depth
Soil	3	3
[Tertiary system, Ogallala formation]		
Tertiary grit	42	45
[*Unconformity*]		
[Cretaceous system]		
Blue clay (Benton)	260	305
Hard blue rock	20	325
Sand with much water rising to 210 feet	5	330

One-half mile south of Santa Fe, Darton (1920, p. 5) reports a thickness of 286 feet for the Ogallala, and 6 miles southwest of the same place a thickness of only 180 feet. Logs are not quoted. The second figure indicates either a local high or an error in the original log or in its interpretation. In view of these uncertainties and of disagreement with other data, this figure was rejected in constructing the bedrock contour map.

Eastward, the bedrock divide continues into Gray county, and, in the southeastern township of that county, Cretaceous limestone crops out. At Montezuma, in the south-central part of the same county, a thickness of 224 feet in indicated for the Ogallala (and overlying Quaternary material) by the log of the railroad well:

Record of railroad well at Montezuma, Gray county, Kansas

	Thickness in feet	Total depth
[Quaternary and Tertiary deposits, undifferentiated]		
Soil	4	4
Brown clay	10	14
Dark clay	9	23
Soft rock	10	33
Hard sand rock	53	86
Soft sand	3	89
Soft sand rock	65	154
Sand and clay	13	167
Soft sand	3	170
Gravel and clay	6	176
Gravel, clay, and sand	22	198
Soft sand	3	201
Gravel, clay, and sand	12	213
Concrete gravel	0.5	213.5
Sticky clay	0.5	214
Concrete gravel	1	215
Sticky clay	0.5	215.5
Concrete gravel	0.5	216
Blue shale	1	217
Concrete gravel	1	218
Blue shale	4	222
Concrete gravel	1	223
Blue shale	0.5	223.5
Gravel	0.5	224
[*Unconformity*]		
[Cretaceous system]		
Blue shale	92	316

This well is probably on the northern flank of the subsurface divide. The upper 23 feet may represent loess or the Quaternary Kingsdown formation or both.

Westward in Grant county, the bedrock divide seems to flatten out, but data are inadequate. At a water well in Ulysses, gravel is logged at a depth of 263 to 268 feet, indicating Ogallala to at least that depth, and suggesting a position south of the bedrock arch. The complete log is as follows:

Record of a well at Ulysses, Grant county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Soil and sand	35	35
Clay	5	40
Sand	28	68
Clay	66	134
Fine sand	23	157
Sandy clay	18	175
Good sand	7	182
Dirty sand	2	184
Fine sand, nice and clean	6	190
Dirty sand	11	201
Fine sand	6	207
Sandy clay	13	220
Hard, tough clay	5	225
Dirty sand	9	234
Tough clay	29	263
Gravel	5	268
[? *Unconformity*]		
[? Cretaceous system, Dakota]		
Good sand	25	293

Six miles north of Ulysses, Darton (1920, p. 5) reports the Ogallala to be 212 feet thick; this point is probably farther up on the south flank of the bedrock arch. Six miles south-southeast of Ulysses (sec. 36, T. 29 S., R. 37 W.), Darton (1920, p. 6; 1905, pp. 299-300) cites a well log that also indicates 212 feet of Ogallala. This points to a local, secondary bedrock high, separated from the main arch to the north by a depression of uncertain extent and outline.

Farther south, in Stevens and Seward counties, a broad and ill-defined basin occurs, in which the Tertiary reaches its maximum thickness of more than 500 feet (Johnson, 1901, p. 628). This basin extends also a considerable distance into Texas county, Oklahoma (Schoff, 1939, fig. 3). It is entirely possible that the Tertiary section in this area includes a considerable thickness of pre-Ogallala beds, conceivably including Eocene or Oligocene deposits. Only by the recovery of identifiable fossils, however, could this be demonstrated satisfactorily.

Water wells at Satanta, in southwestern Haskell county, lie in the northern edge of the basin. The log for the railroad well is as follows:

Record of the railroad well at Satanta, Haskell county, Kansas

	Thickness in feet	Total depth
[Quaternary and Tertiary deposits, undifferentiated]		
Surface material	10	10
Hard rock	5	15
Dark gray clay	15	30
White clay	20	50
Coarse dry sand	50	100
Fine dry sand	30	130
Sandy clay	45	175
Cement gravel	10	185
Sand and gravel	15	200
Coarse sand, water-bearing below 220 ft.	45	245
White clay	13	258
Blue clay	2.5	260.5
Coarse water-bearing sand	49.5	310
[? *Unconformity*]		
[? Pre-Tertiary deposits]		
Hard yellow clay	1	311

This suggests a thickness of at least 310 feet for the Tertiary (and undifferentiated Quaternary) deposits.

Data on the thickness of the Tertiary at Liberal, in southern Seward county, are particularly good. The log for the deepest of the three city wells (center well in park), is as follows:

Record of city well at Liberal, Seward county, Kansas

	Thickness in feet	Total depth
[Quaternary and Tertiary deposits, undifferentiated]		
Soil, clay loam, and dry sand	200	200
Good sand	17	217
Sandy clay	62	279
Hard shell	2	281
Good sand	18	299
Rock	1	300
Hard shell	6	306
Sand	18	324
Sandy clay	31	355
Very hard rock	3	358
Clay and sand, sticky	20	378
Tough clay	21	399
Very good coarse sand	7	406
Clay	19	425
Sand	8	433
Clay	15	448
Good sand	48	496
Clay, and perhaps sand in last foot	6	502

No pre-Tertiary rocks are identifiable in the records of the water wells at Liberal. Consequently, it seems that Quaternary and Tertiary deposits are exceptionally thick in this district. A sample of sand reported to have been taken from a depth of 337 to 347 feet in the test hole for the new irrigation well in the northwest corner of Liberal was examined by me in the office of the City Engineer. It was found to be a coarse, granitic sand or grit, of the type common in the Ogallala. The sand from the bottom of the well logged above was reported by the City Engineer to be similar in character. In the record of another well at Liberal, quoted by Darton (1905, pp. 316-317), coarse sand and gravel is logged at a depth of 445 to 485 feet. From these facts it is concluded that the Tertiary (and undifferentiated Quaternary) deposits have a thickness of approximately 500 feet in the vicinity of Liberal.

In west-central Seward county, the following gas-well log indicates a thickness of 380 feet for the Tertiary:

Record of a well in the SW¼ sec. 33, T. 32 S., R. 34 W., Seward county, Kansas

	Thickness in feet	Total depth
[Quaternary and Tertiary deposits, undifferentiated]		
Quicksand (20-in. casing set at 366 ft.)	380	380
[*Unconformity*]		
[? Permian system]		
Shale, blue	35	415
Shale, light	32	447
Red rock, hole caving	3	450
Red shale	140	590
Red rock	167	757

Farther north, a somewhat greater thickness is indicated by other wells.

Near Arkalon, in central Seward county, a water well for the Panhandle Eastern "booster" station was logged as follows.

Record of well near Arkalon, Seward county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Top soil, sandy clay, and loam	14	14
Dry sand	13	27
Clay	7	34
Fine sand, dry	4	38
Tough clay	25	63
Dry sand	8	71
Blue clay	4	75
Sandy clay	11	86
Soft sand rock	6	92
Sand, water-bearing	11	103
Blue clay	9	112
Soft sand rock	2	114
Good water-bearing sand	21	135
Blue clay	4	139
Fine sand	7	146
Blue clay	3	149
Good sand and gravel	19	168

Along the west side of a tributary draw a few hundred yards east of this well, the following section (beds 1-5) was measured, its base being about 50 feet higher than the floor of the well. Overlying beds (6-8) were studied on the east side of the valley.

Section of Ogallala beds near Panhandle Eastern pump station, Arkalon, Kansas

Tertiary system, Ogallala formation	Thickness in feet
8. Sand, calcareous, containing concretionary nodules	25
7. Sand, calcareous, silty, containing limy concretions, capped by a hard, resistant layer of caliche (pl. 11)	35
6. Covered interval	35
5. "Mortar bed", massive, moderately well cemented	5
4. Sand, cross-bedded, soft, yellowish; a fragment of rhinoceros tusk found in the lower part	9
3. Sand, hard, well cemented	5
2. Sand, unconsolidated, gritty	6
1. Sand, coarse, gritty, pebbly, cross-bedded, slightly consolidated, containing some mud balls	8

The section is overlain by dune sand. The total measured thickness for the Tertiary is 346 feet, and this is minimum.

In Stevens county, the most convincing evidence for the thickness of the Tertiary was found in a series of samples collected by me as a gas well was being drilled near the southwestern corner of the county. One composite sample was collected for each length of drill pipe (average length about 30.5 feet) between the depths of 79 and 627 feet. The sample log is as follows:

Partial record of a well in sec. 34, T. 34 S., R. 38 W., Stevens county, Kansas, based on study of samples

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Sand, silt and clay, mostly soil	18	18
Clean, medium to coarse sand	61	79
Dirty, dark-buff, fine to medium sand and light, gray-buff, compact limestone	30	109
Limestone chips; medium to coarse sand and grit	61	170
Ditto, plus pebbles as much as 0.3 in. long	31	201
Coarse sand, grit, calcareous sandstone, limestone chips, and pebbles of quartz and crystalline rocks as much as 0.5 in. long	30	231
Similar to above, but some reddish staining	31	262
Similar to above, but virtually no reddish color; gray clay toward bottom	30	292
Medium to coarse dirty sand, a few pebbles, and some chips of clay	31	323
Grit, pebbles, and clay	30	353
Similar to above, but sandier	31	384
Similar to above, but containing calcareous, clayey buff silt,	61	445
Dirty, clayey grit, chips of red mudstone, and some pebbles	30	475
Similar to above, but sandier, and containing more red material	31	506
Dirty, reddish sand and grit, some chips of clay	30	536
Sand and grit, clayey in part; a few chips of reddish material	30	566
Dirty, reddish sand grit, and a few small pebbles	31	597
[*Unconformity,* possibly at slightly higher position]		
[Permian system]		
Light reddish sand and silt	30	627

This log is interpreted to indicate a thickness of about 580 feet for the Tertiary. The driller's log of the same well is given below for comparison:

Driller's record of upper part of well in sec. 34, T. 34 S., R. 38 W., Kansas

	Thickness in feet	Total depth
Sand and clay	595	595
Shells	32	627
Sand, clay, and shells	373	1000
Redbeds and gyp rock	70	1070

In the town of Hugoton, a test hole for the municipal well reached a depth of 308 feet, and seemingly ended within the Tertiary. The log is as follows:

Record of a well at Hugoton, Stevens county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Soil	2	2
Clay	6	8
Sandy clay	10	18
Clay	6	24
Sandy clay	7	31
Fine sand	11	42
Sandy clay	4	46
Packed sand	35	81
Coarse sand and gravel	17	98
Clay	3	101
"Gyp" and clay	11	112
Sandy clay	12	124
Clay and "gyp"	10	134
"Gyp"	6	140
Sandy clay	12	152
Fine packed sand	8	160
Clay	40	200
"Gyp"	5	205
Clay	4	209
Rock	2	211
Packed sand	4	215
Rock	1	216
"Gyp"	2	218
Clay and "gyp"	30	248
Coarse sand and gravel	6	254
Clay, sand, and gravel	13	267
Rock	2	269
Clay	4	273
Sandy clay	30	303
Rock	1	304
Clay	4	308

Eight miles east and two miles south of Hugoton (sec. 26, T. 33 S., R. 36 W.), the Heger irrigation well reached a depth of 360 feet without entering bedrock. A sample of the material from the bottom of this well that was shown to me was identified as typical Tertiary grit and gravel.

Elsewhere in Stevens county, gas-well logs indicate depths to bedrock ranging from about 400 to 600 feet. It is possible that some Dakota or other pre-Tertiary rock is represented in some of these, but if present it is probably thin, and in no case is it certain. Typical gas-well logs available for study are quoted below.

Partial record of a well in sec. 3, T. 31 S., R. 37 W., Stevens county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Gravel	170	170
Sand	280	450
Gravel	60	510
[? Pre-Tertiary rocks]		
Clay, yellow	15	525
Red rock and clay	455	980

Partial record of a well in sec. 2, T. 33 S., R. 39 W., Stevens county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Sand	72	72
Sand and yellow clay	100	172
Sand and gravel	162	334
Sand and sand rock	20	354
Sand, hard	19	373
Sand	67	440
[? Pre-Tertiary rocks]		
Redbeds	20	460
Redbeds and shells	167	627

Partial record of a well about 8 miles south of Hugoton in sec. 27, T. 34 S., R. 37 W., Stevens county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Sand and clay	40	40
Clay and sand	250	290
Water sand	32	322
Sand and gravel	238	560
[? Pre-Tertiary rocks]		
Redbeds	40	600

Partial record of a well southeast of Hugoton in sec. 23, T. 33 S., R. 37 W., Stevens county, Kansas

	Thickness in feet	Total depth
[Quaternary and Tertiary deposits, undifferentiated]		
Sand	40	40
Sand, gravel, red clay	250	290
Sand and shells	300	590
[? Pre-Tertiary rocks]		
Redbeds	118	708

The difficulties in distinguishing between Cretaceous and Tertiary strata in such logs are obvious. Where gravel is reported down to the redbeds, however, the absence of Cretaceous rocks is suggested. Individually, the logs are far from satisfactory, and there is a large margin of error in drawing contacts. Collectively, however, they show sufficient rough agreement to outline a subsurface basin in which the thickness of the Tertiary rocks far exceeds the average for the rest of the High Plains region in Kansas.

The bedrock basin seems to become shallower eastward, and it ends against the Meade trough, an elongate bedrock depression that is entirely discordant with general regional trends, and corresponds in position with the Crooked creek valley. Its origin is discussed in the section on structural geology. On the east side of Crooked creek south of Meade, the redbeds crop out in two places (secs. 9 and 32, T. 33 S., R. 28 W.), not shown on the state geologic map (Moore and Landes, 1937). They are overlain by a section of Ogallala of "normal" thickness. Eight miles south of Meade, the following section was measured:

Section of Quaternary and Tertiary deposits 8 miles south of Meade, Kansas

	Thickness in feet
Quaternary system:	
13. Silt, light-brownish, loess-like, clayey, containing limy nodules	9
? Unconformity	
12. Mudstone, greenish-gray, calcareous, containing some caliche in irregular layers and scattered knobs	16
11. Volcanic ash	2 to 6
10. Mudstone like No. 12	8
? Unconformity	
Tertiary system, Ogallala formation	
9. Sand and grit, reddish-buff, some small pebbles, mainly granitic, and layers and scattered nodules of caliche; fossil seeds of *Biorbia fossilia* near base	30
8. Limestone, sandy, moderately hard, grayish	3
7. Sand, light-buff, massive, calcareous	5
6. Limestone, sandy, moderately hard	2
5. Sand, fine, light gray-buff, calcareous	7

Beds 10 to 13 are believed to be Quaternary. The lower part of the section was measured about 0.25 mile west, in a gravel pit by the side of the creek, using bed 5 as a local horizon marker:

Section of Tertiary deposits at gravel pit about 8 miles south of Meade, Kansas

Tertiary system, Ogallala formation	Thickness in feet
7-9. Sand, silty, buff to reddish, limy, including some gray layers	18+
6. Sandstone, hard, calcareous	1
5. Sand, light gray-buff, calcareous, fine	5
4. Limestone, sandy; some sand and caliche	6
3. Sand, gray to reddish, calcareous	10
2. "Mortar bed" sandstone, pebbly to gritty	0.5 to 10
1. Sand, coarse, loose, cross-bedded, and gravel; pebbles dominantly of brown and black sandstone, subordinately of quartzite and volcanic rock; some mudballs and a few ventifacts	30
Total thickness of Ogallala, 103 feet	

The underlying bedrock is not exposed at this point, but from outcrops a few miles north and south, and from the presence of large red pebbles and mudballs in the basal gravels, it is inferred to lie at shallow depth. The basal gravel in this section is among the coarsest found anywhere in undoubted Ogallala, containing some cobbles as much as 8 inches long. In the valley bottom just west of the bluffs in which the above section is exposed, wells are reported to reach depths of 200 feet without encountering the redbeds, indicating an abrupt drop in the bedrock floor.

In contrast to the moderate thickness of Ogallala deposits in the measured section 8 miles south of Meade are the much greater thicknesses of unconsolidated material logged in the Meade and Fowler municipal water wells. Well No. 1 at Meade showed gravel at a depth of 229 to 239 feet, and the bottom may possibly be post-Cretaceous rock, at a depth of 283 feet. The Fowler well ended in gravel at a depth of 285 feet, indicating that the bedrock floor had not been reached. The log is as follows:

Record of water well at Fowler, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Soil and clay	21	21
Fine dry sand	4	25
Sandy clay	28	53
Blue sand	15	68
Blue sandy clay	92	160
Yellow sandy clay	8	168
Fine sand	4	172
Good sand	8	180
Clay	5	185
Sand	7	192
Clay	2	194
Sand	10	204
Hard sand rock	4	208
Streaks of sand and clay	16	224
Hard "gyp"	1	225
Sand, fine and "quicky"	31	256
Clean fine sand	20	276
Gravel	9	285

Logs of wells in the southwestern township of Ford county (Lohman, 1938, pp. 9-10) indicate Tertiary rocks to depths of 210 feet.

On the west side of the Meade trough, only a partial record for one deep well was obtained. This well is located about 5 miles southeast of Plains (sec. 2, T. 33 S., R. 30 W.). Sand and gravel are logged at a depth of 165 to 283 feet, and "chocolate-colored shale" from 283 to 292 feet. Examination of a sample from that interval, supplied by Paul Reusser, showed only a dirty, silty sand typical of the Ogallala. At Plains, the municipal water well was reported to be 365 feet deep, but no log was on file. Inasmuch as the Ogallala is the principal aquifer in this area, it is a reasonable supposition that the bottom of this well is within the Tertiary. Although outcrop and well-log data are meager and spotty, the presence of artesian water in large areas along Crooked creek valley constitutes additional evidence of a structural trough in the bedrock surface.

Character in the eastern area.—In the eastern part of the area, the Ogallala becomes much thinner, and the discernible irregularities of its floor are less marked (fig. 7C). The zone of maximum thickness coincides approximately with the present Arkansas valley. At Dodge City, a depth of 160 feet to bedrock is indicated by the following log of a well located 300 feet east of the water works and ice plant.

Record of a well near the water works at Dodge City, Kansas

	Thickness in feet	Total depth
[Quaternary and Tertiary deposits, undifferentiated]		
Soil	3	3
Sand containing water	27	30
Yellow clay, soft, impermeable	10	40
Water-bearing sand	40	80
Yellow clay and sand	10	90
Fine sand and quicksand, water	60	150
Coarse, clean gravel, water	10	160
[*Unconformity*]		
[Cretaceous system and ? Permian]		
Black, mucky clay, sticky and impermeable	20	180
Black shale	40	220
Yellow sand and sand rock, about 8 to 10 inches of "coal" at bottom	20	240
White sand rock, water	15	255
Dark sandstone	10	265
Black, mucky clay	10	275
Red rock	50	325

The upper 30 feet is probably Quaternary valley fill. Eastward, in the vicinity of Ford, irrigation wells studied by H. A. Waite indicate that the Ogallala is approximately 70 feet thick under the Arkansas valley. Cretaceous rock crops out at several places on the north side of the valley in this locality, however, and it is probable that these wells are on the side rather than on the center of the pre-Ogallala valley. The following well log from southeastern Ford county indicates that the buried valley diverges from the topographic valley in eastern Ford county, and continues southeast where the latter swings to the northeast.

Record of a well in sec. 22, T. 29 S., R. 21 W., Ford county, Kansas

	Thickness in feet	Total depth
[Quaternary system, Kingsdown formation]		
Surface and clay	46	46
Clay	64	110
[Tertiary system, Ogallala formation]		
Sand and gravel	10	120
Water sand	81	201
Sand and gravel	59	260
[*Unconformity*]		
[Cretaceous and older rocks]		
Sticky shale	80	340
Sand	92	432
Shale and redbeds	28	460

If this log is accurate, the depth to bedrock is 260 feet. The upper 110 feet represents the Quaternary Kingsdown formation. It is interesting to note that Darton (1920, p. 3) recognized this probable divergence of the buried and the surface valleys, for he writes:

> From Hartland to Dodge the base of the [Ogallala] formation descends below the bottom of Arkansas river and probably occupies an old depression, which continues eastward through Kiowa and Pratt counties and the western part of Reno county.

The upper part of the Ogallala crops out at many places in the bluffs on the north side of the Arkansas valley, and the basal contact is widely exposed along Sawlog creek, Buckner creek, and Pawnee river. The thickness is nowhere very great, the following section from the railroad well at Spearville being representative:

Partial record of railroad well at Spearville, Ford county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Black soil	6	6
Brown clay	14	20
White "gyp" rock	72	92
Coarse water sand	9	101
[*Unconformity*]		
[Cretaceous system]		
Yellow sandy clay	5	106
Black sticky shale	6	112
Light-blue sticky shale	30	142
Light-blue clay	22	164
Fine gray sand, little water	3	167
Coarse gravel, little water	4	171
Dark-blue clay	13	184

The well continues to a depth of 389 feet, in clay and shale for the greater part of the section. The "coarse" gravel from 167 to 171 feet is unusual, for such material is very rare in the Cretaceous section. A thickness of 101 feet is indicated for the Ogallala and undifferentiated younger deposits. A sample from the bottom of one of the Spearville city wells, at a depth of 85 feet, that was shown to me is typical Cretaceous rock.

Farther north, in Hodgeman and Ness counties, Moss (1932, pp. 13-15) reports that the Ogallala is about 100 feet thick at the west and thins eastward. The bedrock floor (pl. 2) seems to slope somewhat north of east, but data are inadequate, the elevations here being obtained from contour maps to which geological boundaries were transferred from the map by Moss and from the state geologic map.

South of the Arkansas valley, the base of the Tertiary does not crop out until the upper stretches of Bluff creek are reached. There, in the northern edge of Clark county, inliers of Cretaceous (not shown on the state geologic map) are found in the N½ sec. 25, T. 30 S., R. 24 W., and N½ sec. 22, T. 30 S., R. 23 W. Where Bluff creek bends south, the Ogallala is thin and locally absent, so that upper Pliocene and Pleistocene beds rest directly on the Cretaceous. It is uncertain whether this is due to the presence of hills on the pre-Ogallala surface or to post-Ogallala erosion. It is possible that the bedrock surface was never entirely covered by the Ogallala. Near Minneola, in the northwestern part of Clark county, the following well log (Moore and Haynes, 1917, p. 252) indicates that the depth to bedrock is about 125 feet.

Record of a well in the SE¼ sec. 10, T. 30 S., R. 25 W., near Minneola, Clark county, Kansas

[Quaternary and Tertiary deposits, undifferentiated]	Thickness in feet	Total depth
Soft black soil	5	5
Yellow, clayey shale	75	80
Gray sandstone	41	121
Yellow "gyp"	4	125
[Pre-Tertiary rocks]		
Soft red rock	5	130
Soft blue shale	143	273

The upper 80 feet probably represents the Quaternary Kingsdown formation, and it is possible that some Rexroad beds are present below that formation.

In the bluffs on both sides of Bluff creek at Clark County State Lake the Ogallala is well exposed.

Section of Ogallala beds on the west side of Clark County State Lake

Tertiary system, Ogallala formation	Thickness in feet
6. Limestone, caps bluff	5
5. Calcareous bed, massive, porous	4
4. Calcareous bed, nodular, somewhat soft	5
3. Sandstone, calcareous, hard, massive, cavernous	3
2. Sand, a lenticular bed, soft, coarse, uniform buff, containing fossil seeds of *Biorbia fossilia*	3
1. Sand, uniform, fine, light buff, harder and more calcareous toward top where casts of fossil plant stems seem to be present	13
Total thickness of Ogallala, 33 feet	

The section is underlain by Cretaceous shale. Fresh exposures in a road cut show that calcareous beds appearing gray on well-weathered surfaces tend to be light buff on fresh surfaces. On the east side of the valley, the thickness is slightly greater, and some gray-greenish sand and mudstone is present at the base (pl. 9B). The capping limestone is overlain by 40 feet of brownish-buff silty sand of the Kingsdown formation.

In central Clark county, on a high hill in the NW¼ sec. 11, T. 32 S., R. 22 W., the following section is exposed. It does not extend to the base of the Ogallala formation.

Section of Ogallala beds in sec. 11, T. 32 S., R. 22 W., central Clark county

Tertiary system, Ogallala formation	Thickness in feet
5. Sandstone, calcareous, grading up into sandy limestone; weathers irregular to cavernous and platy; some vague casts of plant roots or stems in places; seeds of *Biorbia fossilia* in lower 5 feet	20
4. Sand, medium-grained, clean, loose, buff-colored	10
3. Sand, gray-brown, mottled, silty, fine, containing numerous scattered limy concretions	7
2. Sand, light-buff, fine, calcareous toward top	6
1. Sand and gravel, mostly covered	20+
Exposed thickness of Ogallala, 63 feet	

On the whole, the thickness of the Ogallala in the southeastern part of the area is nowhere very great, and just south of the state line the capping limestone rests directly on the Permian redbeds. On the east rim of Big Basin, in western Clark county, the section is as follows:

Section of Ogallala and underlying beds in the N½ sec. 25, T. 32 S., R. 25 W., Clark county, Kansas

Tertiary system, Ogallala formation	Thickness in feet
6. Limestone, soft to hard, locally cherty	5
5. Sand, buff, containing calcareous nodules	3
4. Limestone, hard, sandy	5
3. Sandstone, soft, massive, light-buff, calcareous, fine-grained	10
2. Sand, gray, very concretionary	5
1. Gravel and coarse sand grading upward into clean, uniform finer sand; some ventifacts; sand arkosic but pebbles are all of ironstone, sandstone, quartzite, and quartz	22
Total thickness of Ogallala, 50 feet	
Pre-Tertiary beds	
Gray-buff shale	5
Black shale	8
Fine-grained light-buff sandstone	10
Redbeds	54

Ventifacts (pl. 10A) are common in the lower part of the Ogallala formation in the southeastern part of the area, but have not yet been found in other districts, perhaps because exposures are less adequate. In addition to the localities noted above, ventifacts have been found in the E½ sec. 10 and W½ sec. 18, T. 32 S., R. 22 W., and the S½ sec. 17, T. 32 S., R. 21 W. Characteristic also of the formation in this part of the area is the virtual absence of granite and other crystalline rocks (except quartzite) from the basal gravel.

AGE AND CORRELATION

The Ogallala is undifferentiated in Darton's original description (1899, pp. 732, 734) and its age is listed as late Tertiary, or Pliocene (?). Osborn (1909, pp. 79-80) later distinguished and dated two zones in the formation: (1) *Procamelus* zone, of late Miocene age, and (2) *Peraceras* zone, representing the last phase of the Miocene or the first phase of the Pliocene. The latter zone was regarded as representing the typical Ogallala. Still later, Osborn (1918, pp. 23-27) modified this dating, and listed the following zones: (1) *Procamelus-Hipparion* zone, of late Miocene or early Pliocene age, and (2) *Peraceras-Pliauchenia* zone, of early Pliocene age, including the typical Ogallala. In 1933, Simpson (p. 104), in a general discussion of Tertiary formations, referred to the Ogallala as a "general name for later Tertiary of the central Great Plains, for the most part of lower Pliocene age." In 1935, Hesse studied the vertebrate fauna from the type locality* of the Ogallala in Keith county, Nebraska, and assigned to it a middle Pliocene age. Stirton, in 1936, in a more comprehensive treatment, presented definitive faunal evidence for the recognition of lower, middle, and upper divisions of the Pliocene, and listed the following faunas from the Pliocene of the Great Plains:

Pliocene vertebrate faunas of the Great Plains

Upper Pliocene
  Texas: Crosby county, *Blanco fauna*
Middle Pliocene
  Nebraska: Keith county, *Feldt Ranch fauna*
  Kansas: Phillips county, (?) *Long Island fauna;* Sherman county, *Edson fauna;* Wallace county, *Rhinoceros Hill fauna,* (?) *Collins Draw fauna,* (?) *Lost Quarry fauna;* Rooks county, (?) *Rooks fauna.*
  Colorado: Yuma county, *Wray or Beecher Island fauna*

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* In his original description Darton did not specify a definite type locality for the formation, but later (1920, p. 6) referred casually to "the type locality near Ogallala station in western Nebraska". Still later, Elias (in Stirton, 1936, pp. 177-178) proposed to designate a specific type section within the general locality mentioned by Darton.

Oklahoma: Texas county, *Optima fauna*
Texas: Armstrong county, *Goodnight fauna;* Hemphill county, *Hemphill fauna;* Lipscomb county, *Higgins fauna*
Lower Pliocene
South Dakota: Todd county, *Little White River fauna, Oak Creek fauna;* Bennett county, *Big Spring Cañon fauna.*
Nebraska: Cherry county, *Burge fauna;* Brown county, (?) *Devil's Gulch fauna;* Sheridan county, (?) *Pine Creek fauna;* Sioux county, *Upper Snake Creek fauna (mixed, includes some Miocene)*
Kansas: Phillips county, *Long Island fauna (in part)*
Colorado: Logan county, *Upper Pawnee Creek fauna*
Oklahoma: Beaver county, *Beaver fauna*
Texas: Donley county, *Clarendon fauna*

Of these faunas, all except the Pine Creek and Upper Snake Creek are referred by Stirton to the Ogallala as interpreted by Elias (in Stirton, 1936, pp. 177, 178). The relations of the Blanco fauna to the Ogallala, however, are controversial.

A paleobotanical approach to the zoning and dating of the Ogallala was presented by Elias in a preliminary paper in 1935. In this paper, and in another published the next year (Chaney and Elias, 1936), it was shown that certain fossil plant seeds are of wide occurrence and of short vertical range, thereby providing a satisfactory bass for stratigraphic zoning. The correlation of these seed zones with mammalian faunas of established age was briefly indicated, and the value of the seeds as guide fossils made clear. Further studies in this direction are soon to be published in full by Elias.

The latest contribution to the study of the Ogallala was made by Lugn in 1939, on the basis of investigations in western Nebraska. He proposed that Ogallala be redefined as a group name to include the following four mappable formations, provisionally dated as indicated: (1) Valentine formation (lower Pliocene), (2) Ash Hollow formation (middle Pliocene), (3) Sidney gravel (upper Pliocene), (4) Kimball formation (very late upper Pliocene). Although complete descriptions of these formations and criteria for their differentiation are as yet unpublished, it may be inferred from the preliminary discussion that the subdivision is based primarily on the succession of fossil seeds, and secondarily on lithology and stratigraphic relations.

In the light of the foregoing, the age relations of the Ogallala in southwestern Kansas may now be considered. Vertebrate fossils are few and far between in this area, but such as have been found point to middle Pliocene age, as defined by Stirton (1936). First may be mentioned the fragment of a rhinoceros tusk found by me in the section just east of Arkalon in Seward county (p. 62). Although closer identification of this material was impossible, the very presence of rhinoceros remains suffices to indicate an age not later than middle Pliocene. A second fossil locality occurs in Clark county about 9 miles north of Ashland (NE¼ sec. 27, T. 31 S., R. 23 W.). A fairly large quarry was opened at this place by Sternberg in recent years, presumably for the Frick laboratory in New York. The one specimen thus far described from this locality was identified by Hesse (1935) as *Capromeryx altidens* and is believed to be of middle Pliocene age. A third fossil locality lies in the bluffs on the east side of Bluff creek at Clark County State Lake (SE¼ sec. 25, T. 30 S., R. 23 W.). At this locality I found numerous fragments, but no identifiable material. It was reported that many good specimens had been taken out by workers from the near-by CCC camp, and had been either lost, carried away, or destroyed. No other localities were found in the area studied. Very significant, however, is the Optima fauna of Texas county, Oklahoma, at a point about 17 miles south of the Kansas state line. Extensive collections of middle Pliocene fossils have been made there by Stovall in beds similar to and presumably continuous with those of Kansas (Schoff, 1939, pp. 61-62).

Also indicative of middle Pliocene age are fossil seeds of *Biorbia fossilia* from the following localities (identifications by M. K. Elias):

Localities from which fossil grass seeds (Biorbia fossilia) have been collected

Clark County
- W½ sec. 25, T. 30 S., R. 23 W. (bluffs on west side of State Lake), see section, p. —.
- NW¼ sec. 18, T. 32 S., R. 22 W. (on west side of county road 5 miles north of Ashland); seeds occur in a 2-foot calcareous bed 32 feet below the top of a 74-foot section. The base of the section is concealed and the top has probably been lowered by erosion.
- Sec. 11, T. 32 S., R. 22 W. (Mt. Jesus locality, northeast of Ashland), see section, p. —.

Meade County
- S½ sec. 16, T. 33 S., R. 28 W. (east side of Crooked creek 8 miles south of Meade), see section, p. —.

The Ogallala elsewhere in the area seems to be continuous with the beds in which fossils have been found, and its lithology is essentially similar. It is therefore concluded that the Ogallala of southwestern Kansas, insofar as it is represented by exposures at the surface, may be assigned to middle Pliocene age. The locally overlying Rexroad formation, of late Pliocene age, is unconformable on the Ogallala, and is not to be regarded as a part of that formation. The underlying chalky beds of southeastern Seward county, provisionally designated as lower Pliocene (?), may possibly constitute a local variant within the Ogallala, but until more specific evidence on this point is forthcoming, their dissimilar lithology and angular discordance with typical overlying Ogallala provide adequate reason for regarding them as an earlier and distinctly separate deposit.

Correlations with the Nebraska section are uncertain. Pending the publication of Lugn's complete results, and the completion of detailed studies in the intervening area, it would be premature to attempt any exact correlation with the Nebraska section. The one type of fossil grass seed thus far found in southwestern Kansas, *Biorbia fossilia,* occurs throughout three of Lugn's divisions. It is true that Lugn's description of the uppermost division of the Tertiary, the Kimball formation, suggests similarity to the capping limestone of southwestern Kansas, but if his provisional assignment of this formation to the very late upper Pliocene is accepted, possibility of this correlation is eliminated, for the capping limestone of the Kansas area is believed to antedate the upper Pliocene Rexroad formation, described elsewhere in this report.

Indeed, it is doubtful whether the Ogallala section of southwestern Kansas is susceptible to any very definitive subdivision. Good exposures are far apart, the exposed thickness is much less than in Nebraska, and fossils are few. It is possible that all the events so well recorded in the Nebraska section are telescoped into a much smaller vertical interval, but it is possible on the other hand that local Pliocene history in these two widely separated areas has been different in detail, so that depositional units are discontinuous, and do not closely correspond in time. In fact, I am more impressed by the variability of the formation, both lateral and vertical, than by any degree of lithologic constancy (with the single exception of the capping limestone). This is in agreement with the reports of well drillers, who commonly make many test holes prior to drilling any large well, and find a marked lack of correspondence between holes only a few hundred feet apart. In the light of these considerations, it is deemed advisable to retain the term Ogallala as no more than a formation name, in the sense originally proposed by Darton, insofar as the area under discussion is concerned.

The age of the Ogallala relative to that of the extensive basaltic lavas of southeastern Colorado and northeastern New Mexico is of some importance in the interpretation of volcanic detritus in sedimentary deposits of uncertain age occurring in this region. Darton (1906, p. 36) stated that—

> on the south side of the Mesa de Maya the basalt is seen to overlie an outlier of later Tertiary gravels, which indicates that the age is post-Pliocene.

Lee (1922, pp. 8, 13) questioned Darton's evidence, but, on general physiographic grounds, accepted Quaternary age for the lavas farther west, in the Raton district. Later, however, Rothrock (1925, p. 72) confirmed Darton's dating, reporting that the lava on Black mesa, in the northwestern corner of Cimarron county, Oklahoma, is underlain by upper Tertiary sand and gravel, presumably equivalent to the Ogallala. In the summer of 1939, in company with members of the U. S. Geological Survey, I found additional confirmation of post-Ogallala age for the lava. On the north side of Carrizo mesa, near the Baca-Las Animas county line in Colorado, several tens of feet of typical Ogallala calcareous sandstone was found between the Dakota sandstone and the basalt. No basaltic detritus was observed in the Ogallala, nor any indication of proximity to active vulcanism. From the foregoing it may be concluded that the basalt flows nearest Kansas are definitely of post-Ogallala age. On the other hand, it may be noted that pebbles of basaltic scoria were found in more or less typical Ogallala deposits of the Point Rock section in western Morton county, and that basaltic pebbles were found in the formation also in Cimarron county, Oklahoma (Rothrock, 1925, p. 61). It is entirely possible that the outpouring of extensive plateau basalts was the climax of a volcanic history that began much earlier. Mertie (in Lee, 1922, p. 10), in fact, has suggested a long and complex volcanic history for Sierra Grande, in northeastern New Mexico. Lee (1922, fig. 7) has pointed out that lavas of several different ages are present in the Raton district. It is very probable that the earliest of these lavas antedates the basalt on mesas farther east, and also antedates the Ogallala. If Hill's correlation of certain gravel beds near Trinidad with the Nussbaum formation is correct (1899, p. 2 and maps), this supposition is confirmed, for the gravels lie more than 2700 feet below the lava on the mesas about 5 miles south.

ORIGIN OF THE FORMATION

Scope of the problem.—Although at first thought to be a lacustrine deposit (Hay, 1890, Williston, 1895), the Ogallala was early shown to be of fluviatile origin (Gilbert, 1896; Haworth, 1897b; Johnson, 1901). In the light of present knowledge, the Ogallala may be described as a warped and dissected piedmont alluvial plain deposit. It is not to be regarded as a composite fan deposit as supposed by some workers, however, for its thickness increases away from the mountain front, whereas that of a fan deposit decreases outward from a point near its apex. In the following pages I propose to outline the origin of the Ogallala in some detail, in the light of new facts that have gradually become known since the publication of Johnson's monograph in 1901. No claim for finality is made, but it is hoped that this synthesis will aid further critical studies. The following questions are discussed in order: (1) significance of climate, (2) source of material, (3) paleophysiography, (4) mode and progress of deposition, (5) cause of deposition, (6) origin of the capping limestone, and (7) correlation with events in the Rocky Mountain area.

Significance of climate.—The climate of Ogallala time may be inferred either from the physical characteristics of the deposits themselves, or from their flora and fauna, particularly the flora. Johnson (1901, chap. 2, esp. pp. 628-632) based his conclusions entirely upon the former. Reasoning deductively in the light of analogies with conditions in the Great Basin, he interpreted the environment of deposition as having been essentially of the desert type, and implied that the climate was more arid than at present. The presence of abundant calcium carbonate in the formation was accepted as supporting evidence. Recent paleobotanical studies by Chaney and Elias (1936) lead to a different conclusion. Detailed analysis of the ecological relations of a flora from lower Pliocene beds in Beaver county, Oklahoma, supplemented by study of the vertebrate fauna, was found to indicate a temperature somewhat warmer than now, and a rainfall about 10 inches greater than at present. From similar studies of a middle Pliocene flora in Logan county, Kansas, it was concluded that the rainfall of that time was about 5 inches greater than that in the same area today, although about 5 inches less than that in Oklahoma in early Pliocene time. The presence of fossil grass seeds in the Ogallala at many other places provides further evidence that the climate was far from a desert type.

Source of materials.—The materials of the Ogallala were derived mainly from the Rocky Mountain region. Pebbles of igneous and metamorphic rocks are predominant in the gravel beds, except for certain beds at the base. Quartz and reddish feldspar, such as are derived from the disintegration of granitic rocks, are prominent in the sandy beds. Some material probably of less distant origin is found, however, in basal gravels. This includes Cretaceous limestone (Arkansas valley), sandstone, ironstone, and quartzite of Dakota aspect (Meade and Clark counties), and Permian redbeds material (Meade county). Detailed tracing of lithologic types to source areas seems to be entirely feasible, but has not yet been undertaken.

The origin of the abundant calcium carbonate in the Ogallala is less obvious. The widespread occurrence of Cretaceous limestone and chalk in eastern Colorado at once suggests a possible source. The proportion of calcareous material, however, is greatest in the upper part of the formation, which must have been deposited after the Cretaceous rocks to the west were almost covered. Furthermore, if the Cretaceous of the Plains were an important source, it would be expected that the lime content of the Ogallala would show significant meridional variations from north to south, according to the lithology of the beds exposed between the mountains and the present outcrop area. No such variations have been observed. Finally, if the Cretaceous beds of eastern Colorado contributed dissolved calcium carbonate to the waters that deposited the Ogallala, it might be expected that they would have contributed also some recognizable fragmental material. That such material has not been found in the upper part of the formation constitutes negative evidence against the postulate. From these considerations, it is concluded that the transported calcareous matter in the Ogallala originated mainly, if not only in the Rocky Mountain area from weathering of Paleozoic limestone and of calcic minerals in the crystalline rocks. Additional lime may have been provided also by weathering *in situ* after deposition.

Similar considerations apply to the silt and disseminated clay in the Ogallala formation. Conceivably these too might have been derived from the Cretaceous shales of eastern Colorado, but this material is relatively more abundant in the upper part of the formation, which must have been deposited when the shale areas were at least partly covered, and it fails to show the meridional variations expected on the postulate of a Cretaceous source. Furthermore, the principal source of sediment must have coincided with the belt of maximum rainfall, which lay in the mountain area, rather than with the belt of minimum rainfall in the plains area. Thus the silt and clay of the Ogallala are best explained as having been derived from soils and weathering products in the mountain area, some minor additions resulting from the comminution of coarser materials during transportation.

Paleophysiography.—Prior to deposition of the Ogallala, there was extensive erosion of older formations. Structures were beveled, more than 1,000 feet or rock was carried away, and, at the east, the entire Cretaceous section was stripped off. This erosion took place intermittently, and there were intervening periods of deposition, represented now by the Oligocene and Miocene deposits of the plains area. The greater part of this erosion was probably effected by through-going streams from the mountains, but streams heading in the plains may also have been important then as now. The material removed during these periods of erosion was probably carried to the Gulf Coast region, where lie the nearest early and middle Tertiary deposits.

At the close of pre-Ogallala time, a widespread erosion surface extended from the Rocky Mountain front eastward to central Kansas. This surface beveled rocks ranging from Permian at the east to Eocene at the west. It was probably composite in character, and comprised the products of more than one cycle of erosion. In the Kansas area, it was by no means a perfect peneplain, but was characterized by considerable local relief, probably more than 200 feet (compare Johnson, 1901, p. 627). The bedrock contour map at the base of the Tertiary (fig. 8), although suggestive, does not represent a true picture of the pre-Ogallala topography. A part of the present bedrock relief is a result of warping and subsidence that took place during or after the deposition of the Ogallala beds. This applies particularly to the Meade trough, the Finney basin, and perhaps also to the basins in Stanton county, and in Stevens and Seward counties. It is possible also that certain of the bedrock valleys and basins antedated the Ogallala, but had been partly filled with older sediments before deposition of the Ogallala rocks began.

The broad, regional relations of the pre-Ogallala surface may be inferred in part from data summarized in the physiographic map, figure 9. On this map it may be observed that the north-south relief of the sub-Ogallala surface gradually increases from east to west. Nearest the mountains, this surface shows a broad arch or divide, corresponding to the present Platte-Arkansas divide, and having a north-south relief of about 1,500 feet. South of the Arkansas valley, the inferred extension of the sub-Ogallala surface rises steadily to or against a second broad upland in southern Colorado and northern New Mexico. These relations suggest two queries: Were the main drainage outlets from the mountains in Ogallala time the same as they are today, and do the present bedrock highs in front

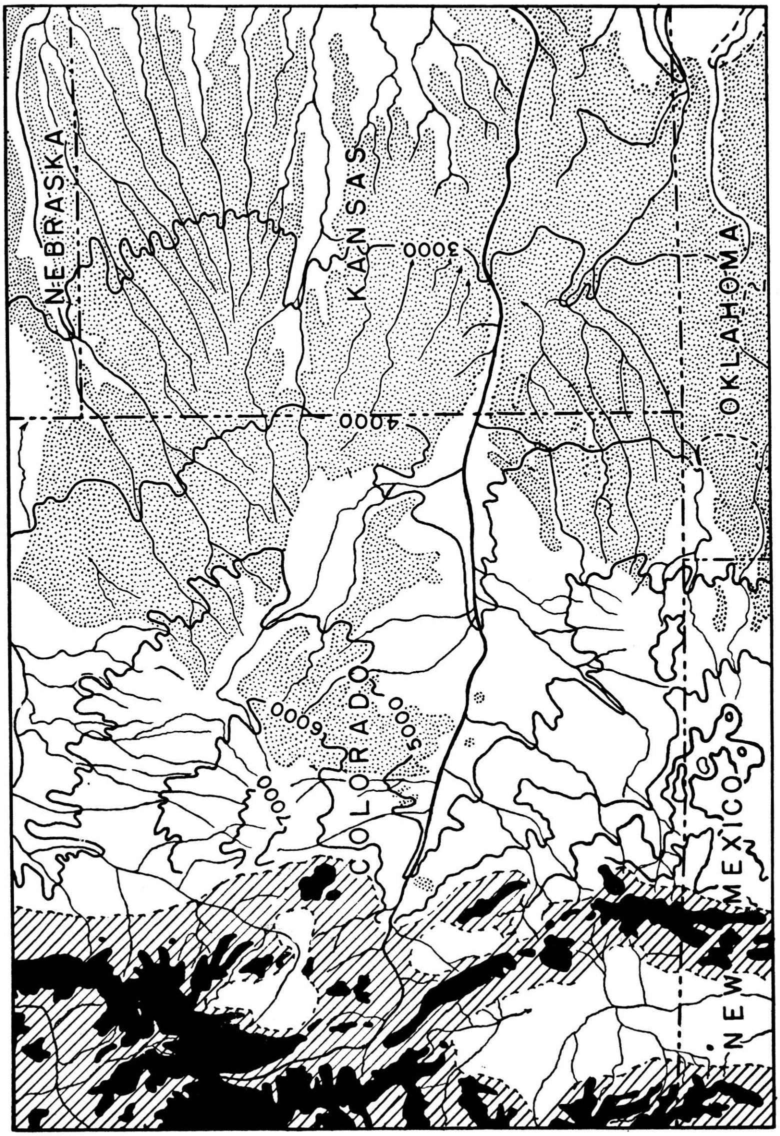

FIG. 9. Physiography of the Ogallala formation. Contour interval 1,000 feet. Stippled areas represent the Ogallala formation. Areas in solid black represent mountain ridges and peaks above 10,000 feet, and cross-hatched areas indicate mountainous areas at lower altitude.

of the mountains represent pre-Ogallala highs of corresponding position and relief? The answer to the first of these questions is difficult. Certainly there must have been drainage outlets from the interior of the mountain area. The volume of Ogallala sediments obviously derived from crystalline rocks is far too great to be accounted for by the mere wearing back of the mountain front, which, so far as the crystalline rocks are concerned, could never have been appreciably farther east than its present position, as shown by structural relations. Of existing streams, only the Platte and the Arkansas penetrate far enough into the mountain interior to answer requirements of Ogallala sedimentation. Fenneman (1931, p. 110) believes that the gap where Arkansas river emerges from the mountains antedates the last uplift, which implies that it was in existence in Ogallala time. Recent studies by Powers (1935) confirm the persistence of the Arkansas drainage since pre-glacial time, but leave some doubt as to the Pliocene history of the river. Conclusions justified by available facts are mainly negative. There are no reasons for doubting the persistence of the principal drainage outlets from intermontane areas since Ogallala time, or for assuming that they were then more numerous than at present. More positive conclusions must await detailed studies on the locus and magnitude of post-Ogallala mountain uplift.

In formulating an answer to the question as to the antiquity of the Platte-Arkansas divide, several possibilities must be considered: (1) that the pre-Ogallala surface had about the same slope and relief as the present sub-Ogallala surface, and has since been modified only by uniform tilting toward the mountains and by erosion; (2) that the pre-Ogallala surface was much flatter than the present surface of the High Plains, had negligible north-south relief, and acquired its present configuration as a result of strongly differential post-Ogallala warping; (3) that inferences as to the true sub-Ogallala surface are invalidated by incorrect mapping and correlation of the formation in eastern Colorado. Concerning the last of these possibilities, it must be observed that no adequate description of the beds mapped as Ogallala in eastern Colorado has yet been published, and that I have no first-hand acquaintance with them. On the other hand, there is no real reason for questioning the mapping in that area, and the topographic surface on the beds in question is certainly continuous with that on undoubted Ogallala beds farther east. This possibility is accordingly dismissed.

The implications of the first (1) of the suggested possibilities—the persistence of a high, bedrock divide throughout Ogallala and post-Ogallala time—may now be considered. This is the hypothesis accepted by Fenneman (1931, p. 35). It requires one of two alternatives: (a) that the divide was completely buried by an essentially level deposit of Ogallala materials, laid down principally by the through-going streams corresponding to the Platte and Arkansas, and having a maximum thickness equal to the north-south relief, about 1,500 feet; or (b) that the deposits on the crest and flanks of the bedrock arch were deposited in their present thickness by a stream or streams issuing from the mountain front at the apex of the divide. The first of these alternatives (a) presents insurmountable difficulties. The present thickness of the Ogallala along the Arkansas valley near the mountain front is nowhere reported to exceed 100 feet. Furthermore, the surface of the formation closely parallels its base, which is easy to explain on the basis of a tilted depositional surface, but extremely difficult to explain as a result of erosional planation of an originally thicker deposit. The second alternative (b) merits more careful consideration, but quickly it is seen to encounter serious objections: The west-east slope is notably steeper along the Platte-Arkansas divide than along the valley of either river. It is difficult to picture conditions permitting the deposition of sediments having similar lithology and thickness by different streams having gradients so strongly contrasted. No streams of significant length issue from the mountain front at the apex area of the Platte-Arkansas divide today, and there is no reason for assuming that the drainage lines of Ogallala time were different in this respect. If any stream did issue from the mountains at the point in question, and followed a course due east, its position must have been extremely precarious, for by a small shift to one side or the other it would have found steeper gradients down the flanks of the divide, would have abandoned its course along the crest, and made an irreversible change in direction, thus leaving the opposite side of the divide free of sediment. If more than one stream is invoked to explain deposition on the top and sides of the divide nearest the apex area, the delicacy of the balance in conditions required to maintain their positions sufficiently long to deposit a continuous mantle of sediment becomes so extraordinary as to tax credulity. Rather it is to be expected that they also would have found courses down the steeper slopes on the sides of the divide, thus leaving a deposit-free zone to the east on the crest of the divide. The surface gradients on the surface of the Ogallala toward its western edge are about 30 feet per mile—steeper than the gradients of youthful streams now dissecting the area. Such gradients, at distances of more than 40 miles from the mountain front, are hardly compatible with the hypothesis of an essentially unmodified depositional surface of regional extent. The objections listed above are believed ample to warrant rejection of the hypothesis to which they apply.

Remaining to contribute to this aspect of Ogallala paleophysiography is the hypothesis (2) of an originally more or less even depositional plain of low latitudinal gradient, subjected later to strong differential tilting. This tilting must have been very moderate along the present Platte and Arkansas valleys, and comparatively steep along the divide between them, the amount of uplift progressively increasing toward the mountains. The Ogallala surface was probably affected as far eastward as the western third of Kansas. The semi-radial drainage pattern of the central High Plains constitutes supporting evidence for this hypothesis, being best explained as of consequent origin on an upwarped depositional surface.

The highland area south of the Arkansas valley in Colorado must be regarded as a separate unit. It is controlled by a broad dome, the Sierra Grande arch, and at present represents, to a large extent, a dip slope on the Dakota sandstone (Lee, 1922, figs. 5 and 6). The Ogallala, so far as known, is entirely absent from all but the lower flanking slopes of the upland. This, together with the structural control of the upland by a supposedly pre-Ogallala fold, suggests that the area was probably a highland in Ogallala time, surrounded by alluvial deposits and perhaps traversed by debris-laden streams, but never itself covered. It does not necessarily follow, however, that the relief was as great in Ogallala time as at present, for it is probable that a very moderate elevation would have been sufficient to prevent burial, and it is further probable that the present deep dissection, affecting Ogallala and pre-Ogallala rocks alike, is due at least partly to post-Ogallala uplift. No critical studies of the physiography of the area have yet been made, however, so any conclusions must be tentative.

The actual relief in the mountain areas during Ogallala time is also problematical. Until the present controversy as to the physiographic history of the Rocky Mountains is settled, no definite answer can be expected. However, it has been noted by the writer in Kansas, and by Toepelman in Colorado (1924, p. 63) that the pebbles in the Ogallala are much smaller than those in Quaternary terrace gravels. This indicates that the transporting power of Ogallala streams was less, and suggests that gradients were gentler and that regional relief was lower than during ensuing periods. The uplifted position and deep dissection of the Ogallala today also points to a modern relief greater than that of Pliocene time. The magnitude of the difference, however, is not easily evaluated.

Mode and progress of deposition.—The deposition of the Ogallala was mainly of the channel and floodplain type. The coarser beds of sand, gravel, and grit represent channel deposits, and in some places the channel form is evident (pl. 9A). The finer materials are best interpreted as representing floodwater deposits formed by the overflow of shallow channels, perhaps approaching the character of sheet-floods locally. No recognizable deposits of eolian sand or silt have been found in the Ogallala in the area studied, but the presence of ventifacts indicates that there must have been appreciable wind action. Theis (1936) goes so far as to postulate that the structureless material common in the formation is principally of eolian emplacement. Although this possibility merits consideration, it is hardly required to account for the structureless character of the material. Rate of deposition rather than agent of deposition is the important factor in this connection. Any agency that deposits thin layers of sediment in the presence of vegetation, at moderately long intervals between successive additions, allows opportunity for the kneading action of plant roots and other soil-building processes to obliterate the original bedding and develop a structureless appearance. Until further proof is adduced, I prefer to regard eolian deposition as a factor of subordinate importance.

The deposition of the Ogallala formation began with the change from stream degradation to aggradation. Just where this reversal first took place along the stream courses is uncertain, but it may plausibly be inferred that the locus of initial deposition corresponds approximately with the zone of maximum thickness in the formation, and thus falls within western Kansas. During the early stages of deposition, there was a topography of moderate relief. The main valleys were occupied by through-going streams from the Rocky Mountains, and the valley bottoms were mantled by normal floodplain deposits. Some local material was probably carried in by side streams, and locally, as in Clark county, there was creep of sizable blocks of rock down the valley sides. In the southern part of the area, there may have been streams heading in the Sierra

Grande arch. Deposition probably began with the filling of stream channels, leading to more frequent overflow and thus to the upbuilding of the floodplains. This soon led to shifting of the channels themselves, and probably to the development of anastomosing patterns. As filling progressed, the valley flat overlapped farther and farther on the slopes of the bordering hills, and the zone of deposition encroached farther and farther east and west. Relief was lowered, the valley plains grew broader, and finally the divides were overtopped, and there followed overlapping and coalescing of the depositional zones of individual streams. As depositional areas grew broader the rate of upbuilding must have declined, allowing greater time for the work of soil processes on the successive accretions of sediment. Undoubtedly the trunk streams deployed into branching distributaries, and these shifted sluggishly across broad and overlapping triangular areas. The bedrock divides were buried deeper and deeper, and one vast, continuous alluvial plain came to extend from the slopes of the Rockies perhaps as far as the Flint Hills in Kansas. Probably the waters of the depositing streams were gradually dissipated as they neared the border of this plain, so that none escaped beyond. Eastward and westward the margins of the alluvial mantle thinned out against the older rocks, and at the south the Sierra Grande highland probably rose gradually above the depositional surface. Over a great area, only one monadnock rose sharply above the alluvial plain—"Two Buttes", in southeastern Colorado, held up by an igneous intrusion and surrounding altered sediments (pl. 13A).

Concurrent with deposition there may have been some subsidence in the Stevens county basin, the Finney basin, and the Stanton county basin, leading to the local accumulation of sediments in abnormal thickness. A part of the subsidence certainly took place in post-Ogallala time, however, and the rest may have taken place in pre-Ogallala time.

The so-called mortar beds are of two types: normal sandstone and conglomerate, and irregular, structureless deposits of sandy, megascopically amorphous calcium carbonate, best described as caliche (pl. 11B). The former represent products of cementation by underground waters, similar to equivalent lithologic types found throughout the geologic column. The second type of "mortar bed", however, is best explained as a product of surficial calichification, formed during a relatively long pause in deposition, probably while the streams involved had shifted to some distant part of their respective zones of influence. During such periods of undisturbed exposure, there was ample opportunity for concentration of calcareous matter in the soil zone by surficial processes. A discussion of the nature of these processes is beyond the scope of the present report, but is found in papers by Price (1933), Theis (1936), Sayre (1937, pp. 67-70), and Schoff (1939, pp. 82-84). The process of calichification was periodically halted by the deposition of new layers of sediment, each time to be resumed at successively higher levels, thus leading to the incorporation of numerous buried caliche zones in the formation. The imprints of plant stems or roots found at some places may be explained as a result of differential deposition of calcium carbonate in sandy casts of plants buried by fluvial deposition, but subsequently left within reach of the zone of calichification.

Cause of deposition—The ultimate cause of the deposition of the Ogallala beds has been variously interpreted. Haworth (1897a, p. 14) correlated the deposition of the formation with uplift in the mountains, but went so far as to assume that the alternation of coarse and fine beds was due to the effect of intermittent uplift in causing repeated steepening of stream gradients. Johnson, on the other hand (1901, p. 628), believed that climatic changes alone were adequate to account both for the deposition and for the subsequent dissection of the formation. Darton (1920, p. 8) later emphasized the tectonic factor, but admitted climatic conditions as a contributing factor, stating that—

> these alternations of later Tertiary deposition and erosion, first in the north and then in the south, were undoubtedly determined by differential uplift, the uplifted region undergoing erosion and the depressed or stationary region receiving deposits from streams whose slope was not sufficient to carry off their loads. This condition was accentuated by the semiarid climate of the plains, where then, as now, the mountain torrents and the resulting vigorous erosion furnished large quantities of debris, which the streams, being of low declivity and constantly diminishing volume as they crossed the plains, were unable to carry to the sea.

Fenneman (1931, p. 35) is noncommital as to the cause of deposition.

Much additional information has become available since these investigators presented their interpretations, and much still remains to be learned. Although it is premature to attempt any final explanation, it is well to integrate the known facts and to explore more fully the several possibilities, with a view to clearing the way for subsequent studies. Such is the endeavor of the following paragraphs.

The importance of (1) the climatic factor in causing deposition may be considered from the following angles: (a) nature of the climatic trends in late Tertiary time; (b) probable effect of climatic control on the locus of deposition; and (c) adequacy of climatic control to account for the deposition of earlier Tertiary formations in the plains region. Evidence as to the nature of climatic trends in late Tertiary time is found mainly in paleobotanical studies. Although fewer fossil floras have been found than is desirable, it is believed that these point toward increasing aridity in Miocene and Pliocene time (Chaney and Elias, 1936, pp. 25-32). The effect of such progressive desiccation on streams would have been increased loss of volume, and consequent deposition, owing to evaporation and to diminution of local inflow from both surface and subsurface drainage. Such effects should have been greatest in the belt of minimum precipitation. At present, that belt lies well to the west of the Kansas-Colorado line, but available figures indicate that the zone of maximum thickness in the Ogallala lies well to the east of the state line. Unless there has been a pronounced shift in rainfall zones since the deposition of the Ogallala, which there is no reason to assume, these considerations cast grave doubts on the adequacy of climate to have been the dominant factor controlling deposition. Furthermore, the climatic factor can hardly be invoked to account for the deposition of the much greater thicknesses of Oligocene and Miocene beds elsewhere in the plains region, and insofar as these beds were laid down under the control of factors other than climatic changes, it is logical likewise to assume similar control for the deposition of the Ogallala itself. Admitting climatic change as an important contributing factor, it is still necessary to look elsewhere for the prime cause of deposition.

Turning now to the role of (2) tectonic factors, the several possible loci of crustal movement may be considered: (a) uplift in the mountain area, (b) downwarping in the plains area, (c) upwarping in the plains area, and (d) combinations of these.

(a) If uplift took place in the mountain area, the effects should have been a steepening of stream gradients, quickening of erosion, increased stream load, and possibly increased rainfall within the mountains. Unless the balance of these effects was such as to leave the streams underloaded on emerging from the area affected by the uplift, which seems very improbable, it is expected that the deposition resulting from these factors would take place immediately beyond the hinge line of the uplift, where stream gradients remained unchanged, and that there the deposits would ultimately attain maximum thickness. If one assumes that the hinge line of the uplift was far to the east of the present mountain front—near the Kansas border—it is entirely feasible to account for the deposition of the Ogallala on this basis. If analogies may be drawn from post-Ogallala uplift, as interpreted by me, this assumption seems entirely plausible, but unless it be granted that the uplift did affect a wide belt of the plains area as well as the mountain area, the explanation for deposition must be sought elsewhere. Additional considerations bearing on this point are discussed in a later paragraph dealing with correlation of events between the plains and the mountains.

(b) It seems to have been generally though tacitly assumed by most writers that the plains area was an essentially passive tectonic element in late Cenozoic time, and that the mountain area was the principal locus of such active crustal movements as occurred. Inasmuch as there is cause for doubting post-Ogallala stability, as pointed out in a later section, it seems unnecessary to assume pre-Ogallala stability, and it becomes pertinent to consider the possible consequences of pre-Ogallala warping entirely within the plains area. If the warping was mainly in the direction of subsidence, deposition would undoubtedly have taken place in the areas affected, would have been limited to those areas, and would have led to maximum thickness of sediment where the amount of subsidence was greatest. It is possible that the unusual thickness of Tertiary deposits in Stevens and Seward counties, and at other points in southwestern Kansas, may have been so caused. Regional downwarping would have been necessary, however, to account for the regional extent of deposition.

(c) Upwarping in the plains, on the other hand, would have been of more far-reaching effect. Stream gradients would have been flattened, or actually reversed locally, and drainage lines might have been broken or shifted, and stream patterns modified. Deposition would have begun at points of change in gradient, and would gradually have extended both upstream and downstream, affecting an area considerably wider than that in which the warping actually took place. A chain of individual upwarps, if not too far separated, could have had a profound effect on areas upstream, and might have been adequate to have effected the deposition of a continuous alluvial mantle. Detailed physiographic studies that might aid in evaluating or elaborating these possibilities are yet to be made.

(d) There remains the possibility of two or more of the above factors in combination, and in summary it may be stated that the deposition of the Ogallala may be adequately explained either on the basis of broad uplift of the mountains together with a wide adjoining section of the plains, or of upwarping in the plains area, or by some combination of these, not necessarily synchronous. Local subsidence may have been an important contributing factor, and the existence of relatively arid climatic conditions, plus any increase in the degree of aridity during Pliocene time, must also have played a significant part. In the light of available information, no definite evaluation of the relative importance of the different possible tectonic factors can be made. It is hoped that future studies, both in the outcrop area of the Ogallala, and in bordering areas to the east and to the west, may contribute to a more definitive interpretation. The hypothesis of epeirogenic upwarping in the plains area as a causal factor is especially commended to the attention of other investigators of late Tertiary history.

Origin of the capping limestone.—The origin of the limestone at the top of the Ogallala is a problem in itself. Two hypotheses have been advanced: (1) Lacustrine deposition, and (2) subaerial origin as a caliche zone.

(1) Lacustrine origin of the capping limestone of the Ogallala has been ably advocated by Elias (1931, p. 141), whose arguments may be summarized as follows: (a) The uniform thickness and persistent lithologic characteristics of the limestone are believed incompatible with fluviatile origin. (b) The concentrically banded structures are thought to be best explained as deposits formed by algae of the genus *Chlorellopsis,* whose modern relatives precipitate calcium carbonate along lake shores, but not in running water. (c) The structure and texture of the limestone are regarded as dissimilar to those of caliche or of related calcareous deposits formed in the soil zone. Elias pictures the rock as having been deposited "on the nearly flat bottom of a very large and very shallow lake at the close of Ogallala time." Such a lake must have been of enormous size, extending from Nebraska to the Oklahoma panhandle or farther, and from Barton county, Kansas, west into Colorado. The considerable difficulties attending this hypothesis are mainly those of satisfactorily explaining the origin of such ponding. If it be granted that upwarping in the plains area was a factor in leading to the deposition of the Ogallala, it follows that a renewal of such movement might result

in ponding of streams from the mountains. Even assuming these conditions, however, there is a strong probability that a balance between inflow and evaporation would have been reached long before the lake or lakes in question attained required size. Furthermore, the amount of uplift necessary to produce a horizontal water surface of the extent postulated would have been much greater than that required merely to flatten stream gradients sufficiently to induce deposition. It must have amounted to hundreds of feet, and therefore would be expected to have left some tangible evidences of its existence. The required shallowness of the postulated ponding presents added difficulties, which demand so delicate a graduation in the amount of uplift from east to west over so large an area as to be challenged by probabilities. Finally, it may be noted that the trend of the postulated uplift would be required to have been nearly transverse to that of the uplift which must have followed shortly thereafter, and which was responsible for the present drainage pattern. Theis (1936) avoids the difficulties of accounting for a single great shallow lake by suggesting that the capping limestone was deposited, either by inorganic or by organic agencies, in unconnected pools. The pools are believed to represent the flooding of shallow depressions by a rising water table under conditions of a cooling climate and probably increasing precipitation associated with the approach of Pleistocene time, but the origin of the depressions is not discussed. It remains to be ascertained how well this concept fits with the distribution of the algae discussed by Elias.

(2) The caliche hypothesis was originally advanced for the Oklahoma area by Gould and Lonsdale (1926, pp. 29-33), and later was provisionally accepted by Schoff (1939, pp. 79-85). Factors favoring the caliche hypothesis are as follows: (a) The limestone grades downward into more or less typical caliche. (b) The limestone is arenaceous. (c) Where the capping limestone rests directly on Permian redbeds, south of Englewood, it grades downward into a pseudo-breccia of redbed chips and blocks surrounded by an irregular boxwork of calcareous cement, suggesting the action of subaerial weathering processes, and hardly compatible with subaqueous processes. (d) At the same locality, scattered pebbles of exotic rock are scattered sparsely through the limestone—a relation difficult to reconcile with the postulated lacustrine environment.

Additional facts from a wide area are necessary for a final solution of the problem. Possibly both hypotheses are partly right, and both caliche and lacustrine limestone are present in different parts of the region, possibly gradational into one another. Insofar as the limestone is a caliche, it corresponds to the old-age type of Price (1933), and represents the effects of more or less recrystallization of the original calcareous deposit, and insofar as it represents a caliche, either wholly or in part, its deposition antedates the Kingsdown formation, and is not to be confused with the products of present-day soil processes. The final solution of the problems of origin will depend principally on the answers to the following questions: Is it possible that the concentric structures, in part, can be attributed to inorganic processes? Granting that some true algae are present, is their distribution uniform or spotty? Can the presence of lime-secreting algae be explained on the basis of environments provided either by sluggish streams or by small, unconnected lakes, as well as by that of a single large lake? Does the capping limestone show any systematic lateral variations in thickness or texture or structure? Is the lateral and vertical distribution of insoluble materials more suggestive of calichification or of lacustrine deposition?

Correlation with events in the Rocky Mountain area.—In closing the discussion of the Ogallala formation, there remains the correlation of depositional history in the plains area with the erosional history of the mountains to the west. The latter being a controversial topic, the history of the Ogallala may be considered in relation to each of the two principal competing hypotheses, in turn.

The older interpretation of Front Range physiography may be termed the "two-surface" hypothesis. It was formulated by Lee (1922a), extended by Mather (1925) and by Little (1925), adopted by Fenneman (1931), and reaffirmed by Atwood (1938). It recognizes the existence of two major erosion surfaces, or peneplains. The older and higher of these surfaces, unrelated to the Ogallala, was named the Flattop peneplain by Lee, and is believed to have been formed before the close of the Eocene. The younger and lower of the major erosion surfaces was referred to as the Rocky Mountain peneplain by Lee, Mather, Little, and Atwood, and as the South Park peneplain by Fenneman (1931, p. 98). It is the formation of this erosion surface that is correlated with the deposition of the Ogallala. As summarized by Fenneman (1931, p. 107)—

> It may be assumed that at the close of the later cycle the greater part of this province and others adjacent were covered by a continuous graded plain, made by degradation of the mountains and aggradation of the Great Plains. The peneplain in the mountain province is believed to correspond in geologic date with the surface of the Pliocene sediments that now cover the High Plains.

Fenneman (1931, p. 35) believes the Ogallala to be the principal depositional correlative of the peneplain, but Atwood (1938, p. 967) includes also the Arikaree, which is of Miocene age (Lugn, 1939), and possibly earlier Tertiary formations (1938, p. 964). Choice between these viewpoints depends on assumptions as to the cause of deposition. If it be assumed that tectonic movements in the mountain area were the prime factors, then it follows that the same uplift must have initiated both the cutting of the Eocene peneplain in the mountains and the deposition of Pliocene sediments in the plains—a somewhat anomalous circumstance. If, on the other hand, it be assumed that crustal warping in the plains was the main factor, then it follows that such movements may have effected simply one or more shifts in the locus of deposition (and erosion) within the plains during one continuous cycle of erosion in the mountains, thus allowing a much longer interval for peneplanation, and fitting better with the two-surface hypothesis.

In any event, according to the two-surface hypothesis, after the deposition of the Ogallala—

> The country then rose to about its present height, not this time as a mountain range but as a gentle arch sloping 100 or 200 feet per mile from the axis to an indefinite base far out on the plains. There was then no mountain "front", no foothills, no mountains in fact, except the residuals of older cycles rising above the upraised peneplain. (Fenneman, 1931, p. 108).

The present abrupt mountain front is attributed to differential erosion in the ensuing "canyon cycle".

The second and more recent of the hypotheses as to Rocky Mountain physiography may be termed the multi-surface hypothesis, and was advanced by Van Tuyl and Lovering (1935). These workers recognize five major erosion surfaces ranging in age from early Eocene to middle Miocene, three subordinate surfaces dating from the late Miocene to the late Pliocene, and three to five Pleistocene terraces. The Mt. Morrison berm, dated as middle Pliocene, is correlated with the surface under the Nussbaum formation, which is regarded as equivalent to the Ogallala. The Mt. Morrison berm represents a mature valley stage restricted to the larger streams near the mountain front, and cut several hundred feet below the Flagstaff Hill berm, next older. It is not specifically stated which erosion surface corresponds to the top of the Nussbaum formation, or which erosion cycle is to be correlated with the deposition of the Ogallala formation, but choice is restricted to either the Mt. Morrison cycle or the Orodell cycle, next ensuing, and in either case the deposition of the Ogallala must be correlated with the cutting of a minor erosion surface of small extent. Analysis of the volumetric relations of Ogallala erosion and deposition at once presents insurmountable difficulties to this interpretation. The present area of the Ogallala surface in Kansas and in eastern Colorado between the same parallels (37° to 40°), restored by interpolation across dissecting valleys, is roughly 1,225 townships. Originally it was probably much greater. The source area of the formation, from the mountain front up to the Rio Grande Divide and the Continental Divide, comprises roughly 300 townships, and originally may have been somewhat larger. These figures indicate that the ratio of erosion per unit area in the mountains to deposition per unit area in the plains was roughly 4 to 1. Assuming that the average thickness of the Ogallala is 100 feet, which seems a conservative estimate, and allowing 20 percent for porosity, it seems that the deposition of the Ogallala beds represented an amount of erosion in the mountains equivalent to a uniform lowering of the surface in the entire area by more than 300 feet. Obviously erosion did not progress in any such areally uniform fashion, but was concentrated along the larger valleys, thus necessitating a proportionately increased volume of erosion in the valley areas to supply material for the Ogallala—an amount of increase depending on the spacing of the streams and on the shape of their valleys at different distances from the mountain front. Although it is difficult to evaluate these factors exactly, the conclusion seems inescapable that the volume of erosion required is altogether incompatible with the small extent of the erosion surfaces, and must have required a major erosion cycle of regional extent. Either the dating by Van Tuyl and Lovering is in error, or the multi-surface hypothesis is unsound elsewhere.

In any event, Ogallala time was probably brought to a close by stream rejuvenation incident to renewed upwarping. This uplift is believed to have affected both the mountains and the plains, in the latter taking the form of a broad, fan-shaped arch the apex of which lay between the present sites of Colorado Springs and Castle Rock. On the upwarped depositional surface consequent streams took their courses in the semi-radial pattern so prominent in the present drainage.

REXROAD FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Rexroad formation is named from exposures along tributaries of Crooked creek on the Rexroad ranch, in sec. 22, T. 33 S., R. 29 W., Meade county, Kansas. The formation is especially distinguished and characterized by an assemblage of vertebrate fossils of late Pliocene age, described by Hibbard (1938a, 1939) from localities in Meade county as the Rexroad fauna. Its known outcrop areas are confined to Meade county and to the headwaters of Bluff creek in northern Clark county. It has previously been mapped as Ogallala. The present description is preliminary only, more comprehensive studies by Hibbard and John C. Frye being in progress.

In Meade county, the Rexroad formation is best exposed southwest of Meade, along tributary streams entering Crooked creek from the west. At localities where diagnostic fossils have been found, it consists of alternating beds of gray to reddish mudstone, buff sandy silt, rusty sand and gravel, and a few thin seams of lignite (pl. 13B). The gravel is locally cemented to form a conglomerate very similar to that found in the Ogallala, but contains some calcareous pebbles seemingly reworked from the Ogallala. Calcareous concretions, some small and knobby, some large and boulder-like, are common in the finer-grained beds. Some beds in the Rexroad are indistinguishable from typical Ogallala, and others are very similar to those found in Pleistocene deposits exposed elsewhere in Meade county, but stratigraphic relations and other features of these beds are believed to be

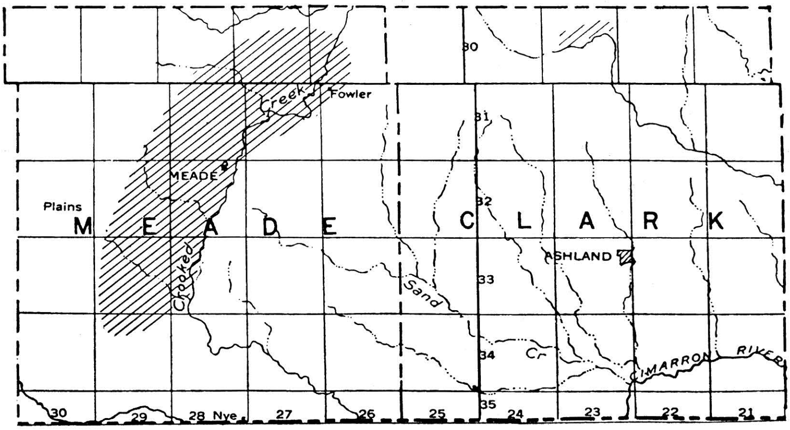

FIG. 10. Sketch map showing the outcrop belt of the Rexroad formation and the inferred minimum extent of the formation under cover.

more or less distinctive. The fossils found in the Rexroad include both vertebrates and invertebrates (Baker, 1938), the latter being absent from the Ogallala of this area, so far as known. Grass-seed floras, common in the Ogallala, have not been found in the Rexroad.

The probable minimum areal extent of the Rexroad, both surface and subsurface, is shown in figure 10. This map is based on interpolation between known fossil localities, and on extrapolation beyond these localities on the basis of lithologic similarity and inferred continuity of the topographic conditions that governed deposition. It may be noted that no recognizable outcrops of the Rexroad were found on the east side of Crooked creek south of Meade. If present there, it is thin, and is lithologically indistinguishable from the Ogallala (see section, p. 66).

The base of the Rexroad is nowhere known to be exposed in Meade county, and the complete thickness is consequently problematical. Individual exposures do not exceed 35 feet in thickness, and correlation between them is inexact. It is probable, however, that the thickness is at least as great as the local relief of the topography, which is about 80 feet, and, according to John C. Frye, recent test drilling indicates that the thickness may exceed 250 feet.

The relations of the Rexroad to the Ogallala must be interpreted from indirect evidence, for no exposure of the contact between the two has been found. Significant are the following facts: (1) on the west side of Crooked creek valley, the Rexroad crops out at lower elevations than the Ogallala on the east side of the valley; (2) Crooked creek valley is known from other evidence to represent a structural trough; (3) no Rexroad deposits have been found east of Crooked creek valley; and (4) the Rexroad seems to contain more or less reworked Ogallala material. These facts strongly suggest that the Rexroad formation was laid down on the deformed surface of the Ogallala, in a structural and topographic depression that was progressively modified by marginal erosion concurrent with deposition. The Rexroad is thus believed to have been originally unconformable on the Ogallala, and later to have been involved also in renewed downward movement, as outlined more fully in the section on structural geology.

In northern Clark county, beds corresponding to the Rexroad occur along the upper stretches of Bluff creek and its tributaries. These deposits consist mainly of sand and gravel, somewhat iron-stained, and moderately well cemented toward the top. Their recognition is based on Hibbard's identification of fragmentary vertebrate fossils. The thickness where the beds are best exposed is about 25 feet. These beds seem to be underlain directly by the Cretaceous in places, and are overlain by the Kingsdown formation of Quaternary age. It is uncertain whether the underlying Cretaceous was originally buried by the Ogallala and later uncovered by stream channeling, or whether it was never entirely covered. Although the outcrops of the Rexroad are confined to a relatively small area, they undoubtedly represent portions of a continuous and more widespread deposit. The true extent of this deposit, whether great or small, however, is thoroughly concealed by the Kingsdown formation and by loess, and can be determined only by test drilling, if at all.

AGE AND CORRELATION

The vertebrate fauna thus far described from the Rexroad formation includes the following (Hibbard, 1938a, 1939):

Vertebrate fauna of the Rexroad formation

Sorex taylori Hibbard
Mustelid sp.
Canidae sp.
Machairodus sp.
Felis sp.
Citellus sp.
Eutamias or *Tamias* sp.
Geomys sp.
Eocastoroides lanei Hibbard
Peromyscus eliasi Hibbard
Sigmodon intermedius Hibbard
Pliolemmus antiquus Hibbard
Phenacomys primaevus Hibbard
Pliopotamys meadensis Hibbard
Neondatra kansasensis Hibbard
Nannippus phlegon (Hay)
Equus (*Plesippus*) cf. *E. simplicidens* Cope
Platygonus sp.
Camelops sp.
Pratilepus kansasensis Hibbard
Dicea lepuscula Hibbard
Hypolagus regalis Hibbard
Nekrolagus progressus (Hibbard)

Large additional collections are now being studied by Hibbard, and the complete fauna is believed by him to point unmistakably to late Pliocene age. It may be noted in addition that the *Hipparion cragini,* reported from the headwaters of Bluff creek by Hay (1917), is thought by Hibbard to be more probably *Nannipus phlegon,* which is of late Pliocene age, and the *Equus leidyi,* described by the same writer from the same place, is regarded as possibly being *Equus cumminsi,* also of late Pliocene age.

The following invertebrate fauna has been described from the Rexroad formation by Baker (1938):

Invertebrate fauna of the Rexroad formation

Vertigo hibbardi Baker
Strobilops sparsicostata Baker
Carychium perexiguum Baker
Menetus kansasensis Baker

These forms all represent new species, and having been correlated with vertebrate faunas of known age may be helpful in distinguishing exposures of Rexroad beds that contain invertebrates but are barren of vertebrates.

No correlatives of the Rexroad are known elsewhere in Kansas nearer than the McPherson area, where the upper part of the Emma Creek formation has yielded a few upper Pliocene fossils (Lohman and Frye, 1940). The Blanco beds in Texas are believed to be the next nearest equivalent. This absence of corresponding deposits within a wide radius, together with a definite age difference, divergent lithology, and apparently unconformable relations to the Ogallala, indicates that the Rexroad may not properly be regarded as a part of the Ogallala, and is best designated as a separate formation.

ORIGIN OF THE FORMATION

The climate of Rexroad time is interpreted by Hibbard (1938a) to have been cooler and more humid than that of the same area today. It is believed also to have been cooler than that of Ogallala time, thus foreshadowing Pleistocene glaciation.

The localization of the Rexroad formation in Meade county is best explained as having been caused by the formation of an elongate structural and topographic depression trending roughly north-northeast. The origin of this trough is discussed in the section on structural geology. The effect of such a trough would have been to trap the water and sediment of any through-flowing streams traversing the area, and to rejuvenate erosion in the steepened flanking slopes. Dissection of the Ogallala beds in these bordering areas, but mainly on the western side, would have occurred, and the reworked materials would have been deposited as an alluvial fill in the axial portion of the trough, gradually overlapping farther and farther onto the side slopes as filling progressed. Probably some ponding occurred also, which would account for the deposition of the clay beds. On this interpretation, it is possible to explain the Rexroad formation of Meade county as a purely local depositional unit, composed entirely of reworked Ogallala material. There is at present no reason for either affirming or denying the likelihood of through-going drainage connections with the Rocky Mountain area. If such connections existed, additional material would have been supplied directly from primary source areas.

In post-Rexroad time there was renewed downward movement of the depositional trough, intervening deposition of a considerable thickness of Pleistocene beds, and ensuing stream dissection.

The Rexroad beds of Clark county are too imperfectly known to be explained adequately. Undoubtedly they were deposited in a drainage system different from that of today, before the present course of Bluff creek was established through piracy, and possibly before any part of Bluff creek had come into existence. Whether they were deposited by local streams or by through-going streams from the mountains, and whether they have any subsurface continuity with the Rexroad beds of Meade county, is unknown. Possibly one or both deposits is related to the abnormal breadth of the outer valley of Arkansas river in southeastern Kearny county, southern Finney county, and central Gray county, as shown on the contour map (pl. 2) and by the width of the sand-hill belt (fig. 15). If this anomalous topographic feature represents a shallow post-Ogallala downwarp, as seems probable, it undoubtedly had an important influence on the ancestral Arkansas and other streams.

QUATERNARY FORMATIONS

The Quaternary deposits of southwestern Kansas are the thickest and most extensive yet discovered in the central High Plains. They occur mainly in Meade and Clark counties, and, for the most part, have not heretofore been differentiated from the Ogallala. Although widespread, their relations are as yet by no means entirely clear. Exposures are discontinuous, covered areas are broad, lateral changes in depositional facies seem to be common, and sedimentation has been controlled in part by local conditions lacking any broad areal significance. Consequently there are difficulties in correlating different sections of the same deposits, and in determining the relative age of different deposits. Lithologic similarities, for the most part, constitute the only available means of correlation, and are supplemented in some instances by physiographic relations. Age determinations are based principally on the evidence of vertebrate fossils. Although numerous vertebrate faunas have been discovered, many of these are lacking in the diagnostic forms required for exact dating, and therefore fail to give complete certainty. Invertebrate faunas, although very common, have thus far given little promise as aids in determining age relations. Until more numerous and more extensive vertebrate faunas are discovered, many questions will probably remain unanswered. The following description is to be regarded only as a progress report; much remains to be learned not only from paleontological studies, but also from detailed areal mapping and from test drilling.

Only two of the Pleistocene deposits in the area seem thus far to be sufficiently distinctive and sufficiently continuous to justify the application of formation names: the Odee, of earlier Pleistocene age, and the Kingsdown, of later Pleistocene age. Other deposits of smaller extent and of less certain relations are designated simply by provisional lithologic, faunal, or locality names. These include the "*Equus niobrarensis* beds", the "Jones Ranch beds", volcanic ash, loess, terrace deposits, dune sand, and alluvium. These several deposits and formations are described in the order of their relative ages as tentatively outlined, and the adequacy of the evidence for such age assignments is discussed in connection with each.

ODEE FORMATION

GENERAL CHARACTER

The Odee formation, here described and distinguished for the first time, is named from typical outcrops in Odee township, in southern Meade county. It consists predominantly of fine-grained material, being composed principally of silt and clay, or of their indurated equivalents. Numerous thin beds of fine sand are present, some locally cemented to form a hard rock, and fewer beds of coarser sand and gravel. A single bed of diatomaceous marl was found. Calcareous nodules are found in some beds, and selenite crystals are common in many parts of the formation. The characteristic color of the formation is dark, reddish brown to deep red, very similar to that found in some of the redbeds of the Permian, with which, in fact, some parts of the formation may easily be confused. A few of the beds show other colors, ranging from gray through greenish to buff, chocolate, and rusty brown. The maximum exposed thickness of the formation is about 300 feet. The formation as a whole seems to represent an alluvial or lacustrine fill in an irregular basin, partly erosional, partly deformational, in the Ogallala. It is best exposed along the Cimarron valley in southern Meade county and in northern Beaver county in Oklahoma. Smaller and more scattered exposures are found also along Crooked creek and its tributaries, and along Little Sandy creek in western Clark county. In many exposures the beds are more or less deformed, dipping as much as 25°. The formation is comparatively soft and easily eroded, forming sharp, steep-sided gulches bearing sparse vegetation.

AREAL DESCRIPTION

Outcrop areas and inferred minimum extent of the Odee formation are shown in figure 11. Typical is the section exposed at locality *A*, along a short tributary gulch on the north side of the Cimarron valley on the XI ranch in the W½ sec. 35, T. 34 S., R. 29 W. The beds are essentially horizontal and undisturbed. The base is concealed.

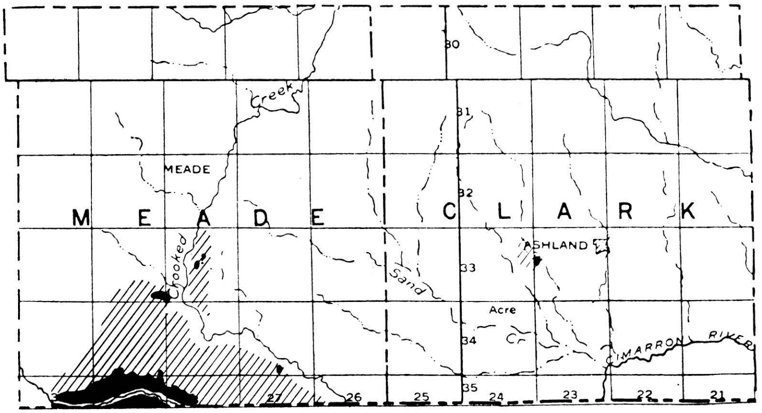

FIG. 11. Sketch map showing distribution of the Odee formation. Outcrop areas are shown in solid black, and the inferred extension under cover is shown by the ruled pattern.

Section of the Odee formation in sec. 35, T. 34 S., R. 29 W., Meade county, Kansas

Quaternary system	Thickness in feet
Soil	3
Odee formation	
8. Sand, structureless, buff-colored, fine-grained, containing caliche nodules	8
7. Mudstone, red	8
6. Silt, buff-colored, containing some red clay bands	4
5. Mudstone, red, containing one thin layer of buff silt; a few invertebrates at top	17
4. Silt and sand beds, gray to buff, containing some interbedded reddish clay; contains invertebrates	6 to 7
3. Mudstone, reddish-brown	13
2. Sand and silt, buff-colored, fine	2
1. Mudstone, red, containing a few layers of sand and silt	35
Total exposed thickness of Odee formation, 94 feet	

Two miles west of the above section, at locality *B,* another section is exposed along a similar tributary gulch. The formation here, however, is considerably distorted, contains local unconformities, and is not quite continuously exposed. Although no complete section is readily measurable, the upper part of the section is approximately as follows:

Section of the Odee formation in sec. 33, T. 34 S., R. 29 W., Meade county, Kansas

Quaternary system, Odee formation:	Thickness in feet
7. Mudstone, light greenish-gray, containing some selenite	6
6. Sand, gray to brownish, fine	11
5. Sand, silty, brownish, calcareous, containing invertebrates	1
4. Sand, silty, fine, soft, gray, containing invertebrates	3
3. Sand, hard, gray, calcareous	2
2. Sand, clayey, gray, mottled with rusty spots	0 to 2
1. Sand, reddish, massive to medium-bedded	20±

This section is underlain by 75 to 100 feet of sand containing some gravelly beds, in part cross-bedded, and ranging from gray through rusty to reddish. No basal contact was found. Fossil remains of *Aenocyon dirus* (Leidy) were identified by Hibbard (1939) from bed No. 4(?) and *Castor sp.* from bed No. 6. Associated with the former were the following invertebrates, identified by F. C. Baker.

Invertebrate fauna of the Odee formation in sec. 33, T. 34 S., R. 29 W.

Fresh-water species:
  Sphaerium sp.
  Stagnicola sp.
Terrestrial species:
  Succinea grosvenori Lea
  Pupoides marginatus (Say)
  Pupilla blandi obtusa Cockerell
  Gastrocopta cristata Pilsbry and Vanatta
  Gastrocopta cristata var. Pilsbry and Vanatta

The westernmost exposure of the Odee observed by me is on the west side of the county road crossing the Cimarron valley south of Plains, in sec. 2, T. 35 S., R. 30 W. The exposed thickness is about 15 feet. The outcrop is about 100 feet above river level and about 140 feet below the Ogallala ledges at the edge of the upland.

At locality *C,* about 7 miles southeast of section *A,* also on the north side of the Cimarron valley (sec. 10, T. 6 N., R. 25 E., Oklahoma), the following section is exposed (pl. 14A):

Section of the Odee formation in sec. 10, T. 6 N., R. 25 E., Oklahoma

	Thickness in feet
Quaternary system	
Soil	3
Odee formation	
13. Sand, light-buff, red clay at base	11
12. Sand and medium gravel, gray, grading upward into very rusty sand; gray sand, containing a few invertebrates, at top	12
Unconformity	
11. Mudstone, brownish, including a few gray streaks	16
10. Silt, thin-bedded, light-buff	1.5
9. Mudstone, red	3.5
8. Sand and silt, grayish, containing a few invertebrates	1
7. Mudstone, brownish, including a few silt layers	9
6. Sand, brown, containing fine pebbles	1
5. Mudstone, brownish	15
4. Silt beds, light-buff, alternating with darker mudstone beds,	4
3. Mudstone, brownish	15
2. Mudstone, reddish, alternating with grayish sand and silt,	6
1. Mudstone, reddish	12

Total exposed thickness of Odee formation, 107 feet

The lower part of the section is very gypsiferous in places. The base is not exposed. Dips are uniformily eastward, and are as steep as 24°.

Just southeast of the above exposure, in section 15 of the same township (locality *D*), a still thicker section of the Odee is exposed in an old, dissected sink. All except the uppermost beds are irregularly deformed, seemingly by the collapse involved in the formation of the sink. Dips are as steep as 27°. Making due allowance for the irregularities of dip, the following approximate thicknesses were measured.

Section of the Odee formation in sec. 15, T. 6 N., R. 25 E., Oklahoma

	Thickness in feet
Quaternary system	
21. Sand, finely laminated, dirty brown, silty	20
20. Clay, silty, dark-gray	5
19. Sand, silty, light greenish-gray, calcareous	12±
Angular Unconformity	
Odee formation	
18. Mudstone, soft, chocolate-colored	15±
17. Mudstone, greenish	1
16. Mudstone, massive, chocolate-colored	17
15. Marl, diatomaceous to sandy, gray to white, contains fossils	4 to 16
14. Sand, soft, fine- to medium-grained, buff-colored	10±

	Thickness in feet
13. Mudstone, chocolate-colored, including greenish lens at base; contains some invertebrates	4
12. Sandstone, soft, thin-bedded, fine-grained, brownish	2
11. Clay and sand beds, gray to brownish	3
10. Sand, fine-grained, and silt, thin- and even-bedded, gray to yellowish, channel filling	2 to 8
9. Mudstone, massive, chocolate-colored	0 to 4
8. Mudstone, chocolate-colored, and some buff sand	8±
7. Covered interval	50±
6. Sand, gravelly, yellowish to buff	9
5. Mudstone, gray to brownish-gray, sandy, contains some invertebrates	20
4. Sand, gravelly, yellowish to rusty	18
3. Sand, fine, yellowish-brown, contains a few invertebrates,	6
2. Sand, loose gravelly	5
1. Mudstone, massive, reddish-brown, gypsiferous toward top	120±

Total exposed thickness of Odee formation, 309 ± feet.

The beds above the unconformity in this section are essentially horizontal, and represent a fill deposited after the formation of the sink, and are therefore somewhat younger than the Odee. At least in part, they are probably lacustrine. Sinks similar to this one, but undissected, are numerous in the southern part of the Meade quadrangle, and some contain temporary lakes. In the true Odee at this locality, vertebrate fossils have been found in one zone, bed No. 15. This bed yielded remains of *Archidiskodon imperator* (Leidy), *Synaptomys bunkeri* Hibbard (1940), a duck of the family Anatidae, and fragmentary fish and amphibian material as yet unidentified. Associated with the vertebrates was the following invertebrate fauna, studied by F. C. Baker:

Invertebrate fauna of the Odee formation in sec. 15, T. 6 N., R. 25 E., Oklahoma

- Fresh-water species
  - *Stagnicola caperata* (Say), rare
  - *Gyraulus altissimus* (F. C. Baker), common
  - *Physa anatina* (Lea), very abundant
  - *Physa hawnii* (Lea), very abundant
  - *Helisoma trivolvis lentum* (Say), very abundant
- Terrestrial species
  - *Succinea grosvenori* Lea

The *Physa* were identified by W. J. Clench. The lower part of the section described above is essentially similar to the section at locality *C*, which, in fact, dips into or under the dissected sink.

North of the Cimarron valley, the Odee is probably widespread, but is mostly covered, and is represented by fewer and smaller exposures. Of these, the best that I found are those along Shorts creek, in sec. 36, T. 33 S., R. 29 W., Meade county, and in the adjoining part of the section to the east. In this locality, gray-green and reddish mudstone are interbedded, and seem to grade laterally into one another. Large, well-developed selenite twins are abundant in the redbeds at many places. The beds dip at low angles to the east, and are cut by a few minor faults (pl. 14B). Invertebrates are common, and bones of a small Pleistocene camel were collected by Hibbard about 25 feet above stream level near the township corner. The following invertebrates associated with this fossil were identified by F. C. Baker:

Invertebrate fauna of the Odee formation in sec. 36, T. 33 S., R. 29 W., Kansas

- Fresh-water species
  - *Pisidium* sp.
  - *Stagnicola caperata* Say
  - *Fossaria parva* (Lea)
  - *Helisoma trivolvis lentum* (Say)
  - *Gyraulus altissimus* (F. C. Baker)
  - *Physa anatina* (Lea)
- Terrestrial species
  - *Succinea grosvenori* Lea
  - *Pupilla blandi* Binney
  - *Vertigo ovata* Say
  - *Vallonia gracilicosta* Reinhardt

A few miles southwest of the above locality, probably in the SE¼ sec. 3, T. 34 S., R. 29 W., Haworth (1897b, p. 274) reports that a well 288 feet deep passed "through nothing but clay, until almost the total depth was reached." This suggests that the well was drilled mainly in Odee, perhaps penetrating some Rexroad beds below.

On the east side of Crooked creek 8 miles south of Meade (sec. 21, T. 33 S., R. 28 W.), the Ogallala is overlain by about 30 feet of greenish-gray calcareous clayey sand to sandy mudstone, containing a lenticular bed of volcanic ash 8 feet above the base (see section, p. 66). On the basis of similarity to the greenish beds of the Shorts creek section, and dissimilarity to beds associated with other deposits of volcanic ash in Meade county, this section is provisionally interpreted as a nonred facies of the Odee formation. Physiographic relations accord with this correlation, for the beds crop out at the eroded edge of a nearly flat upland surface, which lies at the same level as, and seems once to have been continuous with the surface at the top of the Odee along the Cimarron valley. This surface seems best explained as of depositional origin. It has since been modified by erosion, and, on the west side of Crooked creek, seemingly also by downwarping.

Along a short tributary on the south side of Crooked creek 16 miles south and 5 miles east of Meade (secs. 27 and 34, T. 34 S., R. 27 W.), discontinuous exposures of distorted greenish and reddish sandy and clayey beds bear a strong resemblance to the Odee beds, and occur at about the same topographic level as the Odee beds of localities *C* and *D* in the Cimarron valley.

Along Little Sandy creek in western Clark county, about 5 miles west of Ashland (sec. 18, T. 33 S., R. 23 W.), the easternmost outlier of probable Odee was found. The following section is exposed in a steep, undercut bluff on the west side of the creek.

Section of the Odee formation in sec. 18, T. 33 S., R. 23 W., west of Ashland, Clark county, Kansas

Quaternary system, Odee formation	Thickness in feet
5. Sand and silt, soft, even-bedded, reddish-brown, some grit and pebble layers, and a few greenish bands	35
4. Mudstone, thinly laminated, gray to chocolate	8
3. Grit, structureless, reddish, containing a few invertebrates	4
2. Sand, light-buff to rusty-colored, even-bedded	6
1. Mudstone, massive, red	5+

Total exposed thickness of Odee formation, 58 feet.

A few minor faults cut the lower part of the section and bed No. 4 shows intricately contorted minor folds, somewhat similar to those produced experimentally by Rettger (1935) by differential loading. Bed No. 1 is lithologically identical with typical Odee, and beds 2 to 4 are similar. Division No. 5, however, is less typical, and may represent a younger deposit. It is probable that this deposit of Odee was formed in a valley or basin other than that of Meade county, but at the same time and under the same conditions. It is possible that equivalent deposits may be widely distributed in the Ashland basin, although additional exposures were not located during my rapid reconnaissance.

AGE OF THE FORMATION

The few vertebrate fossils found in the Odee beds all indicate a Pleistocene age, and, with one possible exception, all were in the upper part of the formation. The elephant, *Archidiskodon imperator,* has been found in Kansan, Yarmouth, and Iowan deposits in Nebraska, and probably it occurs also in the Aftonian (Schultz, 1934, table A). Its presence in the Odee formation, although not diagnostic, is at least consistent with the postulate of early Pleistocene age suggested by the thickness, upland position, degree of dissection, and probable immediate superposition of the formation on the Rexroad. Future more detailed studies may well lead to subdivision of the Odee and the establishment of age differences within the formation.

ORIGIN OF THE FORMATION

Many questions as to the origin of the Odee formation must await adequate knowledge of its distribution and lateral variations, particularly in Beaver county, Oklahoma. Working hypotheses suggested by the available facts, however, are outlined below.

The color and lithology of the greater part of the Odee deposits contrast sharply with those of the Ogallala, suggesting a different source of material. The prevailing reddish colors, although conceivably a result of climatic control, seem best explained as due to derivation from the erosion and reworking of Permian or Triassic redbeds. The direction and distance of the source area or areas remain to be ascertained. The gravel and coarser sand beds in the formation, however, are such as might have been derived from reworking of Ogallala materials.

The uniform stratification and lithology of the formation indicate deposition under relatively stable conditions, such as might have existed along the flood-plain of a sluggish, aggrading river. The invertebrate faunas studied by F. C. Baker are interpreted as representing a shallow-water, river habitat, into which some land snails were washed. It is probable that lacustrine conditions prevailed at least locally and temporarily, however, as indicated by the diatomaceous marl bed at locality *D*, and it is entirely possible that lacustrine conditions may have been general during the deposition of a part of the formation.

The association of the Odee formation with the present Cimarron valley suggests that the ancestral Cimarron may have played a part in depositing the formation. The facts at hand are insufficient to warrant any attempt to reconstruct the drainage conditions of that time, however, and it is entirely possible that the Cimarron had not yet taken its present course.

The ultimate cause of deposition probably was local downwarping. This may have been an extension of the subsidence more clearly evident farther north along Crooked creek valley. The conspicuous and erratic deformation of the Odee at most of the localities studied, however, suggests that local solution and collapse may have been at least a contributing factor.

LOCAL DEPOSITS OF PLEISTOCENE AGE IN MEADE COUNTY

"*Equus niobrarensis* BEDS"

The name "*Equus niobrarensis* beds" is used provisionally, for want of a better term, to designate four widely separated, fossiliferous Pleistocene deposits having one type of fossil horse in common. Three occur on the west side of Crooked creek valley, and one east of that valley, in a different drainage system. The first three may represent parts of one continuous deposit, but the number and character of exposures are such as to leave a large element of uncertainty. These deposits may correspond in part to the vaguely defined "Meade gravels" of Cragin (1896), a name that seems best abandoned unless future work leads to an adequate understanding of the nature of the beds. The individual deposits are described separately below.

(1) The westernmost occurrence of the "*Equus niobrarensis* beds" known to me is found in an abandoned gravel pit 7 miles west and 4 miles south of Meade (NE¼ sec. 33, T. 32 S., R. 29 W.). The gravel is fairly clean, and contains cobbles as much as 5 inches in length. Pebbles of reworked Ogallala are fairly common, and a few of vesicular basalt were found. The dating of this deposit is based on a few fossil teeth found loose on the surface of the pit. Rexroad beds are present at stream level, at the bottom of the pit, as indicated by teeth of *Equus cumminsi* and *Equus simplicidens*. The pit occurs along a small tributary stream, which heads in the upland slightly more than 1 mile northwest, but the gravel is not a deposit of that stream. Occurring some 50 feet below the upland level, the gravels may have a total thickness exceeding 50 feet.

(2) The second locality to yield fossil remains of *Equus niobrarensis* is the one at which Cragin (1896) collected the fossils later described by Hay (1917). It is located a few miles southwest of Meade, on the Big Springs ranch (SW¼ sec. 17, T. 32 S., R. 28 W.). The bone deposit is situated at the very top of the valley side, about 50 feet above stream level, and is found in silty sand. Exposures are very poor. The vertebrate fauna recorded from this locality is shown in the following list.

Vertebrate fauna of the "Equus niobrarensis _beds" in sec. 17, T. 32 S., R. 28 W., Meade county, Kansas_

*_Testudo equicomes_ Hay
Geomys lutescens (Merriam)
*_Mylodon harlani_ Owen
*_Equus complicatus_ Leidy
*_Equus leidyi_ Hay
Equus francisci Hay
Equus niobrarensis Hay
*_Camelops huerfanensis_ (Cragin)
Camelops kansanus Leidy
*_Canis occidentalis ?_ Richardson
Smilodon sp.
Felis cf. _imperialis_ Leidy
Felis cf. _oregonensis_ Rafinesque
*A large undetermined felid

Associated with the vertebrates were the following invertebrates, collected by Hibbard and identified by F. C. Baker.

Invertebrate fauna of the "Equus niobrarensis _beds" in sec. 17, T. 32 S., R. 28 W., Meade county, Kansas_

Fresh-water species
- _Stagnicola caperata_ Say
- _Helisoma trivolvis lentum_ Say
- _Gyraulus altissimus_ F. C. Baker
- _Physa hawnii_ Lea

Terrestrial species
- _Polygyra monodon_ Rackett
- _Succinea grosvenori_ Lea
- _Gastrocopta armifera similis_ Sterki
- _Helicodiscus singleyanus_ Pilsbry

(3) Along an east-west road cut 7 miles north of Meade (N. edge sec. 2, T. 31 S., R. 28 W.) Hibbard collected _Camelops sp._, _Equus niobrarensis_, and _Paraelephas columbi_ from silt, sand, and gravel deposits. Three teeth found by Millard Moler in greenish clay underlying volcanic ash of the large pit in the same section have also been identified provisionally as _Equus niobrarensis._

The three deposits noted above probably represent a late stage in the filling of the Meade trough by streams from the west. Their extent and degree of contemporaneity remain to be established by further work.

(4) The fourth deposit in Meade county to yield bones of _Equus niobrarensis_ is located along the headwaters of Sand creek, 5 miles east and 6 miles south of Meade. The fossils were found in a road cut on the south side of the creek, in a bed of yellowish silty clay extending from 32 to 42 feet above stream level. This bed is underlain and overlain by grayish silty clay, bringing the total exposed thickness to about 35 feet. Upslope from this section, and separated by a covered interval, there is about 20 feet of yellowish-gray bedded clay that probably represents the "Jones Ranch beds". Associated with the horse bones were remains of _Cynomys ludovici-_

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* Species reported by Hay (1917); others identified by Hibbard (1938, 1939).

anus Hibbard (1939), and the following invertebrates, identified by F. C. Baker: Fresh-water species, *Stagnicola palustris* Müller, var. (immature), *Physa sp.* (mostly immature), *Gyraulus altissimus* F. C. Baker; Terrestrial species, *Succinea grosvenori* Lea.

The *"Equus niobrarensis* beds" of Meade county are probably roughly equivalent in age to the McPherson formation of south-central Kansas. (Haworth and Beede, 1897, Lohman and Frye, 1940), from which fossil remains of *Equus niobrarensis* have been reported by Nininger (1930).

"JONES RANCH BEDS"

The name "Jones Ranch beds" is applied provisionally to local deposits southeast of Meade from which a fauna designated by the same name is described by Hibbard (1940a). These deposits occur along the headwaters of Sand creek, in the southern part of T. 32 S. and the northern part of T. 33 S., R. 27 W. About 4 miles east and 6 miles south of Meade (sec. 8, T. 33 S., R. 27 W.), a 60-foot section of the "Jones Ranch beds" is exposed in a high creek bluff (pl. 15A). It is made up of poorly consolidated sand, silt, and clay beds, and has yielded both vertebrates and invertebrates at two horizons. The vertebrates are described by Hibbard (1940a). The invertebrates have been described by Goodrich (1940), and comprise the following forms.

Invertebrate fauna of the "Jones Ranch beds" in Meade county, Kansas

Gastrocopta armifera abbreviata (Sterki)
Gastrocopta procera (Gould)
Hawaiia minuscula (Binney)
Pupoides inornatus Vanatta
Pupoides marginatus (Say)
Pupilla muscorum (Linnaeus)
Vertigo modesta (Say)
Vertigo ovata (Say)
Vallonia costata (Müller)
Succinea grosvenori Lea
Gyraulus parvus (Say)
Helisoma lentum (Say)
Lymnaea bulimoides cockerelli Pilsbry and Ferriss
Lymnaea caperata Say
Lymnaea palustris (Müller)
Lymnaea stagnalis subsp. ?
Musculium partumeium (Say)
Pisidium abditum Haldeman
Pisidium noveboracense Prime
Valvata tricarinata (Say)

In a road cut a few miles northeast of this locality (NW cor. sec. 3 and NE cor. sec. 4, T. 33 S., R. 27 W.), the following section is exposed.

Section of the "Jones Ranch beds" in sec. 4, T. 33 S., R. 27 W., Meade county, Kansas

Quaternary system, "Jones Ranch beds"	Thickness in feet
6. Soil, dark, sandy	4
5. Sand containing calcareous pebbles	2
4. Sand, silt, and clay, thin- and even-bedded, exhibiting rusty banding	8
3. Clay, sandy, greenish-gray	2
2. Sand, bedded, containing calcareous pebbles at base; some rusty bands	7
1. Sandy clay mostly, poorly exposed	11

Total exposed thickness of Jones Ranch beds, 34 feet.

The above two sections are correlated on the basis of similar physiographic position.

The vertebrate faunas found in the "Jones Ranch beds" indicate Pleistocene age, probably early Pleistocene, but they are not sufficiently diagnostic to give exactly the relative age of the beds with respect to that of other Pleistocene deposits in the area. Probably they are intermediate between the "*Equus niobrarensis* beds" and the Kingsdown.

As pointed out by J. C. Frye, the "Jones Ranch beds" seem to have been deposited in an ancient sink several miles in diameter, now deeply dissected. Evidence for this is found in the centripetal-radial drainage (see Meade topographic sheet), the basined slopes, and the presence of a minor, local artesian basin (Johnson, 1901, p. 721). The beds seem to be at least partly of fluviatile origin, having been laid down by short streams dissecting the margins of the sink and filling the center. Some lacustrine beds may be present also. Both vertebrate and invertebrate faunas are interpreted to indicate deposition during cooler climatic conditions than those of the present.

KINGSDOWN FORMATION

GENERAL CHARACTER

The Kingsdown formation consists of light-colored sand and gravel grading upward into the characteristic light-buff, even-bedded silt and clay, containing some small and scattered calcareous concretions. It is widely exposed in northern Clark county and southern Ford county. Well records indicate that its thickness reaches 110 feet. The formation is very soft, and easily eroded to form characteristic narrow, steep-sided gulches of the badland type (pl. 16). The name revives Cragin's loosely defined "Kingsdown marl"

(1896), of supposed late Pliocene age, here redefined to include beds of Pleistocene age only. It was included in the "Tertiary marl" as mapped by Hay (1890, p. 1).

AREAL DESCRIPTION

The best exposures of the Kingsdown formation are found along the upper stretches of Bluff creek, and along its northerly tributaries. The following typical section was measured on the west bluff of a small tributary on the Stephenson ranch, about 0.5 mile from its junction with Bluff creek (sec. 13, T. 30 S., R. 23 W.). (pl. 16):

Section of the Kingsdown formation in sec. 13, T. 30 S., R. 23 W., Clark county, Kansas

	Thickness in feet
Quaternary system	
Kingsdown formation	
4. Silt, light-buff, clayey, even-bedded to finely laminated below, grading into structureless, loess-like silt toward top	46
3. Sand, silty, gray, containing small pebbly bands below, grading into structureless calcareous silt above; abundant invertebrates	16
2. Sand and gravel, rusty to sooty-black, abundant calcareous pebbles and fragmentary slabs of mortar-bed conglomerate, obviously reworked; contacts indistinct	2
Rexroad formation	
1. Sand and gravel, well cemented toward top	26

The section begins 15 feet above floodplain level. The basal 26 feet, and possibly also the next 2 feet, belong to the Rexroad formation. The vertebra of some large, extinct type of bison was found about 5 feet from the bottom of division No. 4.

Just west of the above section, on the east side of the next valley, 5 feet of clean, even-bedded volcanic ash occurs near the base of the Kingsdown. The ash is underlain by a few feet of gray sand, and this, in turn, by rusty sand and gravel. The ash is overlain by 50 feet of buff silt, evenly laminated in the lower part. Other outcrops of ash are found in the next two valleys to the west, thus extending its outcrop belt to a distance of nearly a mile.

About 2.5 miles south of the Stephenson ranch section, on the east side of Bluff creek, overlooking Clark County State Lake, the capping limestone of the Ogallala is overlain by 40 feet of buff-colored sand and silt of the Kingsdown formation, poorly exposed in the upper portion.

About 4 miles west of the Stephenson ranch section, along a small valley in the N½ sec. 20, T. 30 S., R. 23 W., 40 feet of finely laminated gray to buff and brown silt, clay, and fine sand is exposed (pl. 15B). These beds are seen to be underlain locally by sand and gravel containing abundant concretionary pebbles of limestone, seemingly eroded from the Ogallala. A few miles west of this locality there are some additional deposits of volcanic ash.

Exposures similar to those described above occur in many places along Mulberry creek and along the headwaters of Rattlesnake creek and its tributaries in the vicinity of Bucklin. Similar beds were observed by me also a few miles northwest of Greensburg in Kiowa county, and in the southern part of the city of Pratt, in Pratt county. There is no reason for believing the latter to be continuous with the Kingsdown beds farther west, on basis of present knowledge.

In Ford county, some additional data on the formation are given by well records. At Bucklin, the municipal water well was reported to have been dug in clay to a depth of 90 feet, and in sand and gravel from that point to the bottom at 116 feet. The "clay" undoubtedly represents Kingsdown silt. South-southeast of Bucklin, in sec. 22, T. 29 S., R. 21 W., an oil-well log reports "clay" to a depth of 110 feet. A well near Minneola, in northwestern Clark county, records "yellow clayey shale", underlain by "gray sandstone", to a depth of 80 feet (Moore and Haynes, 1917, p. 252). The former undoubtedly represents Kingsdown beds. Water-well logs in southwestern Ford county (Lohman, 1938) indicate as much as 108 feet of Kingsdown.

The northernmost exposure of Kingsdown observed by me is located a few miles south of Dodge City, along a shallow valley in sec. 14, T. 27 S., R. 25 W., where about 20 feet of silty, fine sand is exposed. The westernmost extent of the Kingsdown is suggested by the log of the railroad well at Montezuma, which reports "clay" to a depth of 23 feet.

The inferred extent of the Kingsdown is shown in figure 12. Its western extension is uncertain, and is inferred only from topographic expression. The area shown on the map is probably a minimum. Additional information will undoubtedly be obtained from drilling. Even this, however, cannot be expected to give complete information, for the Kinsgdown is overlain by loess, and seems locally to grade upward into loess, from which it differs little except in its bedding. Neither from well records or samples, from indifferent exposures, nor from topographic expression is it to be expected that the Kingsdown can be satisfactorily differentiated from the loess.

AGE OF THE KINGSDOWN BEDS

Very few vertebrate fossils have been found in the Kingsdown deposits. Hay (1917, p. 42) reports that Cragin found *Elephas columbi* along the upper part of Bluff creek, on the Thomas ranch. Williston (1897, p. 303) reports teeth of *Equus occidentalis* from Bluff creek, but gives no details. Hibbard, in company with me and others, found one vertebra of *Bison* in the Stephenson ranch section. This fossil did not permit of specific identification, but does indicate some large, extinct type of bison, suggesting middle or late Pleistocene age. Inasmuch as no bison remains whatever have been found in the other Pleistocene deposits already described, this specimen suggests further that the Kingsdown is younger than those deposits.

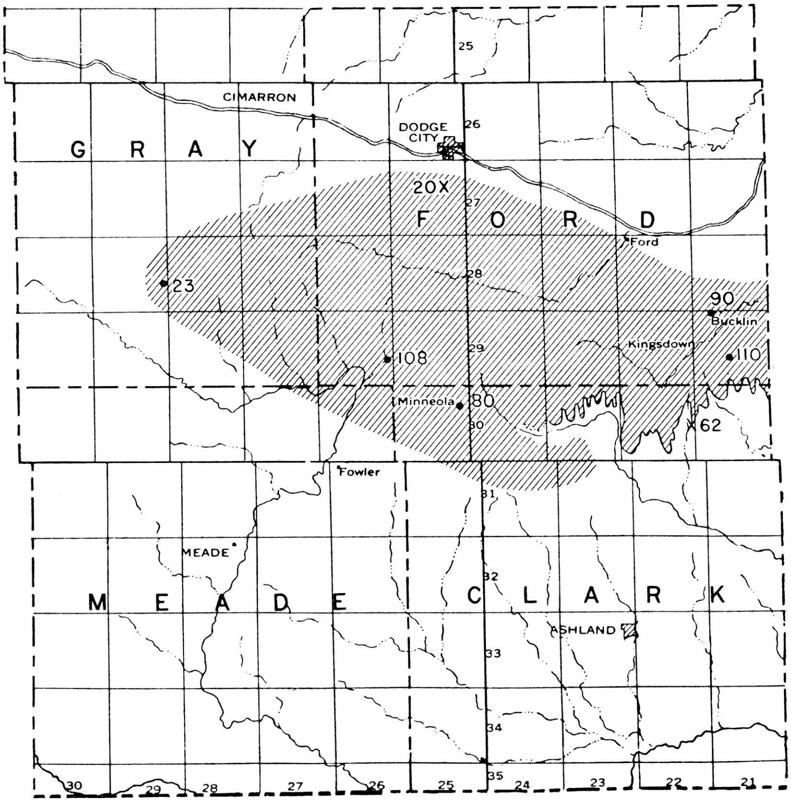

FIG. 12. Sketch map showing distribution of the Kingsdown formation. Crosses indicate exposures and dots show wells at which thickness, noted in figures, was determined.

ORIGIN OF THE FORMATION

The origin of the Kingsdown formation presents many problems, some of which cannot be solved until its extent, thickness, and subsurface relations are better known. The basal sand and gravel was undoubtedly derived from erosion of the Ogallala, and perhaps also of the Rexroad rocks. The abundant silt characterizing the greater part of the formation, however, seems adequately explained only by derivation from eolian loess. The even bedding and fine lamination indicate subaqueous deposition, either by floodwaters or under lacustrine conditions. If lacustrine conditions existed, it is possible that some of the material may have settled directly from the air into the water. The thickness of the formation, however, is too great to be explained wholly on this basis, and fits better with the postulate of material supplied by erosion of loess deposits, either contemporaneous or older, to the west.

The drainage conditions at the time of deposition were undoubtedly different from those of the present. In all probability Bluff creek, if it existed at all, had not yet been beheaded, and its upper stretches still formed a part of the Rattlesnake creek drainage. The same may have been true of Mulberry creek.

The cause of deposition is puzzling. Climatic changes alone seem hardly competent, and would fail to account for the exceptional thickness in one restricted area. They may have been a contributing factor, however, in supplying easily eroded and transported eolian material at a time when other causes were operative. Ultimately, deposition must have been due to a flattening or actual reversal of stream gradients, and this could be explained only as a result of crustal warping. Significant, perhaps, is the fact that the Kingsdown formation occurs in an area where: (1) the general land surface is higher south of the Arkansas valley than on the north; (2) Arkansas river begins its swing northeastward into the very anomalous Great Bend; (3) the Arkansas is perched as much as 180 feet higher than its parallel tributary valleys, Buckner creek, Pawnee river, and Walnut creek, on the north, and (4) the outer Arkansas valley and the sand-hill belt to the west are abnormally wide. It is a plausible surmise that these relations and the deposition of the Kingsdown may be traceable to related tectonic causes. The locus and the timing of the inferred differential warping, however, cannot be ascertained from information now available; possibly it began before the deposition of the Kingsdown beds, and continued during and after that event. The surface of the formation, in fact, does seem to be arched in a north-south direction, pointing to post-Kingsdown movement.

VOLCANIC ASH DEPOSITS

GENERAL CHARACTER

The volcanic ash deposits of southwestern Kansas are mapped in figure 13. All except the one in southern Hamilton county are believed to be of Pleistocene age. The individual deposits represent small, completely isolated bodies, and do not constitute any definite stratigraphic unit to which a formation name seems applicable. All the deposits are essentially similar in lithology, as summarized below. For additional details, the reader is referred to the bulletin by Landes (1928).

The color of the typical pure ash ranges from snow white to light gray. Where impure, owing to admixture of silt or clay, the color verges toward light buff or darker gray. It differs from calcareous deposits of similar color in texture, structure, and failure to effervesce with acid. The ash is characteristically fine grained, but displays minor variations in texture, and in proportion of impurities, from bed to bed. The loose ash is very gritty to the touch, and is dusty and easily blown into the air. Under a magnifying lens it is seen to be composed mainly of angular and extremely irregular shards. Except for a minor degree of bonding by silt and clay impurities, the ash is virtually unindurated.

All deposits of ash examined by me display a fine and remarkably even bedding or lamination, layers on the order of an inch in thickness persisting unchanged to the limits of the exposure, or for distances of as much as 100 feet (pl. 17A). Individual beds in many places show current and oscillation ripples, delicate channeling, and cross-bedding on a minute scale, such as are typical of quiet-water conditions. Breaking the general regularity of the bedding at scattered points on different levels, however, are old channels exhibiting more conspicuous cross-bedding on a much larger scale (pl. 17B). At most exposures, the bedding of the ash is essentially flat, but at several places it has been tilted locally, seemingly by solution and collapse of underlying beds, and shows dips of as much as 13°.

Calcareous concretions are common in the ash. They show a wide variety of shapes, but most conspicuous is an upright, rodlike type, which weathers in relief on old cuts to assume the appearance of an icicle or stalactite (pl. 17B). This type seemingly was formed by

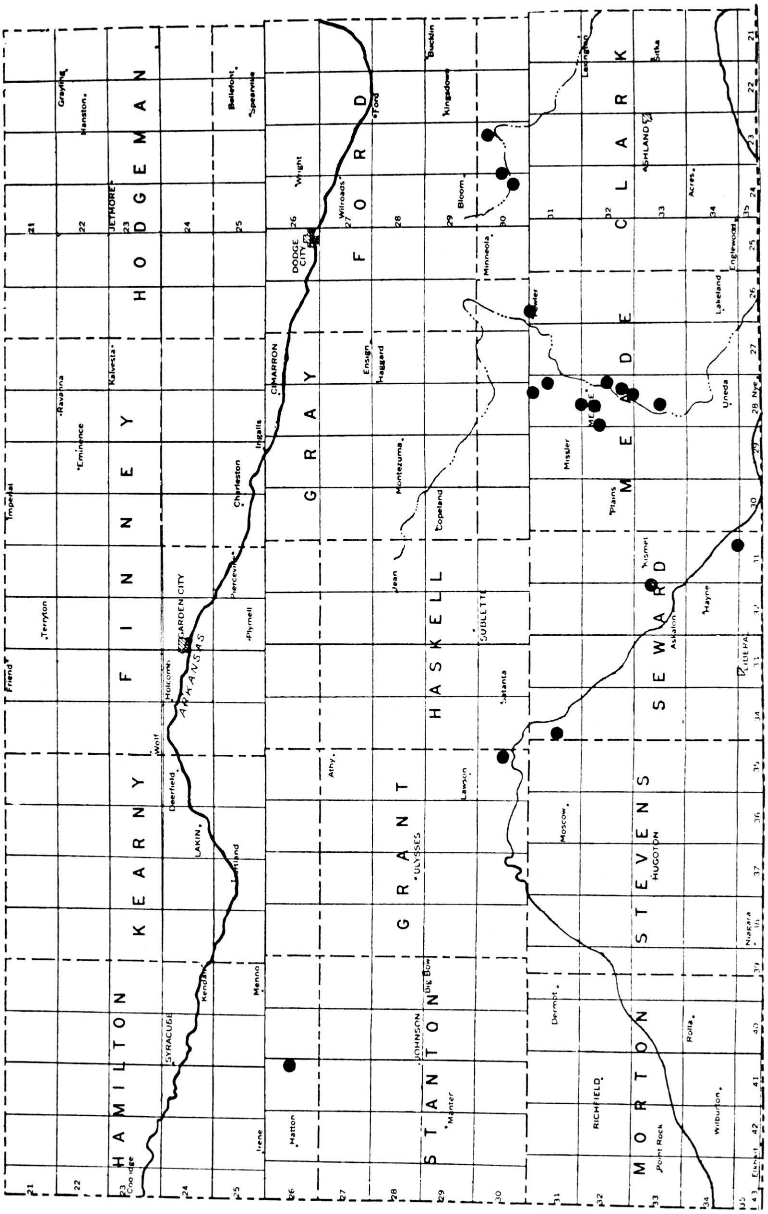

FIG. 13. Map showing location of volcanic ash deposits in southwestern Kansas.

deposition around plant stems followed by deposition in the tubular opening left by rotting of the organic material.

The thickness of the ash ranges from a few feet to a maximum of about 20 feet, and probably averages between 5 and 8 feet. The extent of individual deposits is small, owing seemingly both to the small size of the original deposit and to subsequent reduction by erosion. The average extent is probably only a small fraction of a section.

Owing to the softness of the ash, natural exposures are few, and for the most part occur only on steep slopes freshened by erosion. Where it does crop out, however, the ash is distinctive in color and texture. In a few places, the ash was first brought to light by the burrowing of gophers.

OCCURRENCE

In the following discussion the ash deposits are described by general geographic groups. Detailed locations of individual deposits are given in a subsequent section on mineral resources.

The known volcanic ash deposits of Clark county occur along the headwaters of Bluff creek. All are close to the 2400-foot contour, those at the west being sligthly above, and those to the east at or slightly below that level. Where exposures are adequate, the ash is seen to be underlain by sand or silt, and overlain by silt or fine sand. Invertebrates are present in both underlying and overlying beds at some places. The westernmost deposit of this group has been deformed, and shows a dip of 13°. All these deposits seem to represent local lenses of the Kingsdown formation.

The ash deposits of Meade county are all in the drainage area of Crooked creek, and are mostly clustered about the 2500-foot contour, although a few on the western side occur slightly higher. With the exception of one deposit 1.5 miles west of Meade, and another 8 miles south of Meade, believed to be in the Odee formation, the overburden on the ash is thin, commonly less than 8 feet, and consists mainly of loess or its reworked equivalent. Many deposits are underlain by a plastic, greenish-gray clay containing invertebrates. The bedding in numerous deposits is flat, but in others it dips as much as 5°. The topographic setting of the ash deposits varies. Some deposits occur along small draws, whereas others are close to the upland level.

The ash deposits of Seward county are confined to the area bordering the Cimarron valley, and all occur near the upland level. They were seemingly deposited during a former erosion cycle when the Cimarron flowed at a much higher level than at present. One pit in the northwest corner of the county shows a dip of 13°; the others are essentially flat-lying.

The single deposit in southeastern Grant county visited by me is situated well below the upland level, and is probably younger than those of Seward county. It shows a low dip toward the Cimarron valley.

AGE OF THE ASH DEPOSITS

The ash deposits of northern Clark county are the same in age as the Kingsdown formation. Those of Meade county may represent a considerable range in age. One, at least, seems to be a lentil in the Odee formation. Another, about 1.5 miles west of Meade, is tilted, and shows jointing and slightly superior induration, suggesting a somewhat greater age than that of most other deposits. Conceivably, it may be as old as Tertiary. Possibly the tilted deposits, as a group, are older than those that are flat-lying. The latter certainly are very similar in their geologic setting, and may well be contemporaneous. In the clay underlying the large deposit 6 miles north of Meade, teeth of *Equus niobrarensis* were found, suggesting that the overlying ash may be essentially contemporaneous with the beds named for that fossil. However, no diagnostic fossils have been found in the ash, and physiographic relations are not entirely clear. Until more specific facts are at hand, the relations of these deposits to one another and to those of Clark county must remain conjectural. The one deposit in Grant county seems on physiographic grounds to be younger than those of Seward county, but the relative age of these with respect to those of Meade county is unknown.

Considerations of the origin of the volcanic ash suggest that any one episode of ash eruption must have affected an extremely large area, that all deposits resulting from such an eruption must have been contemporaneous, and that a very few such eruptions, possibly even a single one, would be entirely adequate to account for most of the known deposits. There is, however, no *a priori* reason for assuming that there were so few eruptions, or that the conditions affecting the concentration and preservation of the ash from any one eruption were equally favorable over wide areas and in different drainage systems. Correlation of the ash deposits must rest on a basis more tangible than that of assumptions as to these factors.

In Nebraska, volcanic ash is reported to occur widely at the base of the Loveland formation, of post-Kansan pre-Iowan age (Lugn, 1935, p. 132). In western Iowa, also, volcanic ash has been described from the Loveland formation (Kay and Apfel, 1929, p. 121). It is reasonable to assume that some of the ash in Kansas is of the same age, but it is uncertain just which deposits may be so correlated.

ORIGIN OF THE ASH DEPOSITS

As pointed out by Landes (1928), the original source of the volcanic ash in Kansas must have been volcanic vents to the west, probably in northeastern New Mexico. From eruptions at that center, the ash was showered widely and more or less uniformly over the plains to form a temporary mantle. This primary deposit, however, was at once subjected to reworking, being drifted by the wind and carried along by surficial sheet wash where sufficient slope existed. Sooner or later, a portion of the original ash found its way into valleys, thence to be picked up by streams and redeposited as a secondary accumulation. The final deposition took place in quiet water, as testified by its bedding. Whether this was in lakes or on flooded valley flats is a more or less academic question, for there are many gradations between the two. The presence of distinct channels in several of the ash deposits, however, argues against the idea of a permanent lake or lakes for these particular deposits, and suggests that the valleys of sluggish, aggrading streams, perhaps similar to that of Crooked creek today, were the sites of deposition. Whether aggradation was caused by overloading of the streams with ash or by other factors affecting stream grades at the same time is unknown.

The topography of the area at the time of ash deposition was certainly different from that of the present. Relief was lower, valleys were comparatively shallow, streams were probably in a stage of maturity or old age, and little if any of the piracy responsible for the present courses of Bluff creek and Crooked creek had taken place.

Loess

Although long known from northwestern and central-western Kansas (Darton, 1905, p. 155, pl. 44), loess has not previously been recognized south of the Arkansas valley. The present study, however, shows it to be widely distributed in that part of the state, as indicated in figure 14. It is included in the areas mapped as Colby silt loam, Richfield silt loam, and probably also Richfield silty clay loam by the Soil Survey (Coffey and Rice, 1912), and seemingly is a part of the material designated as "Tertiary marl" by Hay

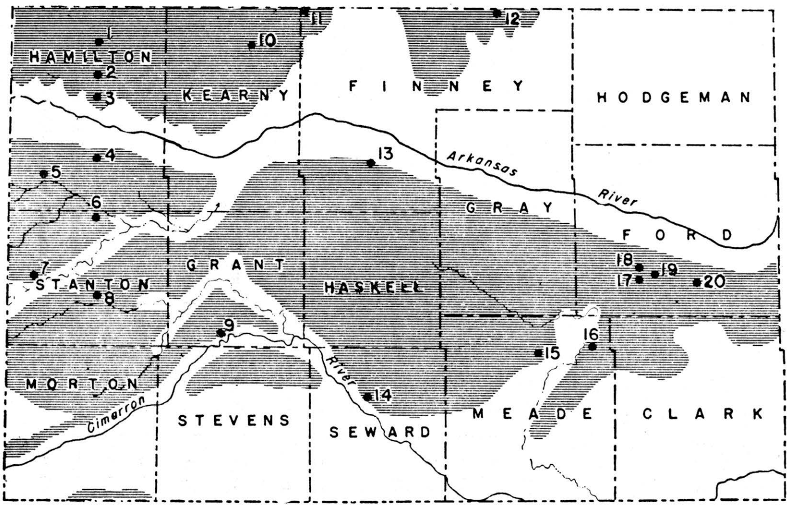

FIG. 14. Sketch map showing distribution of loess deposits in southwestern Kansas. The dots indicate locations of samples listed in table 3, and the numbering corresponds to that in the table.

(1890, pl. 1). Its thickness ranges from a few feet to several tens of feet.

The appearance of the loess is similar to that of typical loess everywhere, except that vertical parting is less prominent. The color ranges from light buff to dark brown, the latter being characteristic of the soil zone, and generally gradational downward into the former. The material is structureless and lacks bedding. In places it contains small, scattered concretionary nodules of limestone. It is of pulverulent texture, and is dusty to the touch. It differs from underlying Tertiary deposits in the virtual absence of any except very fine sand, and therefore cannot be regarded as a weathering product of subjacent strata. Mechanical analyses (table 3) made under my direction by William Truxal, Dale Harpster, and Eugene Maxwell show maxima in the .062-.031 mm division for most of the samples studied, and in the .125-.062 grade for a few of the samples. The former is particularly characteristic of eolian silt (Smith and Fraser, 1935). Fractions above .062 mm were separated by screening, and those below by the pipette method. Preliminary petrographic examination showed quartz and feldspar grains to be the predominant constituents of the loess, the feldspar displaying more or less incipient alteration. Virtually all of the samples except those taken in the humus zone effervesce readily with acid.

TABLE 3—Mechanical analyses of loess and associated materials.
Analyses of non-loessial materials are in italics.
The maxima for all samples are emphasized by heavier type.

No. of sample.	LOCATION.	Depth of sample in feet.	Mechanical composition.						Notes.
			> 0.5 mm	0.5-.25	.25-.125	.125-.062	.062-.031	< .031	
	HAMILTON COUNTY:								
1	SE¼ Sec. 36, T. 21 S., R. 41 W.	2.5	0.03	1.0	6.5	**49.4**	34.5	8.7	Road cut.
2	SW¼ Sec. 31, T. 22 S., R. 40 W.	2±	1.8	.9	6.8	27.9	**47.0**	15.7	Road cut.
3	W½ Sec. 19, T. 23 S., R. 40 W.	4	0	.03	2.2	32.6	**49.5**	15.6	Road cut.
4	SW¼ Sec. 18, T. 25 S., R. 40 W.	3±	.8	1.4	3.2	3.7	45.7	**45.7**	Road cut.
5	NW¼ Sec. 33, T. 25 S., R. 42 W.	1.5	.02	.2	2.0	20.2	**41.5**	36.1	Road cut.
	STANTON COUNTY:								
6	NW¼ Sec. 12, T. 27 S., R. 41 W.	3	0	.3	4.0	**37.7**	36.0	22.0	Road cut.
7	SW¼ Sec. 30, T. 28 S., R. 42 W.	4	.03	.4	3.5	21.1	**58.5**	16.6	Road cut.
8	NE¼ Sec. 24, T. 29 S., R. 41 W.	3	0	.3	4.5	30.8	**48.0**	16.0	Road cut.
	GRANT COUNTY:								
9	E½ Sec. 21, T. 30 S., R. 37 W.	6	0	1.6	3.4	**40.4**	38.5	16.2	Road cut.
	KEARNY COUNTY:								
10	SW¼ Sec. 3, T. 22 S., R. 36 W.	4	.03	.1	9.0	13.6	**57.1**	20.1	Road cut.
	FINNEY COUNTY:								
11	NW¼ Sec. 6, T. 21 S., R. 34 W.	3	.2	.7	5.2	26.2	**52.0**	15.8	Road cut.
12	NE¼ Sec. 2, T. 21 S., R. 29 W.	2±	0	.03	3.5	22.6	**69.5**	4.4	Road cut.
13a	Cent. Sec. 19, T. 25 S., R. 32 W.	1–2.5	0	0	1.1	23.7	**55.8**	19.4	Under dune sand in roadside pit.
13b	Cent. Sec. 19, T. 25 S., R. 32 W.	2.5–4.5	0	1.5	12.1	21.7	**46.0**	18.8	Under dune sand in roadside pit.

TABLE 3—CONCLUDED

No. of sample.	LOCATION.	Depth of sample in feet.	Mechanical composition.						Notes.
			> 0.5 mm	0.5-.25	.25-.125	.125-.062	.062 .031	< .031	
14a	SEWARD COUNTY: NW¼ Sec. 14, T. 32 S., R. 33 W.....	1.5	.6	6.4	18.2	**38.7**	25.3	10.8	Road cut.
14b	NW¼ Sec. 14, T. 32 S., R. 33 W.....	3	.3	1.7	14.8	**44.3**	29.1	9.7	Road cut.
15	MEADE COUNTY: W½ Sec. 2, T. 31 S., R. 28 W.......	3	.03	.7	2.8	28.3	**55.4**	12.8	Above ash in Cudahy pit (pl. 18B).
16a	S. Cent. Sec. 33, T. 30 S., R. 26 W...	0.5	*20.3*	**41.3**	*25.1*	*8.1*	*0.7*	*4.5*	Soil zone on dune sand
16b	S. Cent. Sec. 33, T. 30 S., R. 26 W...	2.5	*26.7*	**46.2**	*15.5*	*7.2*	*0.9*	*3.6*	Dune sand.
16c	S. Cent. Sec. 33, T. 30 S., R. 26 W...	6.0	*7.5*	**27.6**	*27.1*	*17.2*	*11.5*	*9.0*	Weathered dune sand?
16d	S. Cent. Sec. 33, T. 30 S., R. 26 W...	10.0	0.6	4.2	20.3	**39.3**	25.1	10.6	Loess.
16e	S. Cent. Sec. 33, T. 30 S., R. 26 W...	14.0	*2.3*	*7.8*	*14.6*	**47.5**	*27.8*		Impure volcanic ash.
16f	S. Cent. Sec. 33, T. 30 S., R. 26 W...	16	*0*	*.02*	*3.1*	*37.6*	**59.2**		Volcanic ash below loess
17	FORD COUNTY: W½ Sec. 36, T. 28 S., R. 25 W......	4	0.1	0.9	8.3	**32.1**	28.1	30.4	Road cut on U. S. 283.
18	E½ Sec. 23, T. 28 S., R. 25 W.......	5	0	1.4	2.9	.4	**62.6**	32.8	Road cut (possibly reworked).
19	E½ Sec. 29, T. 28 S., R. 24 W.......	3 ±	0	1.9	6.2	35.3	**42.0**	15.0	Road cut.
20a	S½ Sec. 34, T. 28 S., R. 23 W.......	3 ±	0.3	2.5	9.2	24.9	**52.2**	10.9	Road cut; 3 ft. above gray band.
20b	S½ Sec. 34, T. 28 S., R. 23 W.......	....	0	0.3	2.5	27.7	**51.0**	18.0	Road cut; reddish zone 1 ft. below gray band.
20c	S½ Sec. 34, T. 28 S., R. 23 W.......	....	0.1	0.7	6.2	**40.9**	39.6	12.4	Road cut; buff zone 6 ft. below gray layer.

Owing to the incoherent character of the loess, natural exposures are few and small. Road cuts and other man-made excavations provide virtually the only exposures available for study. Because these are generally shallow, the complete thickness of the loess is not readily determinable, and the irregularities of the buried pre-loess surface, if any, are concealed. Only in southern Ford county, along the Mulberry creek drainage, does the loess definitely seem to be very thick. About 5 miles south and 3 miles west of Ford (S½ sec. 34, T. 28 S., R. 23 W.), the loess is exposed through a vertical range of about 50 feet. About 25 feet above the valley bottom it contains a locally persistent and essentially horizontal reddish zone, overlain by a thin gray zone containing sand grains and some shards of volcanic ash, suggesting some interruption to deposition. The horizontality of these zones suggests that the loess is not merely a slope mantle, but represents a once-level fill, since dissected. The nature of the underlying topography is unknown, for no older deposits are exposed for considerable distances. The characteristic topographic expression of the loess in this locality is a shallow, steep-sided, flat-bottomed, U-shaped "draw" (pl. 18A) (compare Haworth, 1897, p. 25).

In the volcanic-ash pits 6 miles north of Meade (pl. 18B) and 1 mile east of Fowler, loess overlies volcanic ash. The contact between the two is moderately sharp, but is not marked by any soil zone, or other indication of elapse of a long time between the deposition of the one and of the other.

The erosional development of the area at the time of loess deposition probably differed from that of the present only in that the valleys were not yet so deep. The presence of dune sand over both terrace alluvium and deeply weathered loess in Finney county suggests that the loess does not post-date the terrace along the Arkansas valley. Additional information is wanting, and uncertainties are introduced by the lack of continuous exposures, and by difficulties in distinguishing original loess from redeposited alluvial silt. The latter, if uncontaminated by addition of coarser material, may be quite as structureless as the former, and for the same cause—the effect of plant roots in kneading together successive additions to the deposit and thus obliterating any stratification initially present.

The age of the loess can be stated only in relative terms, for it has yielded no fossils. At least in part, it probably belongs somewhere in the upper Pleistocene. It is younger than volcanic ash, and older than dune sand at the few localities where it is found in contact with one or the other of these. Possibly it is contemporaneous with and in part grades laterally into the Kingsdown formation. There is no reason, however, for assuming that the loess of the area is all of one age. In northwestern Kansas, two ages of loess have been described by Elias (1937), and in central-western Kansas similar relations were found by me during the summer of 1939. The younger loess of the latter area, in fact, seems to be much less deeply weathered than most of the loess in the southwestern part of the state. Possibly the loess mapped by the Soil Survey as Richland silt loam is of a different age than that mapped as Colby silt loam. Much detailed work will be required, however, to differentiate the loess deposits of the area south of the Arkansas valley definitely.

The source of the loess is uncertain. Much additional information on lateral variations in thickness, texture, and mineralogy, and on general regional relations, are needed to gain definite knowledge on this point.

TERRACE DEPOSITS

Quaternary terrace deposits are widely distributed along the Arkansas valley (Smith, 1938), and somewhat less widespread along the Cimarron valley. In both places they constitute an important source of commercial sand and gravel. Terrace alluvium occurs also along Bluff creek and along Crooked creek, but is of small extent and of somewhat erratic disposition. The significance of these terrace deposits is discussed at greater length in the section on physiography.

The principal terrace of the Arkansas valley lies 15 to 25 feet above present river level, and averages about 20 feet. The exposed thickness of the terrace deposits ranges from about 8 to 20 feet, the base being concealed in many places. The material consists of clean, unconsolidated, cross-bedded sand, alternating from fine to coarse. The sand is more or less pebbly in many places, and there are lenticular beds of gravel. The larger pebbles in the gravel are commonly as much as twice the size of those found in the Ogallala in the vicinity. These deposits are locally stained rusty brown or black. Their age has not been definitely determined. Some fragmentary *Bison* and *Equus* material was found by me, and it is probable also that the *Bison willistoni* (believed by O. P. Hay to be *Bison alleni*), *Elephas primigenius,* and *Equus excelsus,* reported by Martin (1924) from the vicinity of Garden City, were found in the terrace fill. A few miles northeast of Garden City, remains of *Citellus elegans* (Kennicott) were taken from fine-grained alluvium overlying sand and gravel deposits seemingly graded to the river terrace, although not necessarily deposited by the river itself (Hibbard, 1938). These fossils point to late Pleistocene age. The topographic position of the terrace deposits is well below that of the Kingsdown, indicating that they are younger than that formation.

Terrace remnants along the Cimarron valley are scattered and inconspicuous. They occur at elevations ranging from 20 to 85 feet above present river level, and seem to fall into two or possibly three sets. They are underlain by sand and gravel similar to that of the Arkansas terrace, but containing also some pebbles of vesicular basalt, which is not found along the Arkansas valley. Pebbles of reworked Ogallala are numerous, but it is probable that much of the material in the gravels came directly from primary source areas. This is suggested by the size of the pebbles, which commonly reach lengths of 8 inches, and in Morton county attain the dimensions of cobblestones, as much as 12 inches long—far longer than any pebbles found in the Ogallala along the Cimarron valley in Kansas. The age of the Cimarron terrace deposits is not yet ascertainable. One indeterminate elephant tooth was found by me in gravel 80 feet above the Cimarron, and unconformable on deformed Odee, about 21 miles south of Meade. Other fossils have been reported from the Cimarron terrace deposits, but such as have been saved are still in the hands of local collectors, and have not been submitted to scientific study. Obviously the different terraces are of different ages, and probably all fall within the upper Pleistocene. Correlations with the Arkansas valley are wholly conjectural.

QUATERNARY DEPOSITS OF THE ASHLAND BASIN

In large sections of southern Clark county, the Permian redbeds are concealed by alluvial deposits extending 60 feet and more above present stream level, and reaching to undetermined depths below present stream grade. These deposits probably range in age from early Pleistocene to Recent, but represent isolated geographic units, and for the most part, in the absence of fossils, cannot be correlated with the deposits described above from other parts of the area. They are discussed here in one group because of inadequate knowledge of their relations, and in order to direct attention to the problems that they involve.

In the city of Ashland, water-bearing sand and gravel are reported to occur to depths of 120 feet. No sections of comparable thickness were found exposed at the surface in the course of my reconnaissance studies. Five miles west of Ashland, however, exposures were sufficiently good to reveal two ages of alluvium. The older, exposed in a 60-foot creek bluff, is lithologically similar to the Odee, at least in its lower part, and is provisionally correlated with that formation. The younger, a brownish-buff alluvium, forms a 35-foot cut-and-fill terrace against the Odee.

In southeastern Clark county, about 1 mile south of the Cimarron on State highway 34, and about 60 feet above river level (secs. 29 and 30, T. 34 S., R. 21 W.), numerous ventifacts (pl. 10B) were found in reddish gravelly sand of probable Pleistocene age. Most of the ventifacts are cut on chert, probably derived from the Day Creek dolomite. These may be equivalent to the "pitted cobbles" in northwestern Oklahoma described by Waring (1930), although the age of the latter is uncertain. Ventifacts were found also about 0.6 mile north of the Cimarron, and about 50 feet above stream level, in a thin layer of fine gravel exposed in a cut along the same road. Some additional specimens were found at a locality a few miles northeast, in the NW¼ sec. 9, T. 34 S., R. 21 W. Whether the ventifacts in these localities all occur in deposits of the same age or not is not known. It may be noted again, however, that ventifacts occur also at the base of the Ogallala in Clark county.

The only fossil remains thus far reported from Clark county that may have been found in the Ashland basin are those of *Elephas primigenius,* noted by Williston (1897, p. 302) only as having been obtained "from the reddish alluvium of Clark county." In the absence of definite information, the dating of the deposits in southern Clark county must await future study. It may be surmised, however, that the younger deposits correspond either wholly or in part to the Gerlane formation described by Knight (1934) from the Medicine Lodge drainage in Barber county.

DUNE SAND

Dune sand is widely distributed along the south side of the Arkansas valley and in the Cimarron Bend section, and is of more restricted occurrence in many other parts of the area (fig. 15). It is included in the Dunesand, Pratt loamy sand, Pratt sandy loam, and Richfield sandy loam of the Soil Survey (Coffey and Rice, 1912). The original dune sand has undergone considerable reworking by the wind in successive episodes of eolian activity, so that color, degree of weathering, and topographic expression vary widely from place to place. The origin and development of sand dunes is discussed more fully in the section on physiography.

The age of the dune sand cannot be stated definitely. It is certainly not of late Recent origin, however, as seems to have been assumed by some writers. In all probability, the original accumulation of dune sand took place at different times in different places, and the earliest accumulation may date well back into the Pleistocene. Of the deposits studied, the one having the appearance of greatest antiquity is exposed in the new cut of the Rock Island Railroad between Kismet and Cimarron river, in eastern Seward county. This locality illustrates also the range in age of dune-sand deposits, for it reveals two sands of different appearance, separated by a well-defined soil zone, and thus unquestionably of greatly different age. The upper and younger sand is by no means fresh in appearance, but is somewhat indurated, and displays a distinct soil zone and a more or less subdued topographic form. The older sand differs from the younger in its redder color, more advanced degree of induration and weathering, and obscure bedding.

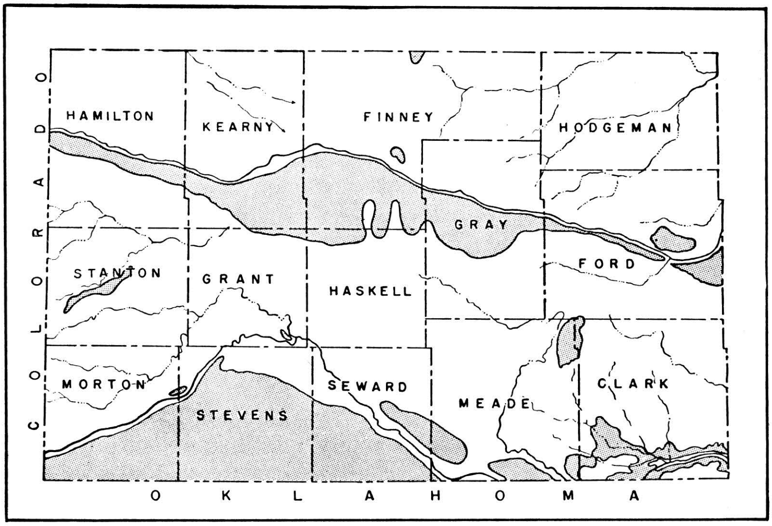

FIG. 15. Sketch map of dune-sand areas in southwestern Kansas.

No reason was found for believing that the dune sand is contemporaneous with loess. In the volcanic-ash pit near Fowler in Meade county and in a small pit along U. S. highway 83 about 7 miles south of Garden City (sec. 19, T. 25 S., R. 32 W.), the dune sand, in fact, overlies a thick soil zone on loess. Dune sand is also younger, although probably only slightly younger, than the terrace sand and gravel of the Arkansas valley, which widely underlies it. There seems to be no genetic relation between the present Arkansas flood plain and any of the dune sand.

VALLEY FILL

Late Quaternary alluvium floors the valleys of all the principal streams in the area. Along the Arkansas valley, the maximum thickness of the alluvium is about 60 feet, but the thickness varies both along and across the valley. At Syracuse, the log of one railroad well shows 63 feet of sand and gravel resting on black shale. Four other wells are reported to show thicknesses of 33, 24, 24, and 20 feet, respectively. In each case, however, the top of the well is somewhat above river level, possibly as much as 25 feet. At Kendall, Darton (1920, p. 10) reports 53 feet of river alluvium. At the "narrows", about 2 miles west of Hartland, Slichter (1906, pp. 23-24) reports depths of about 40 feet to bedrock. East of this point, the base of the Ogallala plunges beneath river level, and well records fail to show a very sharp demarcation between Ogallala and Quaternary alluvium, but suggest that the thickness of the latter commonly ranges from 30 to 50 feet. Possibly a part of the valley fill in some places is of late Pleistocene age, and represents the basal part of a cut-and-fill terrace deposit.

Data on the depth of fill along the Cimarron valley are scanty, but indicate that it is at least 20 feet.

Along Crooked creek valley, the depth to bedrock locally exceeds 280 feet. Undoubtedly a part of the fill consists of Tertiary materials, a part Pleistocene, and a part Recent, but the proportions of each are unknown. Jay Ellis, a well driller of Meade, reported encountering a buried log in the fill at a depth of nearly 200 feet in a well on the west side of Crooked creek a few miles south of Meade. It is possible that a part of the valley fill north of Meade is of lacustrine origin. This is suggested by the evidence for relatively recent areal subsidence found in the bottleneck pattern of the 2,460-foot to 2,500-foot contours, by the large undrained depression west-northwest from Fowler, by the marshy character of much of the bottom land, and by the low gradient and irregular peregrinations of Crooked creek through the basin area. It is interesting to note that the possibility of a lake was considered by Johnson (1901, p. 706), but was dismissed on the general grounds that Crooked creek could not supply enough water to fill the basin. His argument is not stated in quantitative terms, however, and fails to consider the probability that rainfall at various times in the past has been considerably greater than that of the present. If a lake existed, its deposits were later veneered with stream deposits.

STRUCTURAL GEOLOGY

STRUCTURES IN PRE-TERTIARY FORMATIONS

Of pre-Tertiary structures, only those in the Cretaceous have yet been described even in a general way. Bass's reconnaissance structural map of the Dakota sandstone, reproduced here as figure 16, shows a regional dip of about 20 feet per mile to the northeast. In southern Hamilton county there is a local dome named the Syracuse anticline, flanked on the southwest, in Stanton county, by a structural depression.

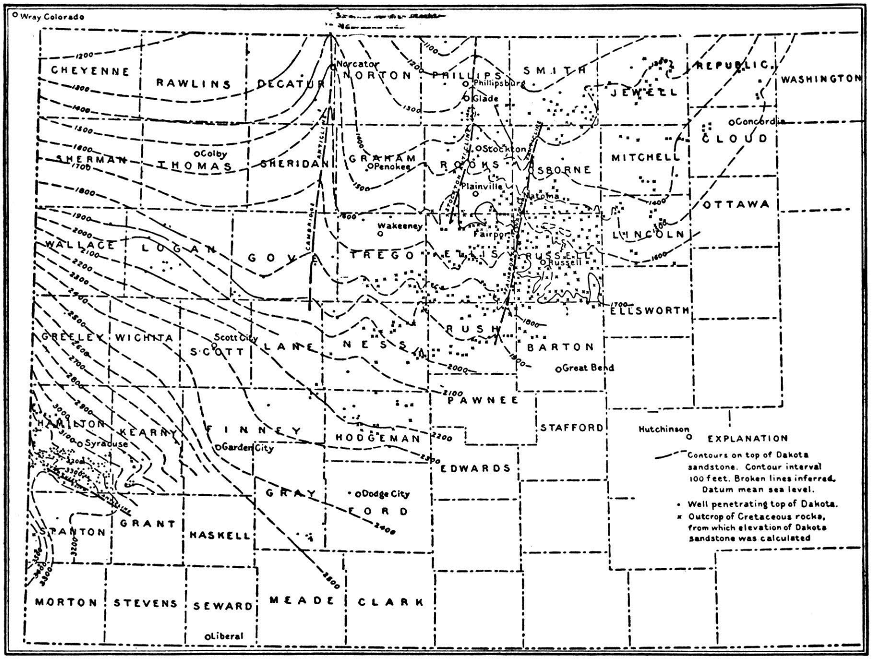

FIG. 16. Reconnaissance structural contour map on the top of the Dakota sandstone in western Kansas. Reprinted from Bass (1926, pl. 7).

STRUCTURES IN TERTIARY AND QUATERNARY BEDS

The regional dip of the Ogallala formation conforms to the plains surface in the greater part of the southwestern Kansas area. It ranges in amount from about 10 to 15 feet per mile, and in direction from southeast to east-northeast. These variations are believed to represent irregularities in broad regional upwarping of post-Ogallala date. At a few places there are sharp departures from and actual reversals of regional dip, and these constitute the structural features of principal interest. Evidence for their existence is mainly physiographic, and has been almost overlooked in the past. In addition, there are numerous minor and very local structures of solution-and-collapse origin. In the following paragraphs the minor structures are discussed first as a group, and then the major structures are described in order.

MINOR SOLUTION-AND-COLLAPSE STRUCTURES

Minor solution-and-collapse structures are indicated at many places by erratic dips in surface exposures, and at a few places may be observed in cross-section in deeper cuts. Some are so recent as to be marked by surface sinks or depressions, whereas others are so old as to have been deeply dissected. Both types are especially common in Meade and Clark counties.

Perhaps the best display of the results of solution and collapse is found at Big Basin and St. Jacob's Well, in western Clark county (secs. 24 and 25, T. 32 S., R. 25 W.). In St. Jacob's Well, one slump block of Ogallala shows a dip of about 35° (pl. 19B), and in Big Basin dips as steep as 30° may be observed in the steep bluffs rimming the basin (pl. 19A). In the bordering area the dips are gentler, as shown in ravines entering the depression (pl. 19C). Cracks and open fissures are numerous. In all instances, the distortion of the beds is disorderly, and takes the form of irregular sags of varying size, shape, and disposition. No clean-cut faults or systematic flexures were observed.

Older structures of similar character are exposed at the following localities: (1) on the north bank of Sand creek about 5 miles east and 6 miles south of Meade (sec. 3, T. 33 S., R. 27 W.) (pl. 19D); (2) on the east side of Crooked creek about 11 miles south of Meade (sec. 32, T. 33 S., R. 28 W.); (3) on the north bank of the Cimarron about 21 miles south of Meade. At the last locality, the deformation is less irregular than at most other places (pl. 14A). Other examples, less adequately exposed, are suggested by strong dips in volcanic-ash beds in northern Clark county and in northwestern Seward county, as noted in preceeding pages. Gentler dips of similar origin are found at numerous places in the more dissected portions of Meade and Clark counties.

Where unconsolidated materials at the surface are affected by collapse, there is some tendency toward systematic structures of a very minor character. Typical forms are concentric slump cracks and scarps with centripetal dips, representing miniature landslide movements toward the center of the depression. These have been amply described and illustrated by Johnson (1901, pls. 131, 132, 136, 138).

The minor structures described above are attributed to solution of underlying salt (or possibly gypsum) beds in the Permian, followed by collapse of insoluble roof rocks. Inspection of the isopach salt map (fig. 17) shows ideal conditions for this process, for the salt

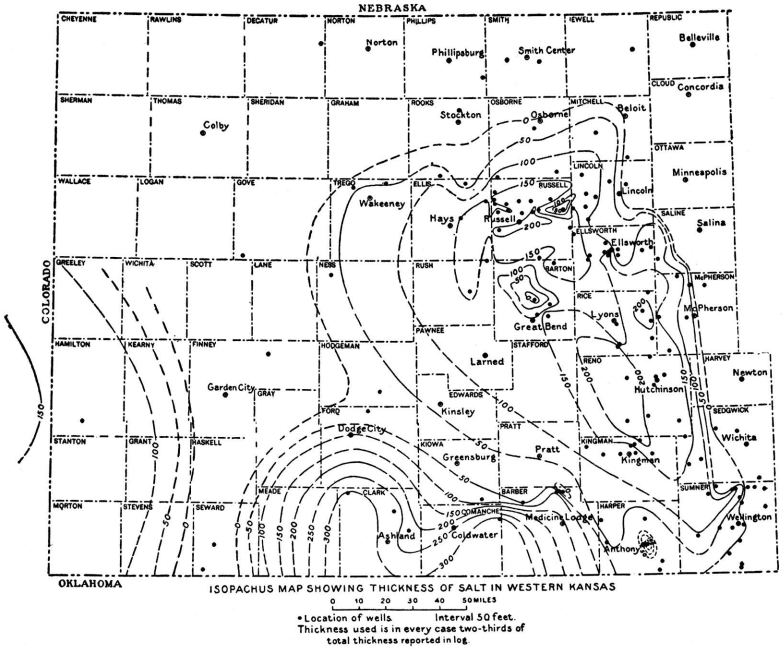

FIG. 17. Isopach map showing thickness of the Permian salt, reprinted from Bass (1926, pl. 8).

reaches a thickness of 300 feet, and its top lies at depths of 300 to 600 feet, being deeper toward the west than at the east.

Solution-and-collapse structures have been given little attention in geologic literature, and, to the best of my knowledge, the mechanics of their formation are yet to be studied. Simple deduction, however, indicates that the character of the deformation is governed chiefly by the following factors: (1) depth of the soluble bed or beds; (2) disposition of competent and incompetent beds in the roof rock; (3) shape, size, and spacing of solutional openings; and (4) mode of failure of the roof rock—whether piecemeal or massive, progressive or climactic. Very probably the progress of solution in salt is different from that in limestone, owing to the relative weakness and plasticity of the salt under load. A detailed analysis of these problems would undoubtedly be fruitful, but is beyond the scope of this paper. Such a study might well draw heavily on engineering investigations of subsidence in connection with coal and metal mining and salt extraction (Rice, 1923, Young, 1927).

THE MEADE TROUGH

The Meade trough is the only structure involving post-Cretaceous beds heretofore recognized in the area, having been described by Haworth as early as 1896. It represents both a topographic and a bedrock depression, the latter being of much greater relief than the former. The trough is about 30 miles long, and extends diagonally across central Meade county into southwestern Ford county (fig. 8), trending approximately north-northeast. Evidence for this structure is partly topographic, partly stratigraphic, and partly hydrologic, as outlined below.

The topographic evidence is perhaps most striking, and consists in the anomalous trend of Crooked creek valley transverse to the regional slope, in the bottleneck pattern of the contours north of Meade, and in the linear character of the valley for more than 10 miles south of Meade. Stratigraphic evidence for a bedrock trough, based both on surface outcrops and on well records, has already been presented in connection with the areal description of the Ogallala formation. Hydrologic evidence consists in the occurrence of artesian water throughout a long strip of the valley belt. Artesian conditions here can be satisfactorily explained only as a result of deformation of the aquifer and confining beds, and thus confirms conclusions from other lines of evidence.

The Meade trough was interpreted by Haworth (1896) as having been formed by a fault, of which the downthrow side is the west side. His evidence, however, although clearly indicating the existence of a structural depression, fails to establish that this depression was caused wholly by faulting, and the possibility of an elongate downwarp, in part unbroken by faulting, seemingly was not considered.

Johnson (1901, pp. 711, 721-725) later took issue with Haworth, postulating that solution and collapse were alone adequate to account for the observed structural and topographic features. His essential arguments rested on: (1) The undoubted presence of considerable thicknesses of salt and gypsum, available to solution, at depth; (2) the large number and wide distribution of much smaller solution-and-collapse depressions, including some formed within historic time; and (3) the assumption that faulting was inimical to the production of artesian pressure. Stripped to their essentials, Johnson's contentions are hardly convincing, and represent unsubstantiated extrapolation from minor to major features. Objections may be summarized as follows: (1) there is little or no adequate geologic precedent for attributing so large a depression to the purely surficial processes in question. This in itself proves nothing, but seems to place the burden of proof on the investigator seeking to establish the new precedent. (2) The solution-and-collapse hypothesis fails to explain the notably elongate character of the depression. (3) This hypothesis fails also to account for the reversed asymmetry of the topography north and south of Meade, and for the discordance of topographic levels on the two sides of the depression, as shown in the profile, figure 18. (4) If solution and collapse occurred over so large an area, it obviously could not have been instantaneous, but must have been effected either by progressive lateral extension from a few initial lines or centers, or by the coalescence of many small depressions developed about innumerable local centers. In either case, it would be expected that there must have been extensive fracturing of the roof rock in the course of these readjustments, and that a very leaky condition would have been produced, leading to contamination of surface waters by saline solutions from depths. Thus it seems that the solution-and-collapse hypothesis raises more questions than it answers, and that a reexamination of Haworth's original interpretation is in order.

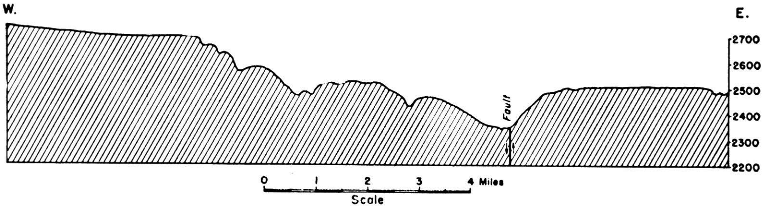

FIG. 18. Topographic profile across the Crooked creek valley south of Meade. The position of the inferred fault is shown by a heavy vertical line.

Haworth's faulting hypothesis seems to apply particularly well to the valley south of Meade. The linear character of the valley, the pronounced topographic asymmetry, and the abrupt descent of the bedrock floor directly west of the escarpment, are all readily explained by a fault of which the downthrow side is the west side. The presence of minor faults at various places within the valley (pl. 14B) is also consistent with this hypothesis, although not necessarily confirmatory. The basin north of Meade, however, fails to display the more striking characters noted above. It slopes more gently toward the center from both sides, and is broadly rounded rather than linear. This suggests either that the fault passes northward into a simple downwarp, or that, if any faulting took place, it was of earlier date, and its topographic expression was obliterated by ensuing erosion and deposition.

On the basis of the tectonic hypothesis, the minor solution-and-collapse structures so common in Meade county may be regarded as results rather than as indicators of the cause of the structural depression. They would be explained as merely having been superimposed upon a tectonic trough, perhaps as a result of the directive effect of that structure on ground-water movement in the soluble beds.

A possible rejoinder to this explanation involves retention of solution and collapse as the primary cause of the trough, but may add that it was localized by a preëxisting fault or flexure or both in the older rocks. Although this meets one of the objections to Johnson's hypothesis, it fails to meet the others, and would be fully as difficult to prove. In the last analysis, however, a final solution to the problem can be given only by drilling a series of test holes sufficiently deep to penetrate any soluble beds that might be involved, and sufficiently numerous to determine whether the surface structure persists with depth. Until this is done, arguments pro and con must rest on a purely inferential basis.

Whatever hypothesis of origin be adopted, stratigraphic and topographic factors suggest that the downward movement was intermittent in time, and that the locus of maximum subsidence shifted from place to place during successive stages of the movement. Although available data are inadequate for the drawing of any very convincing geologic cross-section of the trough, they suggest that the sequence of events was about as follows: (1) possible initial subsidence during Ogallala time; (2) pronounced downfaulting in late Pliocene time, leading to localized deposition of the Rexroad formation; (3) renewal of downward movement along the southern part of the trough in early Pleistocene time, leading to the deposition of the Odee formation; (4) continued movement in later Quaternary time, outlining the details of the present topography and exerting a directive effect on ensuing stream erosion; as suggested by Johnson (1901, pp. 720-721), there may have been two substages of this movement, the earlier effective south of Meade and the later north of Meade. Undoubtedly future studies will contribute to a more definitive outline of the complex history of the Meade trough, and perhaps to the recognition of intermediate stages in the downward movement.

JONES RANCH BASIN

The basin in which the "Jones Ranch beds" were deposited lies east of the Meade trough, and seems to represent an isolated structural depression. Being subcircular in outline and not necessarily much greater than 3 miles in diameter, it may be satisfactorily explained as of solution-and-collapse origin. Although larger than many of the other depressions of this type within the area, it is smaller than the Cheyenne Bottoms basin in Barton county (Great Bend and Russell topographic sheets), which has a diameter of about 7 miles, and seems best explained as a result of that process (Bass, 1926, pp. 94-95).

SYRACUSE FLEXURE AND FAULT

The Syracuse flexure constitutes an abrupt and asymmetrical downwarp separating the Syracuse upland from the Stanton area of the High Plains, in southern Hamilton county. The amount of downward movement is about 150 feet. This post-Ogallala flexure coincides with the south flank of the partly pre-Ogallala Syracuse anticline mapped by Bass (1926, pl. 6, and fig. 16 in this report), and seems to have been at least partly responsible for the southerly dips on the structure.

The evidence for the Syracuse flexure is principally physiographic, and may be examined in the topographic profile (fig. 2A), on the topographic map on the Syracuse quadrangle, and on the generalized topographic map (pl. 2). On the topographic profile, it may be observed that the general level of the plains declines slightly from north to south across the Arkansas valley, from the Kearny area to the Syracuse upland, then drops abruptly to the Stanton area in southern Hamilton county, thereafter to rise regularly and very gradually toward the Oklahoma line, but without regaining its full northerly height. The topographic maps show the contours in the Stanton area to trend slightly west of north up to the base of the

Syracuse upland, where they bend abruptly east, thus marking a pronounced topographic break. Conceivably, this break may represent a product either of erosion or of deformation. A study of the size and spacing of streams in the Stanton area, however, soon leads to the conclusion that post-Ogallala erosion has been very moderate in amount. The streams are few and far apart, and feeble in comparison with the Arkansas, which has carved out a valley that is small in comparison with the lower part of the Stanton area. Furthermore, the westward indentation of the contours in the Stanton area varies inversely with the strength of the traversing streams. The lowest part of the area lies not along Bear creek, a moderately vigorous stream, but along its northern branch, a much shorter and feebler water course. These relations are incompatible with any hypothesis attempting to explain the present topography as a result of dissection and removal of a once thicker Ogallala fill aligned with the top of the Syracuse upland. It is therefore concluded that the observed topographic anomalies represent the result of an abrupt and asymmetrical downwarp of the original Ogallala surface, the trough of the flexure being close against the base of the Syracuse upland.

The rectilinear trend of the north branch of Bear creek (Syracuse topographic sheet) suggests that the flexure was broken by a fault. Northwest of the junction of this branch with the main stream for about 15 miles the course of the tributary is conspicuously linear in comparison with the winding course of Bear creek itself. The trend veers from about N 70° W at the southeast to about N 50° W toward the northwest. On aerial mosaics the linear character of the valley is even more conspicuous and the valley is seen to be marked by a series of depressions, presumably of solutional origin, and localized by the fault. A short *en echelon* fault at the northwest is suggested by a linear tributary valley, also marked by depressions, one of which was formed in historic times, as noted in a later section of this report. It is uncertain what part of the downward movement was effected by faulting—perhaps much, perhaps little.

Eastward, fault and flexure alike die out, and in southwestern Kearny county and northwestern Grant county the Syracuse upland descends to a common level with adjoining sections of the High Plains.

Beyond the fact of its being post-Ogallala, the age of the Syracuse flexure is not entirely certain. On the one hand, it may date back to the regional upwarping at the close of Ogallala time, or, on the other hand, it may have been formed at some later time in a local episode of deformation.

FINNEY BASIN

The Finney basin is a broad and irregular depression in western Finney county. It extends north into Scott county, and is continuous with the Shallow Water basin of that area (Moss, 1933). The bedrock basin has a maximum depth of about 300 feet, and is reflected at the surface by a much shallower topographic depression. Evidence for the bedrock depression is found wholly in well records, as outlined in a preceding section of this report. The topographic depression is a broad, shallow, elongate, asymmetrical feature, extending from Garden City to Scott City. It has no surface drainage outlets, displays no evidence whatever of ancient stream channels, and is dotted with innumerable minor depressions and undrained basins, some of which are almost a mile in length. It obviously cannot be explained as a product of stream erosion, and consequently can be attributed only to post-Ogallala downwarping. As in the case of the Meade trough, the minor depressions are believed to represent solution-and-collapse activity localized by the structural depression.

South of Arkansas river, the land surface fails to rise to the general High Plains level before reaching northern Haskell county (pl. 2, fig. 2B). A broad belt intermediate between the levels of the river valley and of the true upland surface, here designated the Finney sand plain, extends from southeastern Kearny county to central Gray county. This region is marked by a notable expansion in the width of the sand-hill belt, and by an anomalous northeastward bend in the river. It seems far too broad, in comparison with the valley areas to the east and west, to be explained simply as a product of post-Ogallala stream erosion. More probably, it was formed by areal subsidence, continuous with but less regular in outline than that north of the river. This subsidence may have been a factor in leading to the deposition of the Rexroad or Kingsdown or both formations, and it is entirely possible that either or both of these formations covers a part of the area in southern Finney and adjoining counties.

The initiation of the Finney basin seems to date back to Ogallala or pre-Ogallala time, thus accounting for the relatively great thickness of the Tertiary deposits within its area. The later phase or phases of the movement, however, post-date the Ogallala, and antedate the cutting of the present-day valley plain.

ASHLAND BASIN

The Ashland basin (pl. 2) comprises a broad lowland area about 500 feet below the High Plains level. It is drained entirely by Cimarron river and its tributaries. The breadth of the lowland is as much as 12 miles, and thus this basin stands in noteworthy contrast to the narrow Cimarron valley beginning a short distance west. These unusual features were noted by Haworth (1897, pp. 21-22), who attributed the basin somewhat doubtfully to stream erosion alone. Johnson, however (1901, pp. 711-712, 722-724), believed solution and collapse to have been the important factors.

Certainly the lowland is too broad to be attributed wholly to erosion of a once thick cover of Ogallala and redbeds. This would have involved the excavation and removal of a volume of sediment so enormous as to have taxed the transporting power of the Cimarron beyond imaginable limits. Rather it is probable that the work of the stream was made less by a preparatory downwarp of considerable magnitude, and that this, followed by a more moderate amount of erosion, maximum where the structural slope was steepest, and supplemented by more or less solution and collapse, accounts for the present topography. Obviously, this interpretation is in large part speculative, and must await the completion of detailed geologic studies for testing.

RECENT EARTH TREMORS AND THEIR POSSIBLE SIGNIFICANCE

Earth tremors have been felt twice in southwestern Kansas in the last two decades—first in 1925, and again in 1936. Examination of the files of local newspapers in Liberal, Hugoton, and Elkhart has provided the information set forth below.

The first of the two quakes is reported to have taken place at 6:15 a. m. on Thursday, July 30, 1925. Dishes, doors, and windows rattled, and the bell in a switch engine in the railroad yards at Liberal is reported to have tapped. This quake was stronger farther southward, and, according to Udden (1926), its epicenter was near Amarillo, Tex.

The second quake occurred about 9:15 p. m. on Friday, June 18, 1936. It was felt from Morton county to eastern Seward county. At Liberal it was reported that houses quivered, beds shook, and dishes rattled. At Hugoton, the oil-storage tanks along the railroad were said to have swayed for nearly a minute. At least one sleeping man was awakened. At Elkhart, the tremors were feebler and attracted less attention. This quake was reported to have been most intense in the Texas panhandle, suggesting that the epicenter lay in that area.

Although the data are obviously too meager to provide the basis for any positive conclusions, nevertheless the possibility that these earth tremors are genetically related to post-Ogallala crustal movements cannot be lightly dismissed. It is entirely possible either that they represent the delayed readjustments incident to warping long past, or that they are associated with gentle movements now in progress. Certainly too little critical study has been conducted in the epicenter area or areas to test either of these speculations, and the possibilities mentioned invite further investigation.

PHYSIOGRAPHY

PHYSIOGRAPHIC DIVISIONS

Adams, in 1903, classed most of southwestern Kansas as High Plains country, but showed the Smoky Hills upland as entering the extreme northeastern corner of the area, and the Red Hills upland as marking the border of the High Plains at the southeast. Fenneman (1931, pl. 1) maps the area as lying mainly in the central part of the High Plains region, but extending eastward into the Plains Border region. For purposes of local description, the area may be further subdivided. The general nature of these subdivisions has already been noted in the section on topography, and their origin has been considered in part in the sections on stratigraphy and on structure. Here it remains to summarize, systematize, and particularize. The following is an outline of the divisions proposed by me (fig. 19):

List of physiographic divisions of the southwestern Kansas area

- Upland areas:
    - Kearny area
    - Kalvesta area
    - Syracuse upland
    - Stanton area
    - Haskell area
    - Cimarron Bend area
    - Minneola area
    - Odee area
- Intermediate and lowland areas:
    - Pawnee river drainage basin
    - Arkansas valley area
    - Scott-Finney depression
    - Finney sand plain
    - Cimarron valley area
    - Meade area
    - Red Hills
    - Ashland basin

The divisions are based on a detailed study of topography and drainage, together with a consideration of geologic history, so far as known. The broader topographic features involved are shown in the generalized contour map, plate 2, but for details the individual topographic sheets must be consulted. In some places transitions from one area to another are gradual rather than abrupt, and, in the absence of detailed knowledge of geologic history, boundaries must be drawn somewhat arbitrarily. Certain of the boundary lines are therefore to be regarded as provisional, and as subject to revision in the light of such added knowledge as future studies may provide.

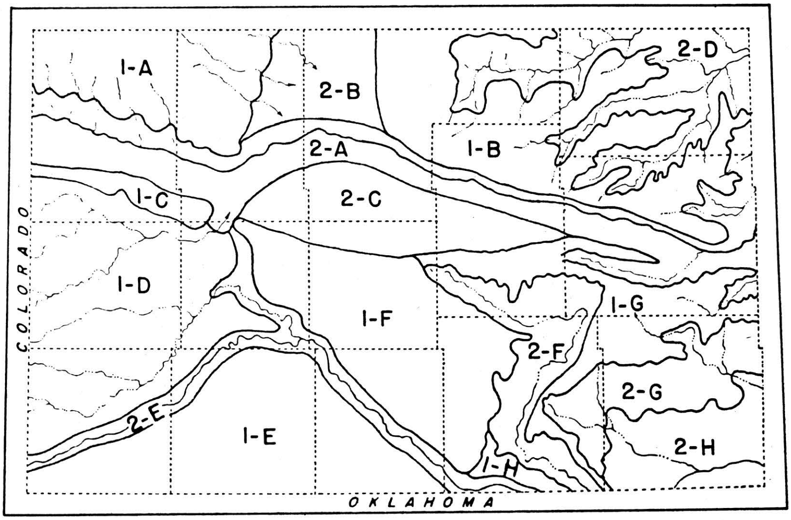

Fig. 19. Physiographic divisions of southwestern Kansas. 1A represents the Kearny area, 1B the Kalvesta area, 1C the Syracuse upland, 1D the Stanton area, 1E the Cimarron Bend area, 1F the Haskell area, 1G the Minneola area, 1H the Odee area, 2A the Arkansas valley area, 2B the Scott-Finney depression, 2C the Finney sand plain, 2D the Pawnee river drainage basin, 2E the Cimarron valley area, 2F the Meade area, 2G the Red Hills, and 2H the Ashland basin.

Upland Areas

The upland areas of southwestern Kansas represent a deformed and dissected depositional surface, mainly on Tertiary formations but partly on Quaternary beds. The several areas differ from one another in amount and direction of topographic slope, in physiographic history, and in details of surface topography. Boundaries between them are controlled partly by stream erosion and partly by post-Ogallala deformation.

KEARNY AREA

The Kearny area lies in northern Hamilton county and northwestern Kearny county, and is named for the latter. It is not limited to the area considered in this report, but extends northward into Greeley and Wichita counties. At the east, it slopes toward and merges with the Scott-Finney depression. At the southeast and south, it slopes toward the Arkansas valley, although in Hamilton county the extent of this valleyward slope is uncertain, owing to lack of any detailed contour map. The area is believed to have been blocked out by post-Ogallala crustal warping, and was cut off from other areas to the south by subsequent stream erosion.

KALVESTA AREA

This area is named for a small settlement in northeastern Finney county. It extends from the Scott-Finney depression at the west into an irregularly digitate set of uplands and divides between the several streams of the Pawnee river and Coon creek drainage systems at the east. Eastward it converges somewhat with the Arkansas valley, and its slope veers from east nearly to east-northeast, owing probably to warping of the original depositional surface. Its slope as a whole is gentler than that in the Kearny area, suggesting that the post-Ogallala tilting was progressively less toward the east.

SYRACUSE UPLAND

The Syracuse upland is a narrow highland paralleling the Arkansas valley in southern Hamilton county. It is named for the town of Syracuse just to the north. It was left in relief by stream erosion at the north and by downbending and faulting at the south. Eastward it converges gradually with adjoining areas.

STANTON AREA

The broad Stanton area is named for the county that it encloses. It extends also into parts of Morton, Stevens, Grant, and Hamilton counties. The Bear creek drainage basin at the north constitutes the lowest part of the area. The southern portion is traversed by a few widely separated shallow valleys, which drain into Cimarron river. The average slope is east-northeast. The area is bounded on the south by the Cimarron valley and on the east by a dry tributary valley. It represents a slightly warped portion of the Ogallala surface.

CIMARRON BEND AREA

The Cimarron Bend area comprises a large area between the Cimarron valley and the Oklahoma state line. It is characterized by broadly undulatory topography, and by the complete absence of surface drainage from any except the marginal portions. There are numerous shallow basins and intervening swells, and many scattered sand-dune areas in various stages of development. Its Quaternary history is somewhat obscure, but probably involved more or less modification of the original Ogallala surface by slight warping, by possible stream deposition, by probable solution-and-collapse activity, and by wind action. The finding of a dip of 13° in volcanic ash in northeastern Seward county lends some support to the likelihood of solution and collapse.

HASKELL AREA

This area is named from Haskell county, which lies in its central portion. Its slopes contrast both in direction and in declivity with those of the Stanton area, being very gentle and dipping to the east-southeast. The area is bounded on the south by the Cimarron valley, on the east by the slopes of Crooked creek valley, and on the north by a moderate break in slope leading down to the Finney sand plain. Although its slopes are mostly regular, many minor irregularities in detail may be seen in the area of the Garden City and Lakin topographic sheets.

MINNEOLA AREA

The Minneola area, named for the town centrally located within it, comprises a sprawling upland in northern Clark county and southern Ford county, characterized by long, irregular projections to the southwest and west. It is separated from the Haskell area at its northwestern tip by a moderate break in slope, and from the Finney sand plain at the north by a similar topographic disconformity of uncertain significance (Garden City and Dodge quadrangles). It is bounded at the south by the Red Hills escarpment, and at the southwest by Crooked creek valley. The area is believed to represent a composite depositional slope on Odee, Kingsdown, and loess deposits, and possibly in part also on older formations. The slopes are essentially continuous, however, thus providing no basis for demarking transitions from one formation to the other. Examination of the topographic maps suggests that there was some broad arching of the depositional surface along an east-west axis in post-Kingsdown time.

ODEE AREA

The Odee area represents the southern extension of the southwestern projection of the Minneola area, severed from that area by the downcutting of Crooked creek. It seems to represent a depositional surface on the Odee formation, modified by the development of many solution-and-collapse depressions and by extensive dune building.

INTERMEDIATE AND LOWLAND AREAS

PAWNEE RIVER DRAINAGE BASIN

This district, comprising the valleys of Pawnee river, Buckner creek, and Sawlog creek, represents a deeply dissected belt in which encroaching streams are gradually destroying the upland. The more rapid progress of erosion here seems to be related to the facts that: (1) the main stream channels are lower than that of the Arkansas, thus providing steeper gradients for dissecting tributaries; (2) the impervious Cretaceous floor of the pervious Ogallala rises above stream grade, thus promoting seepage of and sapping by ground water emerging from the latter formation; (3) the configuration of the bedrock floor seems to be such as to place the ground-water divide close to the Arkansas valley, thus depriving that valley of any but the smallest proportion of subsurface runoff.

ARKANSAS VALLEY AREA

The Arkansas valley area includes all land lying below the High Plains level and sloping toward or draining directly into Arkansas river. It comprises the present floodplain, the terraces (described in later paragraphs), the sand-hill belt in part, and the bordering dissected slopes. The origin of the present course of the Arkansas valley is discussed under drainage history, in the next part of this report. The "perched" position of the valley (fig. 2B, C) with respect to the Cimarron valley at the south and the valleys of Pawnee and Smoky Hill rivers at the north is puzzling. The observed differences in elevation, amounting to more than 200 feet, cannot be explained as a result of Quaternary aggradation, for the valley fill is not known to exceed 50 feet in thickness. Conceivably the relatively greater depth to the impervious bedrock floor along the Arkansas was a factor (see Fenneman, 1931, pp. 23-25). Possibly the volume of sediment carried down from the Rocky Mountains was such as to leave the stream less energy for erosive work, but more probably crustal warping within the Kansas area played an important part in raising, or in preventing the lowering of the stream's gradient along this portion of its course. In any event, it seems probable that the anomalous condition in this area is closely related to events responsible for the Great Bend of the river just to the east. This, however, is a problem beyond the scope of the present paper, requiring for its solution a full knowledge of late Tertiary and Quaternary erosion and deposition within the Great Bend area.

SCOTT-FINNEY DEPRESSION

The asymmetric Scott-Finney depression represents a post-Ogallala downwarp along an axis trending roughly north-south. Numerous solution-and-collapse depressions have been superimposed on the floor of the depression. It slopes irregularly toward the Arkansas valley, but has no surface drainage into that valley.

FINNEY SAND PLAIN

The Finney sand plain comprises a broad, dune-covered area intermediate in level between the river valley and the plains upland of the Haskell area (pl. 2). It may be regarded as the outer part of the Arkansas valley, for it parallels the valley, and together they form a continuous area that lies below the High Plains level. Beginning in Kearny county, the sand plain attains maximum breadth in southern Finney county and northern Haskell county, and wedges out eastward in Gray county. Surface drainage is lacking.

The Finney sand plain is too broad and too irregular to be explained simply as a product of post-Ogallala stream planation. Rather it seems to have been depressed by crustal warping more or less continuous with that responsible for the Scott-Finney depression. It is crossed by certain elongate belts below the general level, which conceivably may represent ancient stream courses, possibly related to the Rexroad or Kingsdown formations (Garden City and Lakin quadrangles).

CIMARRON VALLEY AREA

The Cimarron valley area includes the narrow belt draining into Cimarron river west of Clark county. Its eastward extension is described as the Ashland basin. The cause for the bend in the river's course is discussed under drainage history.

MEADE AREA

The Meade area comprises the drainage basin of Crooked creek. Its anomalous trend is a result of structural control, and its diversified topography was developed by the interaction of faulting, downwarping, stream erosion and deposition, and the solutional work of underground waters. The tectonic movements involved were complex in character, and have not been fully analyzed.

RED HILLS

The Red Hills represent a deeply dissected district in the Permian redbeds and overlying Cretaceous and Tertiary beds, in Clark county and eastern Meade county. The extent of the dissection, in contrast to that farther west along the Cimarron valley, seems to have been controlled by the following factors: (1) the grade of Cimarron river, which constitutes local base level, here lies at maximum depth below the plains level; (2) the relatively impervious sub-Ogallala beds rise well above stream grade, thus favoring the emergence of ground water; and (3) inferred downwarping is believed to have given rise to initial consequent streams of steep gradient, and to have lessened the amount of erosive work necessary to carve out the existing topography.

ASHLAND BASIN

The Ashland basin, named for the principal town within its limits, is a broad lowland crossed by shallow stream valleys. It slopes gently toward Cimarron river. The origin of the basin is obviously related to that of the bordering Red Hills, but has involved considerable stream deposition in its later stages. The history has yet to be worked out in detail, however.

DRAINAGE HISTORY

The drainage history of southwestern Kansas must be considered in relation to that of the central High Plains region as a whole. The stream courses in this region are all believed to be of post-Ogallala origin, and to have been initiated as consequent streams on the differentially upwarped depositional surface of the Ogallala formation (compare Fenneman, 1931, p. 23). These original courses were subsequently modified by piracy to form the existing drainage pattern.

STREAMS NORTH OF THE ARKANSAS VALLEY

The drainage pattern in the area between the Platte and Arkansas valleys, although representing much more territory than is considered in detail in this report, must be considered as a unit. Many of the streams fail to cut through the Ogallala, thus indicating that their origin cannot antedate the deposition of that formation. As there must have been extensive and continuous lateral shifting of streams during Ogallala time, it is evident also that the stream courses cannot antedate latest Ogallala time. All the streams in this part of the region head in the plains, and none receive any runoff from the mountain area. All are essentially parallel to the regional slope, and together they form a semi-radial pattern, diverging from an apical zone in the western part of the Colorado Piedmont (fig. 9). These relations point to consequent origin on the depositional surface, and the pattern itself suggests a broad, fan-shaped uplift of that surface, maximum along an east-west axis. As already pointed out, the physiographic relations of the Ogallala formation in eastern Colorado can be explained satisfactorily only on the basis of differential uplift of the depositional surface, the uplift being along lines inferred from the drainage pattern alone. Since the initiation of the drainage lines, there have been minor modifications. In the Colorado Piedmont, many of the streams within the radial pattern now flow on Cretaceous beds. It seems probable that these may have been superposed from a thin mantle of Ogallala, now stripped away. The sharp bend in Sand creek near the town of River Bend, in eastern Elbert county, where the stream turns abruptly from northeast to southeast, suggests piracy of a former northeastward-flowing stream by a stronger stream from the southeast.

Of the streams within the area of this report, only the unnamed southeastward-flowing streams in northern Kearny county and the Pawnee river system seem to form a part of the pattern described above. It is possible that Pawnee river once extended much farther west, and was continuous with one of the Kearny county streams, later to be dismembered by downwarping athwart its course, but it is equally possible, on the other hand, that all the concerned streams post-date the downwarp, and until the age of that feature is definitely known, uncertainties must remain.

Buckner creek and Sawlog creek depart from the general pattern in showing a northeasterly trend. This, in connection with the north-northwesterly trend of the contours associated, suggests consequent origin on a surface warped divergently from the regional slope, possibly at a later time.

Arkansas River

The Arkansas, alone of the streams in the area, heads in the Rocky Mountains. Its history is probably longer and more complex than that of the other streams, and must be considered in relation to the deposition of the Ogallala beds. Within the mountain area, physiographic studies by Powers (1935) indicate that the present course of the river dates back to pre-glacial time. Its Pliocene history is obscure, however, and much remains to be learned about the physiography of the Southern Rockies. Still there is no reason for doubting that the river's point of issuance from the mountains in Ogallala time was essentially the same as today.

To account for the river's course across the plains, the following hypotheses are presented: (1) stereotyping of a course held in latest Ogallala time; (2) headward extension from some point east of the Ogallala outcrop area; (3) consequent origin by following a trough or series of sags in the post-Ogallala uplift; (4) complex origin, involving combinations of the above, perhaps supplemented by subsequent diversions.

The first of these suggested explanations is readily seen to be inadequate to account for the course of the river as a whole. The late Ogallala streams were aggrading and probably branching in character, and there is a strong likelihood that their waters were dissipated before crossing the depositional area. It is very doubtful whether the course of a stream of this type would have been as straight as that of the present Arkansas. Furthermore, unless by sheer chance such a stream happened to coincide with the trough of the post-Ogallala uplift, its course could hardly have been maintained. This may have been the case in some stretches and perhaps the present river locally does follow segments of late Ogallala stream courses. This possibility seems to apply with less difficulty to the more easterly stretches, where post-Ogallala uplift was relatively mild. Even so, there is a probability that Quaternary crustal movements may have been sufficient to modify that portion of the stream's course, however acquired.

The second possibility, that of headward extension to establish the stream's course, is also untenable except possibly as a local factor applicable to minor irregularities in the trend of the valley. Any adequate explanation for the river's course must take account of the relatively large volume of water issuing from the mountain areas, and this must have been much greater during the glacial stages of the Pleistocene time than at present.

The hypothesis of consequent origin is more promising. The trend of post-Ogallala warping, as indicated on figure 9 and described previously, was such as to elevate areas north and south of the present Arkansas valley, while leaving that district as a broad sag or trough. It is obvious that any water issuing from the mountain area must have sought the lowest path across the plains, and that this would have been provided by the low place or places in the regional uplift. Either the river found its valley ready-made as a continuous trough, or developed it by the integration of a series of sags through filling and overflow. Subsequent dissection in the Colorado part of the plains region has been too deep and extensive to leave much evidence bearing on these details. In the Kansas portion, the evidence for a trough in the post-Ogallala upwarp is even less obvious, for the amount of uplift was less and the resultant relief lower. It seems probable, however, that the present course of the Arkansas represents its original course at least as far as central Kearny county. It is possible that beyond that point there have been shifts and diversions as a result of Quaternary warping. The northward bend in Finney county, for example, may have been caused by one or more diversions produced by continued subsidence along the southern part of the Scott-Finney depression.

The rough parallelism of the river valley and a bedrock depression in part of the western Kansas area is puzzling. Perhaps this parallelism is actually less close than appears on the bedrock contour map (fig. 8), which, because of inadequate data, is oversimplified. On the other hand, it is possible that the position of the river valley was controlled by downwarping along a zone of recurrent subsidence dating back to Ogallala or pre-Ogallala time.

Streams South of the Arkansas Valley

The stream pattern south of the Arkansas valley shows certain anomalies that must be accounted for in any hypothesis as to origin: (1) the parallelism of the northeasterly stretch of the Cimarron, its North Fork, and Bear creek; (2) the abrupt bend in the Cimarron from northeast to southeast; and (3) the abrupt bends in the upper stretches of Crooked creek and Bluff creek (pls. 1 and 2).

The subparallel streams at the west are essentially normal to the contour lines, suggesting that they were consequent on the lower flank of the Sierra Grande upwarp. If that is true, it is probable that, like Bear creek today, the western stretch of the Cimarron and its tributaries originally drained into the Arkansas valley. In that event, their present courses may readily be explained by piracy due to headward cutting of what is now the southeasterly stretch of the Cimarron. Such a stream would have had the advantage of a much shorter distance to trunk drainage lines, and thus a steeper grade. As a matter of fact, Bear creek could easily be diverted to the Cimarron drainage today by a trench about 20 feet deep and a few miles long.

The course of Bluff creek also seems best explained by piracy. The headward stretch of this stream aligns perfectly with a tributary of Rattlesnake creek (see Ashland topographic sheet and pl. 16), suggesting that it once formed a part of that drainage system. This ancestor of Bluff creek, however, must have originated later than the streams in the western part of the area, for it flowed on the Quaternary Kingsdown formation, and presumably was related genetically to the events of late Kingsdown time. The present sharp bend to the south is best explained as a result of piracy by a more vigorous stream of steeper gradient, cutting back from the Cimarron.

The history of Crooked creek is probably more complicated, for it shows more than one anomalous bend. The headward stretches, like those of Bluff creek, seem to be inherited from an ancestral stream draining into the Arkansas, but the course of this earlier stream is not ascertainable definitely. Haworth (1896, p. 371) suggested that it might have passed north of Minneola, thus implying that it may have been continuous with the upper stretches of Bluff creek. An alternative though less plausible interpretation is that it joined Mulberry creek. In any event, the sharp bend in the present stream is best explained as a result of disruption and beheading of the original stream by the Meade downwarp, the south-southwesterly stretch of the stream being consequent on the downwarp. Its development may have involved the tapping of a lake at the north by headward erosion of the stretch at the south. The southeastern bend in Crooked creek farther downstream suggests another case of piracy, but the cause is obscure. Conceivably it may have resulted from the integration of a series of sinks, such as are numerous in the upland strip of the adjoining Odee area to the south.

RIVER TERRACES

Arkansas Valley

Two recognizable terraces occur along the Arkansas valley in southwestern Kansas and it is possible that there are obscure remnants of one or more others at higher levels. The lower terrace, locally referred to as "second bottoms" (Darton, 1920, p. 3), lies about 5 to 8 feet above floodplain level. It is well displayed south of Syracuse, just northwest of Kendall, south of Holcomb, on the southwest side of Garden City, and south of Dodge City. This terrace is included in areas mapped as Laurel series by the Soil Survey (Coffey and Rice, 1912, pp. 77-82). The relation of the terrace to the floodplain suggests that it is of cut-and-fill origin, and of late glacial or post-glacial age.

Remnants of the higher terrace lie about 15 to 25 feet above the floodplain. It is possible that this terrace has some slope toward the river level to which it was graded, and that the interception of the terrace by the present floodplain at different points along this slope accounts in part for the differences in height. Available figures indicate that the average height of the terrace is about 20 feet, and suggest that the height may be slightly greater at the west than at the east. This terrace is underlain by sand and gravel having a maximum exposed thickness of about 20 feet. At Garden City and points west, the underlying Ogallala is exposed, but east of Garden City it generally is not, implying that the bottom of the terrace deposits passes under the floodplain level. The terrace is best exposed on the south side of the river, where, in many places, it forms a low bluff bordering the valley bottom. Elsewhere, however, it is masked by dune sand, or is marked by an inconspicuous transitional slope. The width of the terrace is uncertain, owing to the superimposed sand-hill topography. Probably it averages only a mile or two.

In Hamilton county there are gravel deposits that suggest terrace remnants at elevations of as much as 40 feet above floodplain level. Whether these represent a westward tilting of the 20-foot terrace or belong to a higher terrace unrecognized farther east remains to be ascertained.

The significance of the terraces in Kansas can be determined only through correlations with Colorado, where terrace remnants are more numerous and more prominent. West of the Royal Gorge, Powers (1935) described a series of seven terraces at heights of 20 to 390 feet above present river level. The lowest of the series is post-glacial, the next four fall within the glacial epoch, and the upper two are pre-glacial. East of the Royal Gorge, fewer terraces have been recognized, and correlations through the Gorge are uncertain. During reconnaissance observations, I found terrace remnants at various places in the Canon City quadrangle at elevations of 20, 70, 95, 120, 170, and 195 feet above river level. These represent at least three, probably four, and possibly five distinct terraces. In the Pueblo quadrangle, Gilbert (1897) recognized several terrace levels, but gave no details, and mapped them all together. I measured terraces, however, at heights of 20, 60 to 70, 80, 100, and 135 feet. In the Nepesta quadrangle, Fisher (1906) has mapped two terraces, the lower at about 40 feet, and the upper about 80 feet above the floodplain. Both are rock-cut terraces and both slope toward the river, a condition found also in other parts of the region. Farther east, in the Catlin quadrangle, Toepelman (1924a) has mapped three different terraces. The lowest is stated to have its base about 25 to 30 feet above the floodplain, the middle one about 50 feet higher, and the highest about 40 feet above the middle one. In the La Junta area, Patton (1924) recognized only two terraces. The elevation of the lower one was not stated, but may be inferred, from a comparison of his geologic map with the topographic map, to be 40 to 60 feet. The higher terrace was stated to be about 30 feet above the lower. Toepelman believes that these terraces correspond to his middle and upper levels. East of the La Junta area, no detailed physiographic studies have been made, but reconnaissance by me indicates existence of terrace remnants about 80 feet above floodplain level at Caddoa and near Granada, the latter place being about 15 miles from the Kansas line. Remnants of a low terrace at about 15 to 20 feet were found also.

Conclusions drawn from the foregoing data must be indefinite. Although terraces and terrace remnants are numerous, and occur at several different levels, it is obvious that they cannot be reliably correlated until more detailed field studies have been completed. There is a probability that certain of the terrace levels converge eastward, and that a single terrace level in Kansas may be equivalent to two or more of the Colorado terraces. Possibly the 80-foot terrace of the Granada area is represented by the questionable terrace remnants 40 feet above the floodplain in Hamilton county, or perhaps erosion has destroyed the topographic expression, or dune sand obscured it. The lowest terrace of the Colorado section, at 15 to 20 feet, seems to be persistent, and may correlate with either the 8-foot or the 20-foot terrace in Kansas. In any event, it seems probable that the axis of the Scott-Finney depression may have served as a hinge line in the intermittent uplift responsible for the cutting of the terraces, and that, unless this depression is of more recent origin than supposed, no remnants of high terraces will be found to the east. Thus, although the Pieistocene history of the river is recorded in the terraces, the record is not easily deciphered, and only by continuous correlations from Kansas to the area west of the Royal Gorge, where terraces have been related to glacial stages, is it to be expected that an adequate outline of the history can be prepared.

CIMARRON VALLEY

The terraces of the Cimarron valley, especially the higher ones, are relatively inconspicuous, and in most places their presence is inferred from occurrence of gravel deposits rather than on the basis of topographic expression. Topographic forms produced by erosion in earlier cycles seem to have been destroyed or obscured by erosion in later cycles, so that remnants are few and discontinuous.

In Morton county, 5 miles north and 1 mile east of Elkhart, a deposit of coarse gravel uncovered in a gravel pit may represent a high-level terrace at 70 to 75 feet above the floodplain, almost masked by sand dunes. On the north side of the river 1 mile east of Rolla, another gravel pit is cut in the coarse alluvial cover of a 20-foot terrace.

In northwestern Stevens county, near the crossing of a county road, thin gravel deposits capping an undoubted lower terrace and a probable higher terrace were found at levels of 20 and 55 feet, respectively, above the Cimarron plain.

North of Liberal in Seward county, terrace gravels occur at heights of 40 to 50 feet above river level. Along U. S. highway 54, northeast of Liberal, a thick deposit of similar gravel lies 80 feet above stream level. A possible low terrace lies at 20 feet.

The correlation and dating of terrace remnants along the Cimarron valley must await much additional study. It is evident, however, that post-Ogallala erosion involved more than one cycle of downcutting.

SAND DUNES

GENERAL FEATURES

The sand hills, or dunes, of southwestern Kansas vary greatly in relief, contour, soil cover, and stability. At many scattered points there is now vigorous drifting of free sand and in a very few places there are wide expanses of bare sand. By far the greater part of the area, however, is well covered with grass and shrubs (pl. 20A), and is thus protected from wind attack. The grass-covered dunes range from steep and irregular hillocks to broad, subdued swells. Transitions from the one to the other, and from dune to nondune areas, are abrupt in some places, but elsewhere are so gradual that it is difficult to map boundaries of dune areas. Some parts of the area are suited for cultivation but others are not.

The maximum local relief of the sand-hill areas is about 70 feet, and the average relief is nearer half that figure. Individual dunes range in length from about 100 to 450 yards, but a few exceptional forms reach a length of 1 mile or more.

The dune areas are all alike in having no surface drainage. Local rainfall is absorbed or accumulates in the innumerable hollows, there to be dissipated by evaporation or seepage. Streams entering the dune belt from bordering slopes are almost all lost within a short distance.

On the ground, the dune areas show everywhere a repetition of the basic alternation of hills and hollows, but with endless variations in shape and size. In some places there are smooth, well-rounded forms, but in other places there are abruptly varied shapes. Little system can be discerned, and the topography as a whole seems best described as chaotic.

Available topographic sheets contribute little to a better picture of dune topography, and fail to give any adequate concept of dune morphology. On aerial photographs and mosaics, however, minute details of form are distinctly shown, and some pattern may be distinguished. Forms are forked, hooked, corded, pitted, furrowed, looped, reniform, amoeboid, and irregular. Patterns are reticulate, nucleate, and jumbled, they range from coarse to fine.

Only a preliminary account of the general features of dune history is essayed now, a more extended analysis of the dune forms, and comparison to other dune areas of the world, being reserved for a later paper. In succeeding paragraphs, modern wind work is described, then a general scheme of dune development is outlined, and finally the questions of sand source and wind direction are considered.

MODERN WIND ACTION

Eolian action of today seems to be partly a continuation of activities long in progress under natural conditions, and partly a consequence of abnormal conditions more recently inaugurated by widespread farming and grazing. The former comprises the development of minor blowouts in older grass-covered dunes, and the continued modification of certain younger dunes not yet stabilized by vegetation. The latter includes a considerable range of phenomena, from minor sand drifting to the development of true dune forms. The results of natural versus unnatural conditions are generally distinguishable, sometimes strikingly so. Both are described below.

SAND DRIFTS RELATED TO CULTIVATED FIELDS

Familiar sights in the "Dust Bowl" are the fence-line and hedgerow "dunes" (pl. 21A, B). These result from the surficial erosion of a thin layer of soil from a broad surface loosened by cultivation. Hedges, weed-choked fences, or other obstacles trap the drifting material and give rise to an essentially stationary type of dune. In some places, the buildings of farmsteads have caused sand accumulation on a considerably larger scale, with unfortunate consequences for the occupants (pl. 21C). "Dead air" spaces associated with trenchlike road and railroad cuts provide another effective type of sand trap, leading commonly to the accumulation of sufficient sand to block or displace the line of travel. In Stevens county, the sand must frequently be plowed from the railroad tracks along many stretches to keep the lines open.

In some places, where no definite obstacle is encountered, drifting sand locally spreads over the ground as a thin sheet, overriding and destroying such crops as lie in its path (pl. 22A).

TABLE 4. Mechanical analyses of wind-drifted soil material, giving size of grains in millimeters.

SIZE GRADE.	Sample number.		
	1*a*.	1*b*.	2.
1.0 —0.5	1.06	0.0	0.05
0.5 —0.25	12.1	12.5	8.2
0.25 —0.125	18.6	40.0	36.0
0.125—0.062	45.4	30.5	28.7
< 0.062	22.9	17.0	27.1

Location of samples: (1) Hedge-row dune 2 miles east of Johnson (pl. 21); 1*a*, Partly compacted "dirt" from south side; 1*b*, Loose, mobile "dirt" from north side; (2) Fence-line dune along U. S. highway 50N, northeast of Garden City (surface loose).

None of the samples were subjected to disaggregating procedure, but some attrition probably took place during shaking.

Drifts of the types described are produced both from sandy soil and from silt-clay soil. The former in many places represents old dune sand, and, once started, drifts the more readily of the two. As soon as "blowing" is well under way, a surface of reduced resistance is developed, and much additional material is released by sand abrasion. The silt-clay soil is somewhat more stable. The drifts or dunes derived from it are made up partly of silt or clay pellets rather than of true sand. Such material, when soaked by rain water, tends to become more or less compacted and stabilized by the bonding action of the redistributed clay particles. Mechanical analyses of the material from two representative sand or dust drifts are tabulated in Table 4.

The material in all samples is somewhat dark, owing to the presence of organic material. In the fractions between 0.5 and 0.062 mm from samples *1b* and *2,* microscopic examination showed that 10 to 40 percent of the material consists of pellets or granules of silt and clay, rather than of true sand grains. In sample *1a* the percentage is smaller. This sample more nearly represents the true composition of the soil material, having been subjected to the action of rain water and weathering processes subsequent to eolian movement, thus leading to partial breakdown of the original clay pellets. Analyses of samples *1b* and *2* resemble those for typical dune sand (Wentworth, 1932, pp. 12-19) in showing maxima in the 0.25- to 0.125-mm fraction, but differ in the larger proportion of finer material.

SAND DRIFTS ALONG STREAM CHANNELS

Along the floodplain of the Arkansas, no dunes or sand drifts were anywhere observed to be forming. Eolian action has been limited to the rippling of exposed channel sands. Along Cimarron river, however, some sand drifting is in progress, particularly in Morton and Stevens counties. North of Elkhart, considerable sand is being heaped up on the south bank of the river, and a minor amount has been drifted locally on the north bank. Farther east, in Clark county, there seems to be some minor drifting of sand on the north bank also. These phenomena are undoubtedly of very recent inception, for as pointed out in a later section of this report, the Cimarron channel was not such as to have provided a source of free sand when the area was first settled.

BLOWOUTS

At many places in the sand-hill areas, grass-covered dunes are pitted or notched by small though active blowouts (pl. 22B). These lend a distinctive character to the landscape, and contribute to the scenic diversity of the dune areas. There is no reason for believing that this aspect of wind action has been limited to historic time, although it seems probable that it has been accentuated since the coming of white men.

Blowouts of a different and much larger type are found in many places where farming has been attempted in old, subdued dune-sand areas. On aerial photographs, these blowouts stand out as bare, white patches of elongate, rudely lobate, or irregular outline. They range from a few hundred feet to more than half a mile in length, and are broad in proportion. The soil may be eroded to a depth of several feet, thus involving more intense wind scour than that responsible for the ordinary fence-line dunes. Either an irregularly pitted surface or a shallow basin may be produced (pl. 22C). Additional sand is released continually by the abrasive action of wind-driven sand already present, and the denuded floor of the depression, where composed of semi-indurated material, commonly displays the miniature fluting, pitting, and studding characteristic of wind-etched surfaces (pl. 23A). The sand thus freed accumulates as an irregular sheet, as a series of drifts or humps (pl. 23B), or as a broad mound on the leeward side of the source area. The combined loci of erosion and of deposition, by reason of the broad area and comparatively low relief of the features involved, may be designated as an *areal blowout,* in contradistinction to the relatively deep and narrow form of the smaller blowouts.

BARCHANS AND TRANSVERSE DUNE RIDGES

In a few of the larger areal blowouts, transverse dune ridges and barchan or sub-barchan forms have developed. These attain a maximum height of about 20 feet. They are especially well displayed at localities in southwestern Kearny county (sec. 27, T. 25 S., R. 38 W.) and in central Hamilton county (sec. 28, T. 24 S., R. 41 W.). At the former locality (pl. 23C) these dunes were reported to have been formed during the last few years. Two abandoned windmills near the center of the dune area suggest that the trampling of stock was responsible for breaking the sod cover and allowing wind action to start.

Comparison of the profiles of dune ridges and barchans of various sizes, and of the profile at points of different height along the same dune, indicates that the profile of the dune varies with its height. No steep leeward slope was found on dunes less than 3 feet high. Above that height, the relation of the lee slope to the gentler windward slope varies systematically. On low dunes, the rounded windward slope curves over the top and bends down the opposite side before intercepting the angle-of-repose slope. On dunes somewhat higher, the windward slope simply flattens out on top before meeting the lee slope. On dunes still higher, above 15 feet, the windward slope rises continuously and meets the lee slope at a sharp crest. This suggests that there is a gradual and continuous transition from a low, rounded sand heap to the typical sharp-crested dune form, thus according essentially with the observations of Oldham (1903) in India and of King (1918) in the Libyan desert.

The crest of the typical migratory dune is a puzzling feature. Although the reason for its perpetuation, once formed, is not difficult to understand, the cause for its inception is less clear. I suggest that the initiation of the steep leeward slope is due to a transition from laminar to turbulent flow of air currents, and that, for winds of a given velocity, which would be the maximum velocity at any particular locality, there is a critical dune height at which laminar or streamline flow breaks down on the foreward slope of the dune, leading immediately to the dropping of such sand as may be in transit, at the angle of repose. Once initiated, the break in slope itself would probably induce turbulence in winds of less than maximum velocity, and thus perpetuate itself. This hypothesis is consistent with the observations of Whitfield (1939), who found that artificial reduction of the crest and lee slope of a dune, by means of a drag pole, allowed sand to be carried well beyond the dune and, in the absence of new additions of sand from the windward side, led to a marked lowering of dune height. This suggests the restoration of laminar flow. Obviously dune growth can take place only when the winds reaching the dune are already more or less "loaded" with sand. When the winds are fully loaded, dune growth should involve simple leeward extension without any corresponding shift of the windward slope, or perhaps with slight retrogressive banking of sand on that slope. When the approaching winds are underloaded with sand, moderate erosion may be expected on the windward side of the dune, followed by deposition of sand thus acquired plus sand already carried, on the leeward slope, leading to differential movement of the dune as a whole, more rapid at the front than at the rear, thus involving an increase in the breadth of the dune. Under either of these conditions of dune growth, it seems that the point of inflection in the profile gradually should shift toward the top of the dune, perhaps in relation to the stronger wind velocity encountered at greater height above the ground surface, where the retarding effect of frictional drag dies out. When the winds reaching the dune are carrying virtually no sand, maximum erosion on the windward slope is to be expected. If turbulence sets in at the crest or on the leeward slope, the sand thus won would be dropped, and the dune would advance uniformly, without lagging of the tail, but under conditions of laminar flow over the entire dune, there would be no abrupt dropping of sand, and the results reported by Whitfield would be in order. A more extended analysis of the aerodynamics of dune building, however, must be reserved for later papers.

In one locality, bare transverse dune ridges of much larger size and greater extent than those described above are found (pl. 27), and are believed to antedate the settlement of the area. These dunes are found in a belt about 1.5 miles wide and about 4 miles long on the south side of the Arkansas valley beginning just west of Syracuse. They constitute the largest expanse of free dune sand in the state of Kansas. They have the appearance of great waves of sand as much as 30 feet high, and nearly a mile long. Individual dune ridges trend approximately east-west, and range in plan from rectilinear through curvilinear to undulatory. Along the margins of the main belt, the sand ridges break down into smaller sub-barchan, lobate, and irregular forms. These dunes are being imperceptibly modified by every strong wind, and the sand is gradually being moved toward the river. They occur in an older dune belt, and seem to be of secondary origin, having been formed in much the same way as the smaller dune ridges of more recent origin, but on a far larger scale and under natural conditions. They are believed to represent the culmination of blowout action.

An area of somewhat similar dune ridges, but separated by strips of vegetation, and seemingly in process of stabilization, occurs in Kearny county a few miles southwest of Hartland.

THE SAND-DUNE CYCLE

The wind action that has been described mostly represents only a minor and superficial modification of a much older dune topography. The history of this antecedent dune mass is complex, and may best be understood in terms of an ideal cycle of development (Smith, 1939). This developmental scheme is based partly on deductions from the internal structure of old dunes as revealed in various cuts, partly on inductive reasoning directed toward the linking of diverse forms in some orderly genetic sequence, and partly on analogies with current forms and processes, as no true homologues for certain of the original dune types are now definitely known to be in course of formation within the area. It must be emphasized that the wind work of today is insignificant in comparison with that at various times in the past, and that dune forms now being built under natural conditions are on a scale much smaller than that of the original dunes. It is probable that the major dune-building episodes of the past took place under climatic conditions very different from those of the present.

The dune cycle embraces two distinct phases, characterized by different processes: first an *eolian,* or active stage, and, second, an *eluvial,* or passive phase. During the eolian phase, the dune is built up. Stabilization by vegetation introduces the eluvial phase, throughout which the dune is protected from wind attack, and undergoes gradual wastage through weathering and creep. This second phase of the cycle, however, is subject to interruption through rejuvenation, whereby wind action is resumed and a new cycle inaugurated. In this second cycle, and in any subsequent cycles, the two phases of the initial cycle are repeated, though with variations in the stages attained and in the resultant morphology.

EOLIAN PHASE

The initial dune cycle begins with wind scour on some bare sandy surface. This develops into a *primary blowout,* which is of the *areal* type. It consists of two parts: (1) a zone of sand removal, and (2) a zone of accumulation. Illustrative are the fence-line and hedge-row dunes and artificially induced areal blowouts already described. Topographic expression in the zone of removal depends on whether the source of sand is replenishable or nonreplenishable. The former condition exists only along stream channels or lake shores, and no lasting topographic expression is to be expected. Where the source is nonreplenishable, which is probably the more common case, either a wind-swept pavement or a wind-scoured hollow is produced, depending on the duration and intensity of wind attack, and on whether the locus of removal is stationary or migratory, confined or expansible.

The zone of accumulation is marginal to the sand source, and is commonly controlled by the vegetal mat, as witnessed both by observations on modern wind action and by analogous interpretation of rude casts of plant stems or roots in old, dissected dunes. Accumulation may begin as a sheet or drift of sand (pl. 23B), or may early take the form of a mound or ridge, according to the degree of resistance offered by the vegetation. In either case, a mound of some type generally develops sooner or later if accumulation proceeds. It may grow by the addition either of foreset, topset, or backset beds, or by combinations of these, depending on the equilibrium between the rate of plant growth and the rate of burial by sand. Steep foreset beds develop only when sand is swept in more rapidly than plant growth can keep pace, hence to meet with little resistance and be carried over the crest of the dune and be deposited on the leeward side at the angle of repose. Such bedding is very rare in the area under discussion, having been seen at only one place (pl. 26A). Backset bedding, the common type, is developed when plant growth keeps ahead of the influx of sand, thus to trap the sand and cause it to bank up, layer upon layer, on the windward side (pl. 26A). This type of bedding has a low angle of dip, and involves retrogressive growth of the dune, in the direction from which the wind is blowing. Topset beds may be laid down over either of the other types, and may be essentially continuous with the backset beds, differing only in their position at the top of the dune and in their essentially flat dip. Examination of numerous cuts through old dunes shows the backset type of bedding to be the prevalent one of the region. The original dunes grew upward and backward by accretion, under the continuous influence of vegetation, and were fixed in position from the beginning. Dunes so formed, or otherwise developed under the governing influence of vegetation, are here classed as *phytogenic.**

In ground plan, the primary blowout ridge is controlled by the shape of the source area and by the degree of differential erosion and accumulation during formation. Unmodified primary dune forms are extremely uncommon in the area studied, unfortunately, and their outline is largely a matter of conjecture. In one locality, however, south of Englewood in southwestern Clark county, presumably true primary forms occur (pl. 25). Their form ranges from roughly U-shaped to irregular, and probably corresponds to that of the so-called parabolic dunes of certain European writers. A progressive rather than retrogressive type of development is suggested, thus leaving some doubt as to whether they are representative of the still earlier generation of dunes of more widespread occurrence.

ELUVIAL PHASE

Primary blowout activity ceases and the eolian phase of the cycle comes to an end when plants in and around the dunes are enabled, through temporary climatic advantage, to spread sufficiently to cover completely and to stabilize the sand-swept area. This transition

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* The term phytogenic, signifying building through the agency of plant growth, was selected with the help of Professor Emeritus M. W. Sterling, of the Department of Greek at the University of Kansas.

may be either abrupt and general or protracted and progressive. In the latter case, continued wind action on the blowout mound after the source area was stabilized may have an important effect on the final dune form.

After stabilization there begins the eluvial, or passive phase of the cycle, and the gradual degradation of the dune. Henceforth the main processes are soil building and soil creep. The incoherent sands are bonded together by silt and clay released through chemical weathering of silicates, and by organic material accumulating from the decay of vegetal matter. Some additional fine material may be added by dustfalls. The essential nature of these changes was recognized by Coffey and Rice (1912, pp. 51-52), who wrote that—

> When the sand hills become stationary, weathering immediately begins to work changes in the character of the soil. A large proportion of the sand grains are feldspar and minerals other than quartz, and they break down readily and undergo chemical changes with comparative rapidity when exposed to weathering. While the original material varies in composition, the dune-shaped hills, which are now stationary, must owe their present loamy character to the decomposition of the sands once loose and incoherent. In some localities the hills have long been stationary and the dune-like contours have been modified by weathering and erosion.

As a result of mass creeping of sand and soil downslope, relief is decreased, the slopes are reduced, and the original blowout hollows and interdune depressions are gradually filled. The dune mass is lowered and spread out. Contours are rounded and simplified. These changes are essentially gradational and continuous throughout, but for convenience the eluvial phase may be somewhat arbitrarily divided into stages of *youth, maturity,* and *old age.*

During youth, a soil zone is formed and the steeper slopes are lowered. Youth is a transitional stage, somewhat precarious in character, and subject to easy reverses. Passage into maturity may be said to occur when the entire dune presents a smooth and regular profile. Breaks in slope are eliminated, angularities smoothed, and symmetry established. During maturity the major amount of degradation is effected, and the soil becomes thicker and more stable, sufficiently stable in some places to permit judicious cultivation. The slopes become less pervious, giving rain wash and even gullying greater opportunity to supplement the work of creep. The final transition to old age may be said to occur when the original form of the dune has become unrecognizable (pls. 26B, C and 24). Thereafter the same processes continue, but with waning vigor. The landscape is characterized by broad and gentle undulations, which, as time passes, grow fainter and fainter. In this stage, there is a likelihood that drainage integration may be effected—integration of inter-dune basins with one another, and with outside drainage.

The stages outlined, although not necessarily of the first cycle, may be roughly correlated with the units mapped by the Soil Survey (Coffey and Rice, 1912). Youthful dunes, together with dunes still in the eolian stage, are mapped as Dunesand. Mature to old-age dune areas are included in the Richfield sandy loam, the Pratt sandy loam, and the Pratt loamy sand. The Richfield sandy loam, however, includes also some material that is not of eolian origin.

INTERRUPTION OF THE CYCLE

The eluvial phase may be interrupted at any stage by rejuvenation, and the eolian phase of a new cycle initiated. Wind attack may be renewed whenever the vegetal mantle is locally weakened or broken, as by drought, prairie fires, the trampling by herds of buffalo or cattle, lowering of water table incident to stream incision, cultivation, or other factors. As a result, *secondary blowouts* develop, and primary dune forms undergo dissection and reworking. These secondary blowouts are of three general types, all gradational into one another: the spot, the linear, and the areal types. The spot blowout is simply a pit or crater-like depression near the top of a preëxisting dune mound or ridge (pl. 22B). It may grow into a linear blowout, which is a steep-sided, elongate, trough- or scoop-shaped depression, deep in proportion to breadth. The sand blown from this excavation may be spread out as a fan or apron, or may be heaped in a secondary mound or ridge, depending on the slope of the older dune and on the resistance of the vegetation. Where individual blowouts of this type are closely spaced, they may converge laterally, even to the extent of entirely obliterating the original dune topography and giving rise to a new generation of dunes. The transverse dune ridges west of Syracuse (pl. 27) were probably formed in this way.

The areal blowout (pl. 22C), in contrast to the other two types, is similar to the primary blowout of the first cycle. It is very shallow in proportion to breadth, and is irregular in outline. It is formed most readily where the preëxisting dune topography was of low relief. In rare instances, vegetation may be so completely overpowered as to permit the rise of barchans or of transverse dune ridges, as in certain abandoned fields in the "Dust Bowl", such as those described here (pl. 23C) and those reported by Whitfield (1939). The end product of this type of blowout may be indistinguishable from that produced by the aggregate effect of many closely-spaced blowouts of the linear type, but the intermediate stages are very different.

Secondary blowouts, like their primary precursors, may be halted at any point by stabilization. When this takes place, the eluvial phase begins anew, and proceeds as before. Blowout scars are healed and topographic discordances incident to secondary wind sculpture are gradually smoothed. Eventually, barring interruptions, the markings of rejuvenation are obscured, and the end forms of the second cycle come to resemble those of the first cycle, differing only in the texture of the topographic pattern if at all.

MULTI-CYCLE DUNE TOPOGRAPHY

Given time enough, and freedom from external interference, the dune cycle may be repeated as many times as conditions permit. A multi-cycle topography, indeed, is characteristic of the area under consideration. The sequence of events in different localities may be different, however. New, first-cycle dunes may spring up in one place while earlier dunes undergo the vicissitudes of advanced age elsewhere, and the dunes of one locality may proceed uneventfully toward eluvial old age while neighboring localities undergo one or more episodes of rejuvenation. Examples of this are found in the dune belt south of Garden City (pl. 28). Heterogeneity seems to be the rule. Although local and sporadic wind action has been in progress much of the time, it is probable that the major periods of dune building were of general effect, were distinctly separated in time, and were related to climatic fluctuations of regional importance. No detailed analysis is attempted in this paper, however.

In interpreting dune topography, it must be remembered that it is only the records of partial cycles that survive in the lineaments of the final landscape. Each complete cycle destroys all topographic vestiges of its predecessors. Stratigraphic indications of earlier cycles, however, may be preserved as soil zones or unconformities in the dune, and it is only from this type of evidence that the earlier history of many dune areas is likely to be worked out.

Thus through the continued interplay of wind, sand, and vegetation the dune complex of southwestern Kansas was evolved. So far as known, the dunes were essentially fixed in position in the beginning, were never of the truly desert type, and assumed their distinctive characteristics through the all-important role of vegetation.

AGRONOMIC IMPLICATIONS OF THE DUNE CYCLE

As a dune area progresses through the eluvial phase of the cycle, its soil cover becomes progressively thicker and more stable, and eventually may permit cultivation. This depends partly on climate, however, so that, in the eastern part of the area, it seems probable that the safe point for breaking of the sod comes earlier than in the western part, where rainfall is less, and the strength of the wind may be greater. In late youth and early maturity, the dune is obviously not yet ready for any type of cultivation. It may, however, be used for grazing, provided that care is taken to prevent overgrazing and excessive localized trampling, as around watering places. In advanced maturity or old age, according to the climatic belt in which the dune lies, the soil is sufficiently deep and sufficiently well bonded with silt, clay, and organic material, and slopes are sufficiently gentle, to allow farming if sufficient care is exercised. Any local spots where the topography has been set back in the cycle by rejuvenation are to be avoided, however, for they represent vulnerable points where "blowing" is easily started. Until the dune mass as a whole is well advanced in old age, more than ordinary care must be exercised in farming practices, for even in the early-old-age dune area of northeastern Meade county several large areal blowouts of recent origin, some having sharp fence-line boundaries, may be observed. During periods of drought, or at places of very low rainfall, as in eastern Colorado, it is probably unsafe to attempt cultivation of dune-sand areas, however far advanced in the cycle.

HYDROLOGIC IMPLICATIONS OF THE DUNE CYCLE

The effectiveness of dune areas for ground-water intake and recharge varies with their position in the cycle. The more advanced their place in the cycle, the less pervious the soil, and the less readily is rain water absorbed. Thus in maturity and old age, infiltration is reduced, and the amount of surface runoff is increased. The latter, having no outlet to the exterior, accumulates in the interdune depressions, forming temporary ponds, from which a part of the water is lost by evaporation. The more advanced the eluvial development of the area as a whole, the broader and shallower are the depressions, and the greater the loss from this cause.

SOURCE OF THE DUNE SAND

The dune sands of southwestern Kansas seem to have been derived from sources very close to their present position. There is no reason for believing that truly migratory dunes of the desert type were ever important, for the steep leeward bedding associated with such dunes is extremely rare. Even where present, this type of bedding does not necessarily imply dune migration, but may simply represent headward growth of an essentially static dune. It might be argued, of course, that migratory forms were once common, but were completely destroyed by blowout activity during progressive fixation. Although it is true that the topographic form of the dune could thus be effaced, it seems unlikely that there would have been such complete reworking as to destroy internal structure, and consequently this possibility may be dismissed for want of any substantiating evidence.

It remains, therefore, to discover a near-by source for the dune sand. It has been assumed by some previous writers (Darton, 1916, p. 42; 1920, p. 3) that the present river floodplains constituted this source. Along the Arkansas valley, this is certainly not true, for no movement of sand from the channel toward the dune belt is to be observed. In fact, there are few if any dunes of any consequence either on the floodplain or on the lowest terrace, and the dune belt is far too wide to have been supplied from the present valley unless there was extensive movement of migratory dunes. The dune belt on the south side of the river overlies the 20-foot terrace along the strip nearest the river, and extends southward onto higher ground. It is probable that the sand was derived at least in part from the terrace deposits, but it is uncertain whether dune building took place when the present terrace was still a part of the floodplain, or after downcutting to a lower level. Toward the southern part of the dune belt, there was probably a different source or sources of sand. At different places the sand may have been provided by older and higher terraces, as yet unrecognized, or by Rexroad or Kingsdown sands, or simply by denuded slopes cut in the Ogallala formation.

The source of the dune sand in the small, scattered areas north of the Arkansas valley is uncertain. It is unlikely that the Ogallala could have contributed unless the hard calcareous beds at the top were first eroded away, so as to uncover the softer sand beds below.

The sand of the small dune belt of Stanton county was probably derived from Bear creek when that stream flowed at a higher level.

The dunes of the Cimarron Bend area present a problem. In the belt within the river valley at the west, the materials were probably derived from floodplain and terrace deposits. On the broad upland areas, however, the source is uncertain. Possibly a part of this area is covered with post-Ogallala fluviatile sands. Possibly solution-and-collapse basins affected the development of ponds at some time in the past, and led to sufficient reworking of surrounding Ogallala beds to release some sand to be picked up by the wind.

The high-level dune belt in eastern Seward county and southwestern Meade county may have had a source similar to that in the Cimarron Bend area, or may have been related to high-level deposits of Cimarron river. The dune belt in southern Meade county, however, seems to be superimposed on the depositional surface of the Odee formation, and probably derived its sand from that formation.

The dunes in northeastern Meade county are closely associated with Crooked creek valley. It is possible that the sand was derived, either wholly or in part, from the strand flats of a lake, which, it is believed, may once have occupied a part of the basin. At the one point where a dune is well exposed in cross-section, the dune sand overlies a soil zone on loess, and its bedding shows a low westerly dip, suggesting that the sand came from the west.

The sand of the dunes in southern Clark county was undoubtedly derived from fluviatile deposits of Cimarron river and Big Sandy creek. At least in part, the dunes were probably built when these streams were flowing at higher levels than at present.

Direction of Dune-building Winds

WINDS OF THE PRESENT

The effective sand-moving winds of the present time, contrary to opinions previously stated, are predominantly southerly. Evidence for this, in fact, was mentioned by Haworth (1897b, p. 279), but seemingly was underrated. Along the Arkansas valley west of Syracuse, it is clearly seen that the steep leeward sides of the transverse dune ridges face north, and that sand is now being drifted toward the river. Similar evidence is presented by recent blowouts in many other parts of the area. In some places, however, a subordinate amount of sand has been moved in the opposite direction, as along Cimarron river north of Elkhart. Such sand movement is more or less irreversible in part, for the sand is generally trapped by vegetation, and is protected by that vegetation from return drifting by reversed winds. Thus persisting, this sand reveals the effects of northerly winds despite the greater strength of southerly winds.

WINDS OF THE PAST

The dune-building winds of the past, in the greater part of the area, were from a direction opposite to that of the winds now effective. The great extent of the dune belt on the south side of Arkansas river, in contrast to the absence of any but a few small patches on the north side of the valley, itself points to development by winds from the north. The testimony of dune bedding agrees, for where low-angle backset bedding is to be seen, it commonly shows a northerly dip (pl. 22C). It is evident that dune-building dates back to a time when wind movement was different from that of today, and it is suggested that the presence of a continental icesheet during one or more of the Pleistocene glacial stages would have provided a ready cause for altered wind directions.

At exposures in northeastern Meade county and in eastern Seward county (pl. 26A), the apparent dip of backset bedding is westerly. This may indicate winds of intermediate direction during an intermediate interval of dune-building (compare Melton, 1938).

Along the Cimarron valley in Clark county, and along Beaver river in Oklahoma (Gould and Lonsdale, 1926, p. 13), the dune belt lies on the north side of the valley. This suggests either that the northerly winds were less effective at these latitudes, or that the dunes in these areas were formed more recently, after the prevailing wind system of today had been established. The early mature U-shaped dunes south of Englewood (pl. 25), for example, indicate a wind direction differing little from that of the present. These dunes may correspond to the intermediate series described by Melton (1938) from the southern High Plains. Correlation with his oldest series, however, is uncertain.

SINKS AND DEPRESSIONS

SINKS DEVELOPED WITHIN HISTORIC TIME

At least two sinks are known to have developed in the area within the last 70 years. The more recent of the two is situated in southern Hamilton county, about 11 miles south of Coolidge (NE corner sec. 22, T. 25 S., R. 43 W.). This sink is reported to have been formed in 1929 (Bass, 1931). Originally, it is said to have had a diameter of only about 60 feet, and lay just beside a county road. Subsequently its diameter has increased to about 200 feet, and it has engulfed the road, necessitating a slight detour. When visited by Bass in 1930, the sink was 40 to 50 feet deep, had overhanging walls, and contained a shallow pool at the bottom. Today, it is filled with water to a level within about 10 feet of the ground surface (pl. 29A), and the rim has been modified by slump and by short, steep gulleys. There is no visible overhang.

Bass (1931) postulated that this sink was formed by solution of the Greenhorn limestone. Landes (1931), however, presented evidence that the solution more probably took place in pre-Dakota salt or gypsum beds. Bass suggested that the sink represents renewal of movement in an older, broader sink, and I found, from examination of an aerial mosaic, that it is but one in a linear series of sinks, the relations of which are such as to indicate that it occurs along the line of a post-Ogallala fault.

The other sink of historic origin is situated on the east side of Crooked creek valley, less than 2 miles south of Meade (Johnson, 1901, pp. 706-710). It was formed in 1879, and was known locally as the "Salt Well", having filled with strongly saline water to a level about 14 feet below the ground surface. For a time it was used locally as a source of salt (St. John, 1887, p. 135). When described by Johnson in 1901, the Salt Well was a cup-shaped depression 150 to 200 feet in diameter, and about 35 feet deep to the level of standing water, which was 9 feet deep. The sink was surrounded by a broad zone of roughly concentric sod cracks. Further details may be found in Johnson's excellent photographs, map, and description. Today, the appearance of the sink is very different. The sides are deeply gullied, and the bottom has been filled, containing now only a shallow pool of stagnant rain water.

This sink is believed to have been formed by solution of underlying Permian salt beds. According to Johnson, a test well on the rim encountered bedrock at a depth of 292 feet, and gave strong indications of salt in the next 16 feet.

Other sinks may have formed within historic time, but have received less publicity. A phenomenon probably related is the development of deep cracks in the ground. Such a crack was formed across a county road near the edge of the upland about 6 miles north of Ashland, in 1938 (pl. 29B). The observed crack was as much as 8 feet deep and 2 feet wide. Considerable fill was necessary to make the road passable. Similar difficulties were encountered on the state highway through Big Basin, described below.

BIG BASIN AND ST. JACOB'S WELL

Big Basin and St. Jacob's Well, in western Clark county (secs. 24 and 25, T. 32 S., R. 25 W.) are perhaps the best known and most accessible of Kansas sinks. Both were figured by Johnson (1901, pls. 134, 135), and his photographs have been reprinted in other publications to illustrate solutional topography.

Big Basin (pl. 30) is a subcircular undrained basin about 1 mile in diameter and about 100 feet deep. It is crossed by U. S. highway 283. The rim on the east, south, and west sides is notched by small gullies, and at the north there are deeper and longer ravines, which probably represent beheaded segments of streams that crossed the site of the sink before subsidence took place. Except for minor undulations, the floor of the basin is essentially flat. At times it contains shallow, wet-weather ponds. In the sides of the basin, Permian, Cretaceous, and Tertiary rocks are exposed. Near the east side of the basin, a renewal of the downsinking is indicated by a small, steep-sided hole in the floor, seemingly of very recent origin. On the sides of this hole, moderately coarse gravels are exposed.

Although Big Basin is undoubtedly of solution-and-collapse origin, it is uncertain whether it was formed by large-scale or by piecemeal downsinking. Its close association with smaller sinks at the southwest and at the east suggests the possibility of gradual coalescence of a cluster of smaller sinks, although its outline is less irregular than might be expected on that basis. In any event, the floor of the basin has undoubtedly been smoothed by the deposition of a veneer of fluvial sediments carried in by the streams from the north and by the gullies around the other sides.

The age of Big Basin is geologically not great, but undoubtedly ranges back several hundreds or even thousands of years. Some time must have been required for the streams at the north to have cut down from their original grade to the level of the basin floor, to which they are now graded.

St. Jacob's Well is a smaller sink, just east of Big Basin. The "well" is a deep pool of standing water. The sides of the sink are deeply gullied, and its age may be equal to that of Big Basin.

OTHER DEPRESSIONS

Shallower and less striking basins than those described above are extremely common in many other parts of the area, and occur to some extent virtually everywhere in the upland areas. They are especially numerous, however, along the Scott-Finney depression, and in the Odee district (see Meade topographic sheet), where some are as much as 1 mile long, but are shallow and saucer-shaped in contrast to Big Basin. Some hold temporary ponds, and many have a marshy type of vegetation. These depressions are probably a result of subsidence due to solution of salt or gypsum beds in Permian or early Mesozoic formations, or possibly, in the case of the Scott-Finney depression, of calcareous beds in the Cretaceous. Some of the depressions may represent actual sink holes that reached the surface, and were later filled by slump and wash from bordering areas, but probably the greater number represent merely the sagging of yielding roof rocks over cavities that never reached the surface. They are probably more or less analogous to the subsidence area formed in Hutchinson as a result of extraction of rock salt at a depth of about 300 feet by the pumping method (Young, 1927).

It was suggested by Johnson (1901, p. 711) that "the innumerable upland basins, especially where the floor is Cretaceous to great depths, are clearly to be ascribed to grain-by-grain processes of readjustment and compacting, at work within the Tertiary only." Convincing proof of this process, however, is yet to be adduced.

LARGE IMBRICATE BLOCKS OF BLUFF CREEK

About 0.5 mile south of the point where Bluff creek makes its sharp bend to the south, the stream channel shows a unique occurrence of large imbricate blocks (pl. 31A, B). Large, angular slabs of Cretaceous limestone, as much as 5 feet long, are stacked shingle-fashion along the bottom and in the banks of the channel. Virtually all the slabs dip upstream, at angles as steep as 35°. The individual blocks are about 6 to 10 inches thick. Similar though less striking imbricate structure is found at various points for about 200 yards downstream, and for about 350 yards upstream, to the point where a limestone ledge across the stream forms a falls about 2.7 feet high. The rock in this ledge is similar to that of the blocks. The stream gradient here is about 40 feet per mile. It was not definitely ascertained whether the blocks are being moved by present floods, but it seems doubtful that more than minor readjustments are effected.

Two possible explanations suggest themselves for the origin of the imbricate structure: (1) ice-jam action, and (2) torrential flood velocities. The former, although at first favored, was finally abandoned for lack of any supporting evidence. The likelihood of the latter was substantiated by the finding of concrete slabs in a comparable attitude a few tens of feet downstream from the dam at Meade County State Lake. The slabs were derived from the breakup of the spillway, and were carried downstream by overflow waters of abnormal volume and velocity. Although only a very few slabs were involved, their size was comparable to that of the imbricate blocks, and their final disposition was similar (pl. 31C).

Under the hypothesis of flood velocities, the blocks would have been loosened by undermining incident to falls-recession, and their imbrication would have resulted from short-distance transportation by floods having abnormally great velocities owing to local steepening of hydraulic gradient by the falls. This would involve transportation of individual blocks only a few feet or a few tens of feet at most, leaving them stranded at the point where velocity declined and carrying-power was reduced. As the point of heightened flood velocity receded with the falls, new crops of blocks would be stacked at points successively farther upstream, and older ones would undergo only minor jostling by undercutting.

At this point, it might be asked whether any imbricate blocks were actually found immediately in advance of the falls noted above. A few tens of feet below the falls, one small group was found embedded in the stream bank, on the outside of a slight curve in the channel. Under the lip of the falls there were a few flat slabs. Perhaps these were detached at a time of relatively moderate flow, and were awaiting imbrication by the next major flood. Although the display of imbrication here is less striking than might be expected, it is consistent with the hypothesis. A consideration of the processes involved indicates that the progress and continuity of imbrication would vary with the following factors: (1) size of available blocks, as governed by joints, thickness, and rate of detachment; (2) changes in the height of the falls during recession, owing to convergence or divergence of stream grade with the governing bed of hard rock; (3) chronologic spacing of minor and major floods; (4) lateral shifts in the line of swiftest current; (5) depth of channel scour and fill, in relation to opportunities for burial of imbricate blocks along some stretches.

A few hundred yards west of the bend in Bluff creek, an accumulation of somewhat smaller imbricate blocks was noted. No falls was found immediately upstream, but the channel was observed to be floored with bedrock in that direction, and a noticeable steepening of channel gradient was seen to be associated.

In summary, the giant imbricate blocks, for want of any better explanation, are attributed to the action of occasional major floods of locally accelerated velocities on slabs detached by falls recession. Plunge pool action may give the channel bottom an upward turn below the falls for a short distance, and the updrag of the flat blocks on this slope may result in the characteristic upstream dip and overlap. Possibly at one or more times in the past, climatic conditions were slightly different, and more favorable to torrential floods.

MINOR VALLEY FORMS

In many parts of the area, minor valleys have the form of blunt-headed, round-bottomed, steep-sided "draws". The bottom is generally grassy, and there is no distinct channel. The rim is sharp, and the sides may present a scalloped appearance. Sod cracks, somewhat crescentic in plan, are commonly found above the heads of these draws (pl. 29C) and in places there are definite depressions also (see Johnson, 1901, pl. 139). Little opportunity for study of these features was afforded during the field work on which this report is based, and for a consideration of their origin the reader is referred to discussions by Haworth (1897a, pp. 18-21), Fenneman (1922, pp. 126-132), and Rubey (1928).

HISTORIC CHANGES IN STREAM CHANNELS

ARKANSAS RIVER

St. John, in 1887 (pp. 133, 135), described Arkansas river as occupying—

> a broad shallow valley comprising an immense area of level bottom-land, usually presenting two low benches, the narrower of which forms the present flood-plain along the margin of the stream, and which affords valuable meadows. The stream itself presents a very uniform appearance—a broad sandy bed threaded by shallow channels and bearing grassy islets, and confined within low earth-banks. In places the bars are composed of gravel; elsewhere treacherous quicksands prevail. The melting of the snow in the mountains about the sources of the Arkansas fill its banks brimful of turbid, sediment-laden water in early summer, when the volume of the stream is at is greatest. . . . None of these streams today have any timber, except a few scattering trees along the courses of some of the north-side affluents, in Hamilton county. Indeed, along the banks of the Arkansas only a slender belt of cottonwoods is seen in the same quarter.

According to Mead (1896), the stream was navigable during these times of flood, and—

> as early as 1852 boats were built at Pueblo, Colorado, in which mountain traders and trappers, sometimes in parties of 15 or 20 in one boat, with their effects, floated down the swift current of the river to Arkansas.

Today the appearance of the channel is much the same as it was when St. John wrote, but the banks are different in being well wooded, supporting heavy stands of cottonwood and other trees. It is somewhat doubtful whether boats could now descend the river as reported by Mead.

Haworth, in 1897, noted that some filling of the channel had already taken place by that time, and stated that, in the preceding 15 years, the stream bed had been raised by as much as 15 feet (1897a, p. 28). It has not been ascertained whether filling has continued since that time, but some channel shrinkage does seem to be in progress. From west to east, the width of the present channel decreases by one-half or more. This seems to be at least partly a result of the recent encroachment of heavy stands of scrub cottonwood and other vegetation, for sandy strips of a recently wider channel may be seen beneath the undergrowth.

Physiographic evidence for changes in channel regime is suggested by the abandoned meanders west of Syracuse—a feature rare along the river in this section. The abandoned stretches of the channel seem to be considerably narrower than the present sandy, braided channel alongside, and suggest that the stream formerly flowed in a simple, open channel. The date of the change is not known (pl. 27).

Farther east, in the Wichita area, changes in the channel of the Arkansas were noted as early as 1896 by Mead, whose observations dated back to 1859. He reported the transition from a stream once flowing bank-full most of the time, to a sandy waste traversed by an insignificant thread of water.

The cause of the changes outlined above undoubtedly lies in the extensive diversion of river water for irrigation in eastern Colorado and in the western counties of Kansas. It was Mead who first noted the importance of this factor.

CIMARRON RIVER

Along Cimarron river, the changes have been of a different kind. In 1887, St. John (p. 133) described that stream as—

> a small brook only a few yards wide, and in places during a portion of the year its waters are lost in the sandy bed. In early summer its low banks are sometimes overflowed. The above-mentioned affluents mostly afford pools the year round, and like the larger stream they are subject to overflow from the heavy local rains that occur during the summer months. In the past these pools were the resort of herds that pastured the adjacent plains, and the Cimarron valley was, until recently, entirely occupied by stock ranches and thousands of cattle.

Johnson (1902, p. 663) later referred to the Cimarron as—

> A notable example of such a valley floor, almost unvisited by runoff floods, yet with a perennial stream of constant volume looping intricately upon it. . . . The spring stream here merely occupies the valley; it has no part itself in valley making. It does not run full length. Though in some of its live sections it is a strong stream, unvarying in volume, there are other sections in which the bed is permanently dry to depths of 20 or 30 feet. . . . It happens that the Cimarron valley floor lies approximately at the ground-water level, though not precisely. At one point it may be a little above, at another a little below.
>
> A few miles above Arkalon, in southwestern Kansas, there is a feeble "reappearance", as it may be termed, of the Cimarron, following a long dry section.

Haworth (1897, p. 63), writing of the Cimarron valley in Clark county and parts of Seward county, stated that the—

> Cimarron river carries a large amount of water during a part of the year, and is rarely dry in this part of the state, as it is fed by springs.

Parker (1911, pp. 306-307) later wrote that—

> from the old post office of Metcalf, Okla., to Point of Rocks, Kans., a distance of 25 miles, the channel of the Cimarron is often dry, but at Point of Rocks, Kans., the water comes to the surface at Wagon Bed Springs, a famous camp on the old Santa Fe trail, and the channel is usually full for a number of miles. It gradually sinks again before reaching Oklahoma a second time. . . . In Kansas, from Arkalon southward, the Cimarron river usually has water in it throughout the greater part of the year. The stream is subject to a June rise, which is caused by the melting of snows in the mountains at its head. . . . William Easton Hutchinson states that the Cimarron river is a constantly running stream throughout the entire width of Morton county, where it has a valley on one side or the other of the channel from one-half to three miles in width, on which an abundant crop of natural hay is cut. In Stevens county there is running water in Cimarron river at all seasons of the year. . . . In Grant county the river flows constantly and has a fine fertile valley on each side of the channel that is sometimes covered by floods.

Although this account contains certain minor inconsistencies, the general picture is clear.

Early residents of the area agree that the Cimarron originally had a narrow channel, clear water, and many fish and beaver. Today, only one short stretch of the river, in southwestern Haskell county and contiguous sections, retains any semblance of these characteristics (pl. 5B). Even this stretch has widened noticeably since I first visited it in 1937. Elsewhere the channel has widened enormously, and at the west its width has progressively increased to as much as 800 feet (pl. 5A). The stream bed has become a barren sandy waste, and there is little or no flow during much of the year. The fish and beaver have vanished. Much valuable meadow land, where hay was formerly cut, has been destroyed. From time to time it has been necessary to lengthen bridges to span the broadened channel. Whether these changes have involved any deepening or shallowing of the channel has not been ascertained.

Changes of similar character are reported to have occurred along many tributary streams. Once flowing in grassy channels through many pools, they have been converted to dry sand beds (pl. 32B).

At least in part, the changes in the Cimarron are reported to have been started by a severe flood in 1914. Antecedent causes undoubtedly lay in regional weakening or breaking of the sod cover by grazing and farming, leading to more rapid runoff, decreased groundwater recharge, and lessened protection of the soft Tertiary sediments. Long-range climatic fluctuations may have been an antecedent factor also.

ECONOMIC RESOURCES

Soils

Soil takes first place among the natural resources of southwestern Kansas, and with it must rank water, without which utilization of the soil would be impossible. It is upon these that the permanent economy of the area must be based. Other resources, although locally and temporarily important, are of minor significance from the long-range viewpoint, and are unlikely to benefit more than a small percentage of the inhabitants.

The soils of the area have been described at length by Coffey and Rice (1912), and in more summary form by Hayes and Stoeckeler (1935) and by Joel (1937). In the greater part of the area, the soil has been developed on a loessial mantle, and elsewhere it was formed on dune sand, on floodplain and terrace alluvium, and on dissected slopes in Tertiary and older formations. The loessial soils are characteristic of the upland areas, and provide the main basis for the dry-farming industry.

Data on land utilization and agricultural economics for the counties in southwestern Kansas are presented in a report by Throckmorton, Hodges, Pine, and Grimes (1937). Although much of the area was used originally only as grazing land, the only large sections still devoted to stock raising are in southern Meade and Clark counties. Smaller areas of pasture land, however, are found in all the other counties, and are largest in the sand-hill belts and in the more deeply dissected zones. The rest of the region is under cultivation. Wheat is by far the most important crop. Of subordinate importance, listed in order of decreasing acreage, are: grain sorghums, corn, barley, oats, alfalfa, and sugar beets. The last is raised only along the Arkansas valley, mainly in Finney county. Alfalfa is almost restricted to the Arkansas valley.

Although constituting the most valuable natural resource of the area, soils have been seriously endangered by erosion over wide areas. In many places, in fact, they have been irremediably damaged, and unless proper conservation measures are carried out, the future prospects are none too encouraging. Erosion by water has been marked locally, but erosion by wind is of far greater importance. Each of these is considered below.

SOIL EROSION BY WATER

Gullying and sheet wash in cultivated fields (pl. 32C) are important locally on the steeper slopes of the Cimarron drainage area. Both are favored by improper methods of cultivation and by attempts to farm slopes that are too steep to be kept under control easily. Remedial measures consist in terracing, contour tillage, strip-cropping, and other practices designed to retard surface runoff. A demonstration area to show the use of these methods has been set up by the U. S. Soil Conservation Service in north-central Seward county.

Roadside drainage ditches provide another common starting point for gullying in many places (pl. 32A). This may be retarded by the use of suitable check dams.

Gullying is by no means restricted to areas where the sod cover has been broken. It occurs also in places where the native vegetation has been merely weakened by overgrazing and drought (pl. 32B). This has the effect of increasing surface runoff, and thus leads to more rapid filling of water courses at times of torrential rainfall. Under conditions of lessened protection by vegetation, gullying results. With increased surface runoff there is decreased replenishment of soil moisture by infiltration, and as a consequence the grass is further weakened, and the danger of overgrazing becomes greater. The dividing line between safe grazing and overgrazing is relative, for the amount of grazing that any given area can safely support varies with the moisture available, and thus is lessened in time of drought, just when increased demands may be made upon it owing to shortage of feed. One remedial measure that promises to be of some help in preventing accelerated runoff is the use of pasture furrows on the contour (pl. 16).

SOIL EROSION BY WIND

Soil erosion by wind constitutes the most serious threat to the agricultural economy of large areas in southwestern Kansas. In the "Dust Bowl" counties (Hamilton, Stanton, Grant, Morton, Stevens, and Seward), it was found that the percentage of the total area seriously affected by wind erosion and accumulation ranged from 24.8 for Grant county to 74.8 for Stevens county, and averaged 55.7 percent for the six counties surveyed (Joel, 1937, p. 43).

The destructive effects of wind erosion are manifold. Most familiar and far-reaching are the dust storms. These constitute a menace to health and cause damage to automobiles, farm machinery, and other property, injury and loss of livestock, lower attendance at schools, suspension of travel and other activities, and generally lower morale of the people. More localized, but no less important, is the effect on soil, vegetation, and crops. In many places the topsoil has been thinned or removed, and—

> the portion of the soil which contains most of the organic matter, most of the readily available plant food materials, and the part having the highest absorbing capacity for water is lost. (Throckmorton and Compton, 1938, p. 23.)

Growing crops are cut off, undermined, or buried by drifting soil (pl. 22A). Pasture land is commonly injured by the drifting of "dirt" from adjoining cultivated tracts. Roads are locally blocked, fences are choked, farmsteads invaded, and trees killed by drifting sand and silt (pl. 21).

In the area under discussion, soil "blowing" first reached serious proportions in 1934. The immediate cause lay in drought and crop failure, but wind erosion and dust storms were by no means unprecedented in the region, having been known locally for many decades (McDonald, 1938, pp. 7-12, Throckmorton and Compton, 1938, pp. 7-8). The unexampled magnitude and extent of these phenomena during recent years was primarily a result of the tremendously increased acreage under cultivation, and of the fact that within this acreage was included much marginal land.

Antecedent factors leading to the dusty years were deeply rooted in the political and economic history of the area, and are discussed at length in the report of the Great Plains Committee (1936). Outstanding in this history, however, were the facts that—

> The World War and the following inflation pushed the price of wheat to new high levels and caused a remarkable extension of the area planted to this crop

> [wheat]. When the price collapsed during the post-war period Great Plains farmers continued to plant large wheat acreages in a desperate endeavor to get money with which to pay debt charges, taxes, and other unavoidable expenses. They had no choice in the matter. Without money they could not remain solvent or continue to farm. Yet to get money they were obliged to extend farming practices which were collectively ruinous. . . . But the result was actually to produce an unsalable surplus. (Great Plains Committee, 1936, p. 4).

Absentee ownership and operation, itself partly a result of these factors, contributed still further to the final outcome.

> It is but an expression of human nature that renters and absentee owners are more interested in immediate returns than in future values. (Joel, 1937, p. 21).

Another contributing factor was poor soil management.

> Much of the soil has received shallow cultivation as a result of the general use of disk implements throughout the region, soil has been cultivated when extremely dry, and no effort has been made, in most cases, to return organic matter to the soil. These practices brought about a condition in which the immediate surface layer of soil became finely divided, low in organic matter, and subject to crusting immediately following a rain. When cultivated in a dry condition such a soil became loose and dusty. There are individual farmers throughout the region who have followed good methods of soil management and have found it possible to prevent soil blowing on their farms, except where soil blown from adjoining farms encroached upon their fields. (Throckmorton and Compton, 1938, pp. 19-20).

In the light of this background, the actual course of events may now be pictured. Drought first led to crop failure. This was followed in some places by abandonment of fields, and in others by attempts to raise a crop the following year. Abandonment of land without any protective cover gave the prevailingly high winds every opportunity to begin erosion. The loess and dune sand on which the soils of large areas had been developed provided excellent material for wind attack.

> The relatively low precipitation, low relative humidity, and frequent winds all work toward the drying out of the soil. The rain or snow which fall during the critical winter and spring blowing periods are usually not sufficient to protect the soil by covering or moistening it for an appreciable length of time. In fact, such precipitation promotes erosion to some extent by having a loosening effect on the heavier soils, the result of alternate wetting and drying. Alternate freezing and thawing also work toward the same result. (Joel, 1937, p. 22).

Abrasion by sand and soil particles thus loosened leads to the dislodging of others, and a vicious circle is inaugurated. Initial abrasion produces a surface of minimum resistance to the wind, and thus promotes further erosion. The coarser materials are swept along the surface of the ground (pl. 33A), until checked temporarily or permanently by obstacles, and the finer materials are carried aloft as dust. These conditions prevent the growth of any type of vegetation, and lead to the development of a hard, tight surface that inhibits absorption of rain water, and favors rapid runoff where there is sufficient slope. Thus the soil remains dry, conditions remain adverse for plant growth, and even weeds cannot get a start. Starting from small local areas, erosion

> may expand rapidly and lead to serious blowing over an entire farm. If there are many of these areas, they gradually unite so that blowing may occur over an entire county or several counties. (Throckmorton and Compton, 1938, p. 21).

To break this vicious circle, only the coming of an excessively moist period or the employment of artificial control measures can be effective. The latter include such methods of cultivation as will break the force of the wind and at the same time promote the absorption of rain water by the soil, thus to make plant growth possible.

When crop failure was followed by cultivation and replanting, under conditions of continued deficiency in rainfall and soil moisture, and the continued use of incorrect methods, the results were aggravated. Such stubble as might have retarded wind attack was destroyed, and the working of the dry soil rendered it more susceptible to blowing. Another crop failure naturally followed, and unless precautionary measures were taken meanwhile, erosion proceeded apace.

In the control of wind erosion, preventive methods are obviously to be preferred. These consist essentially in protection of the soil (1) by permanent restoration of a vegetative cover, (2) through coverage with suitable crops adapted to the prevailing conditions, or (3) by mechanical methods of maintaining a surface of maximum resistance to wind attack. Methods directed toward these ends are described at some length by Chilcott (1937), Joel (1937), and Throckmorton and Compton (1938). Their recommendations may be summarized as follows:

(1) Moisture conservation. All practices that lead to replenishment of soil moisture help automatically to check wind erosion.

(2) Protection of soil during preparation for and starting of a crop. This involves the use of judicious methods and proper implements. It is recommended that stubble and crop residue be left on the ground as long as possible before cultivation for the next crop, and that this material be thoroughly worked into the soil when

cultivation is started. Tillage should be undertaken only when the soil is moist, and should be such as to leave a ridged and cloddy surface. Furrows should be transverse to the direction of the prevailing winds if not on the contour. More specific procedures for varying conditions are given by Chilcott (1937).

(3) Strip farming. This involves the alternation of strips of wheat with strips either of fallow land or of row-crops. Strips should be laid out either on the contour or transverse to prevailing winds. This method, to be effective, must be used in conjunction with the other practices listed. It has not yet come into very wide usage in this area, although widely employed at other places. Obviously some experimentation may be needed to adapt it to local conditions and to determine its possibilities and limitations (Throckmorton and Compton, 1938, pp. 34-35; Chilcott, 1937, pp. 24-25).

(4) Avoidance of seeding when the soil is too dry.

> Recent studies have indicated that unless the soil contains enough water to germinate wheat and maintain its fall growth there is little hope of maturing a paying yield. Nevertheless large acreages of wheat are planted nearly every year under such conditions. A considerable portion of this acreage is planted on late-prepared land as an adventure or gamble. (Chilcott, 1937, p. 15).

Instead, the land should be left in stubble or deeply furrowed.

(5) Protection of ground after failure of wheat crop. The use of off-season emergency cover crops is recommended by Joel (1937, p. 49).

(6) Windbreaks. Where conditions are favorable for their survival, rows of trees help locally to decrease the force of the wind and check the drifting of soil from one field to another. Buffer strips of shrubs help partly to serve the same purpose (Chilcott, 1937, p. 23). Trees also have the advantage of protecting the farmyard and making it more livable. Recently, large-scale tree planting has been undertaken by the Federal Government in connection with the Shelterbelt Project (Zon, 1935). The results of this experiment may be awaited with considerable interest.

(7) Permanent revegetation of marginal land. It was early concluded by Johnson (1902, p. 653) that much of the High Plains area is "hopelessly nonagricultural" and suited only for grazing. Recent events lend support to his judgment. Of the nine soil groups distinguished in Joel's survey (1937), it was concluded that at least five are unsuited for farming, and should be returned to pasture land. The areas covered by the latter comprise a large percentage of the total acreage, and consist principally of ancient dune sand.

Much of the land on which wind erosion is most severe should never have been plowed in the first place, and can never be expected to permit crop production at a profit under average conditions of rainfall. Obviously, the only permanent solution for the problem of wind erosion must entail provisions for the reëstablishment of a vegetative cover on this land, and its restriction to grazing use thereafter. This is a difficult and costly procedure, and, if done on a large scale, must involve certain economic and sociological readjustments. It is a step hardly within the reach of the average landowner, but rather to be undertaken by governmental agencies. Some progress in this direction has already been made, and certain tracts in Morton county have been taken over by the Resettlement Administration. As a result of conservation measures in these areas, fields that I observed to be bare and blowing badly in 1937 were seen to be well covered by weeds in 1939. Although regrassing is the ultimate goal, some experimentation as to feasible methods seems to be needed, and a cover of weeds at least provides protection against wind attack.

Although prevention is the desideratum, there frequently arises the need for emergency palliative measures when wind erosion does begin, and such measures, in fact, are required by state law (Throckmorton and Compton, 1938, pp. 45-47). These emergency measures are almost wholly of a mechanical nature (Rule, 1937), and consist in the use of such tillage methods as will leave a rough, cloddy surface on the ground. Immediate action is necessary to prevent the enlargement of spots where blowing starts. Deep furrowing with the "lister" type of plow has been especially recommended. The effect of this is greatly to increase the frictional resistance offered to the wind, and thus to check its velocity nearest the ground surface. The furrows serve also to trap any soil material that may begin to drift, before it can gather momentum, and thus to prevent abrasive action. In some instances, furrowing in strips suffices to check wind attack, but where the danger of blowing is greater, solid "listing" of the entire area may be necessary. In both cases, the furrows should be transverse to the direction of the prevailing winds. However—

> Listing is not a very effective means of preventing soil blowing on the more sandy types of soil, and usually cannot be employed to advantage on such soils. (Throckmorton and Compton, 1938, p. 41.)

Obviously, the surface roughening produced by any method of tillage is temporary. Although checked, wind action is not wholly prevented. Not all winds blow from the prevailing direction, and some will blow more nearly parallel to the furrows, and thus meet with less resistance. Hence there is a tendency for the furrows to be gradually modified. The impact of falling rain is an important factor also, for it tends to pack and "puddle" the upturned soil, and to smooth out the surface irregularities. Resistance to the sweep of the wind is decreased, and finally a point is reached at which repeated cultivation becomes necessary. In fact, a marked increase in the amount of dust in the air is commonly observed within a day or two after heavy rainfall. Plate 33 shows the contrast in wind action between that part of a field just cultivated (darker color) and the part not yet cultivated. The gusts of wind stir up no dust before reaching the uncultivated part, but produce dust aplenty as soon as the dividing line is crossed. On the leeward side of the uncultivated patch, the coarser particles carried nearer the ground are quickly dropped, allowing the finer dust carried higher up to thin out gradually for want of replenishment.

The control of drifting dune sand presents a somewhat different problem. Locally, snow fences are used to check the drifting of sand across roads, etc. Other control measures on a larger scale have recently been worked out by Whitfield (1939) on an experimental tract near Dalhart, Texas. His procedure consists in: (1) mechanical methods of reducing dune height; (2) deep listing of surrounding ground to check movement of sand to and from dunes; and (3) development of a suitable crop or of a cover of native vegetation, using prescribed methods of tillage. The applicability of these methods to other areas remains to be tested. The experimental area itself seems to lie in an old-age dune topography, where there has been opportunity for the development of a moderately deep and stable soil cover. As a result of artificial disturbance of this soil, small active dunes were developed, and it was for these that the control measures were devised. Whether or not the remedial practices suited for these conditions can also be applied to drifting sand derived from dunes less advanced in the cycle, or to active dunes that developed under natural conditions, cannot easily be predicted. The mechanical composition of the drifting sand is also a factor of importance. If, as seems probable, the dunes of the experimental tract contain a considerable percentage of silt and clay pellets, as do the fence-line dunes discussed on preceding pages of this report, stabilization would naturally be easier than on dunes composed entirely of true sand. Further studies of these factors would be of considerable interest.

The long-range problems of land utilization, however, do not end with the control of wind erosion of soil. To insure a permanently stable agricultural economy, it is necessary that provisions be made for checking unwarranted expansion during periods of abnormal rainfall, and for meeting the exigencies of intervening dry periods, which have been repeated more than once in the past, and will undoubtedly recur in the future. In past decades, these climatic fluctuations have led to alternations from "boom" times, agricultural expansion, rising land values, and immigration, to depressions, crop failure, bankruptcy, and emigration. To minimize such effects in the future, and to establish a greater degree of security for the permanent inhabitants of the area, extended readjustments in land utilization policies seem to be in order. These would necessarily have far-reaching implications of an economic and sociological nature, as well. For a discussion of these problems, the reader is referred to the reports of Joel (1937) and of the Great Plains Committee (1936).

SURFACE WATERS

Surface waters are only locally of importance in southwestern Kansas. Along the Arkansas valley, river water is diverted (pl. 34A) for irrigation in Hamilton, Kearny, and Finney counties, and to a much smaller extent farther east. Some temporary storage of water is effected in a large shallow reservoir a few miles northeast of Lakin. At times of deficient flow in the river, a pumping plant at Deerfield, which has a capacity of about 22,500 gallons a minute, has been used to put well waters in one of the main ditches. Farther east, in Gray and Ford counties, a ditch leading onto the upland areas around Spearville was constructed at one time, but has been abandoned for lack of sufficient water to fill it. Much of what little surface flow enters the state is diverted before crossing the two westernmost counties, and heavy pumping at many places along the valley may also have some effect on stream flow. Quantitative data on stream flow are presented in reports issued by the Division of Water Resources of the Kansas State Board of Agriculture.

Along the Cimarron valley there is no diversion of water within the Kansas area, so far as I was able to learn. During the greater part of the year there is little flow, and it is doubtful that much of the valley land is irrigable. In 1902, however, Johnson (p. 664) wrote that—

> At a point on the Cimarron where its valley bottom is abnormally broad—the Englewood Basin—a beginning in irrigation has been made. . . . Here, by ditch diversion, 1,200 acres are watered, and yet about a third only of the perennial run of the stream is utilized.

A map of the irrigated area was previously presented by Haworth (1897, pl. 12). It is reported that there is still some use of river water for irrigation on the Oklahoma side of the state line, but I did not have opportunity to learn any details.

Ground Water

GENERAL RELATIONS

Together with soil, ground water is foremost in importance among the natural resources of southwestern Kansas. Upon it the stock-raising industry, a part of the agricultural industry, and the habitability of the area are dependent, and on it are based many hopes for the future. The validity of these hopes, and the soundness of any investments to which they may give rise, can be determined only from the results of detailed geologic and hydrologic studies.

The ground water of southwestern Kansas occurs under diverse conditions in rocks of widely differing age. A minor amount is obtained from the older redbeds, but this is strongly mineralized, and of slight usefulness. More is obtained from the Dakota sandstone, in small areas, and most from the Tertiary and Quaternary formations. In the pre-Tertiary beds, the water is commonly under some artesian pressure, and flowing wells are found in a few places. In the broad upland areas underlain by the Ogallala formation, the ground water is commonly referred to as "sheet water", and may be reached at virtually any place by drilling a well to a depth of 50 to 200 feet. Locally, in Meade county, artesian conditions exist in the Tertiary and Quaternary (?) aquifers, and there are many flowing wells. Along the Arkansas valley, water is obtained both from the Quaternary alluvium and from the underlying Ogallala where the latter is present. The depth to water nowhere exceeds a few tens of feet, and the volume of water is more than ample for all demands as yet made upon it. The ground water of the valley areas is commonly referred to as "underflow". Along the valleys of Buckner creek and of Cimarron river also, water is found in the alluvium at shallow depth.

Natural discharge of ground water by springs occurs in a few places, notably on the west side of Crooked creek valley south of Meade. These, however, constitute a very minor part of the total water supply.

Except for the water in the redbeds, the quality of the ground water in southwestern Kansas is satisfactory for all uses required of it. Detailed analyses have been presented by Parker (1911), and additional data will be provided in forthcoming reports on individual counties. The proportion of total dissolved solids ranges from about 200 to more than 1,000 parts per million, but averages about 350 parts. The composition of the water varies both laterally and vertically. Recently, special studies of the fluoride content of well waters have been made in connection with the problem of mottled enamel in children's teeth (Gottlieb, 1934; Boyce, 1934). Of the municipal well waters in this area, only those for the following towns were found to contain as much as one part per million of fluorides: Dodge City, Satanta, and Spearville. In 1939, however, the new analyses showed a fluoride content of only 0.4 part per million at Dodge City.

Detailed studies of the ground-water conditions in Ford, Stanton, and Morton counties have already been completed by other workers, and reports will soon be published. Studies in the other counties of this area are either in progress or in project. These studies, started in 1937, are being carried out jointly by the United States Geological Survey and the Kansas State Geological Survey, with coöperation from the Division of Sanitation of the State Board of Health and Division of Water Resources, State Board of Agriculture. In previous years, the measurement of ground-water levels in Finney and Scott counties had been started by the Division of Water Resources. At present, periodic water-level measurements in about 350 observation wells are being made by the state and federal agencies, and are recorded in the annual water-level reports of the Federal Geological Survey. In the present report, only a broad general outline of ground-water relations is essayed. For quantitative data and for a more detailed analysis of local hydrologic conditions, the reader is referred to the forthcoming separate reports on individual areas.

UTILIZATION OF GROUND WATER

The municipal water supplies of southwestern Kansas are all obtained from deep wells. The water is used for domestic and industrial purposes, for swimming pools, for irrigation of lawns and gardens, and, in recent years, for various types of air-conditioning equipment. Certain of the latter make extremely heavy demands on the ground-water supply, and introduce problems of returning water to the aquifers to prevent undue wastage.

In rural areas, well water is used for household purposes, for watering livestock, and for irrigation (fig. 20). Wells of shallow to

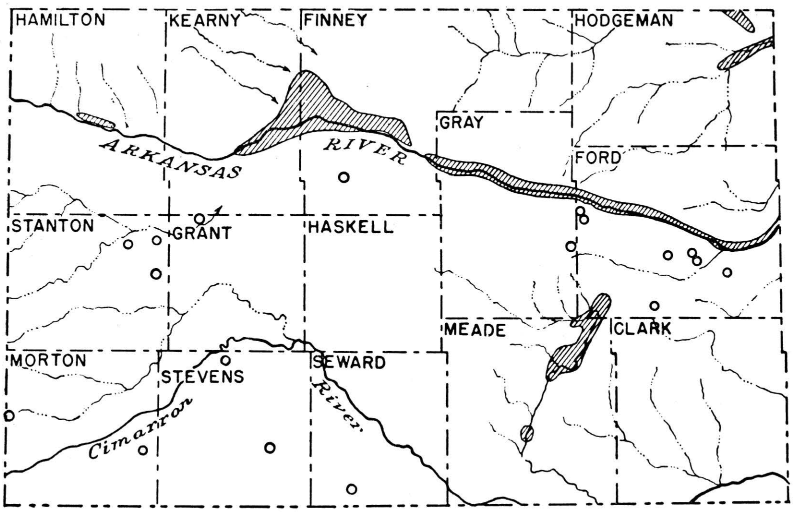

FIG. 20. Map showing areas irrigated by pumping. The circles indicate isolated deep-well irrigation projects, as of 1938. Compiled with the assistance of Kenneth McCall and H. A. Waite.

moderate depth, pumped by windmill power, commonly supply sufficient water for the first two of these uses. The requirements for irrigation on any very large scale, however, are much greater, and demand the use of larger or deeper wells and of power equipment for pumping. Along the Arkansas valley, where irrigation by pumping has been practiced for several decades, methods have been more or less standardized, and pumping presents no special problems. On the upland areas, however, the situation is different. The recent period of drought and crop failure has led to considerable interest in the possibilities of deep-well irrigation, and several experimental projects have been started. Some individuals, in fact, tend to look to irrigation as a general solution for all the difficulties of dry farming. A consideration of the conditions requisite for successful irrigation farming shows that the feasibility of general irrigation on the upland areas must depend on: (1) topography and soil, (2) adequacy of the ground-water supply, and (3) cost of pumping relative to profits obtained.

Unless the topography is moderately flat, or can be artificially levelled, ditch construction is impractical. Unless the soil is sufficiently productive, and at least moderately retentive of water, irrigation would be of little avail. These particular requirements are satisfactorily met in large portions of the upland areas, however.

The adequacy of the water supply is relative. Broadly speaking, from a regional standpoint, the supply is certainly more than sufficient for present pumping demands. As emphasized by Johnson in 1902 (pp. 645-652), however, it is by no means inexhaustible, and there is very definitely a limit to the number of irrigation wells that can be put into operation without causing a general lowering of the water table. This point of safe yield can be estimated only from the results of detailed hydrologic surveys. From the local standpoint, the adequacy of the water supply depends on local conditions, particularly on the thickness and permeability of the water-bearing beds encountered in a well. These vary both locally and regionally. In any given locality, where the Ogallala is the aquifer, the lenticularity of the beds is commonly such as to cause wide variations in the yield of wells only a short distance apart. For this reason, it is good practice to drill a series of preliminary test holes before selecting the exact spot for the desired well. Then the hole that shows the greatest thickness of sand and gravel below water level may be enlarged to make a well. In some parts of the area, however, the chances of obtaining wells of sufficient yield to warrant irrigation are very meager. This applies particularly to those places where the Ogallala is thin, and the vertical distance from the water table to bedrock is small.

The relative cost of pumping is one of the most important factors of immediate concern when irrigation is contemplated. This is a complex factor, depending on several variables: (1) interest on the investment; (2) maintenance and depreciation of equipment; (3) depth from which water must be pumped; (4) type and cost of power used. The first of these depends on the cost of the well and pumping equipment, and the first two constitute fixed costs, which must be met regardless of how much or how little the equipment is used. In some instances, these costs may be kept at a minimum by using serviceable second-hand or improvised equipment, or by the owner's providing a part of the labor required to construct the well. The amount of power required for pumping varies directly with the height to which the water must be lifted, and depends on the type and efficiency of the pump. For the better wells of large capacity the draw-down ranges from 20 to 50 feet, but in many other wells it exceeds 100 feet. The cost of pumping for any given amount of lift depends upon the type of power used and varies with the prevailing rates at the particular locality. Data on these factors are set forth in reports of the Division of Water Resources of the State Board of Agriculture.

Obviously, the change from dry farming to irrigation farming can be successful only when the increase in profits realized exceeds the total cost of pumping. Other things being equal, this depends on the efficiency in the use of the water, and on the marketability of the crops produced. Efficiency in the use of water varies with the skill, experience, and industry of the individual farmer. The methods used in irrigation farming are different from those in dry farming, and cannot be learned overnight. Some information on this subject is given in a bulletin by Fortier (1932). The marketability of crops depends on the type of crop, on the demand, and on the distance to markets. These are factors that must be carefully evaluated for individual localities. Truck gardening, for example, might be profitable to the point of meeting the needs of near-by towns, but unprofitable in competition for more distant markets.

Thus many factors other than the geologic and the hydrologic determine the practicability of irrigation at particular places. The geologic and hydrologic factors, however, do impose certain absolute limitations, and in long-range planning these must be given full consideration.

ARTESIAN WATER IN THE REDBEDS

Artesian water in the redbeds has been tapped in at least three places in Morton county, and is strongly mineralized. The first is in Richfield, where wells 600 to 700 feet deep were reported originally to have flowed at rates of 300 to 400 gallons a minute (Darton, 1905, p. 308; Haworth, 1913, p. 100). Today, the flow of the one well observed by me has dwindled to a mere trickle (pl. 34B), owing probably to rusting and clogging of the casing. This is confirmed by the report that water in surrounding shallow wells has been becoming harder, indicating leakage into and contamination of aquifers at higher levels.

One of the Elkhart city wells is reported to have encountered hard artesian water at a depth of 460 feet. This water rose within about 50 feet of the surface. It was plugged off.

A well drilled for gas along the Cimarron valley north of Elkhart (sec. 22, T. 34 S., R. 43 W.) is reported also to have encountered artesian water, at a depth of about 212 feet. This well was later plugged.

Although the volume of water in the redbeds may be considerable, the quality is poor, and it is not satisfactory for domestic or stock water. The intake areas and direction of movement are unknown.

WATER IN THE DAKOTA SANDSTONE

The Dakota sandstone is an important aquifer in Stanton, Hamilton, Ford, and Hodgeman counties, and in parts of Morton county. Its possible significance in other places is overshadowed by the Ogallala formation, which provides all water needed over large areas. Ground-water conditions in the Syracuse and Lakin quadrangles have been described at length by Darton (1920). In this area, the aquifer or aquifers lie at depths as great as 400 feet. The water generally rises to a level within 100 feet of the surface, particularly along the Arkansas valley. At one time, there were several flowing wells in the vicinity of Coolidge (Haworth, 1913, p. 96). According to Darton, the Dakota water is comparatively soft, and of great volume.

Darton (1905, p. 308) reports that flowing wells were obtained at depths of 90 to 105 feet in the Dakota along the Cimarron valley south and southwest of Richfield. Recent studies, however, suggest some doubt as to his correlation of the water-bearing beds.

In Hodgeman county, a few wells draw their water from the Dakota, which lies at depths of as much as 800 feet (Moss, 1932, p. 45). Some flowing wells are reported to occur in the southern part of the county.

In southeastern Colorado, also, the Dakota is an important aquifer, and the water is under more or less artesian pressure at many places (Darton, 1906; Patton, 1924). Along the Arkansas valley, flowing wells were common between Las Animas and Florence when Darton wrote. Since that time, however, the flow of many wells has declined, and pumping has become necessary (Toepelman, 1924, p. 66).

The Dakota water in southwestern Kansas is derived mainly from rainfall in southeastern Colorado. Contrary to popular belief and to the assumption of Haworth (1913, p. 99), there is no reason for believing that any of the water in the formation comes from the foothills of the Rockies. Inspection of the structural contours on the Dakota in eastern Colorado (fig. 21) shows that a broad structural arch forms a barrier between Kansas and the mountain areas. Inspection of the geologic map of Colorado shows also that the outcrop areas of the Dakota along the mountain front south of the Arkansas valley are cut off from areas to the east by the deep canyon of

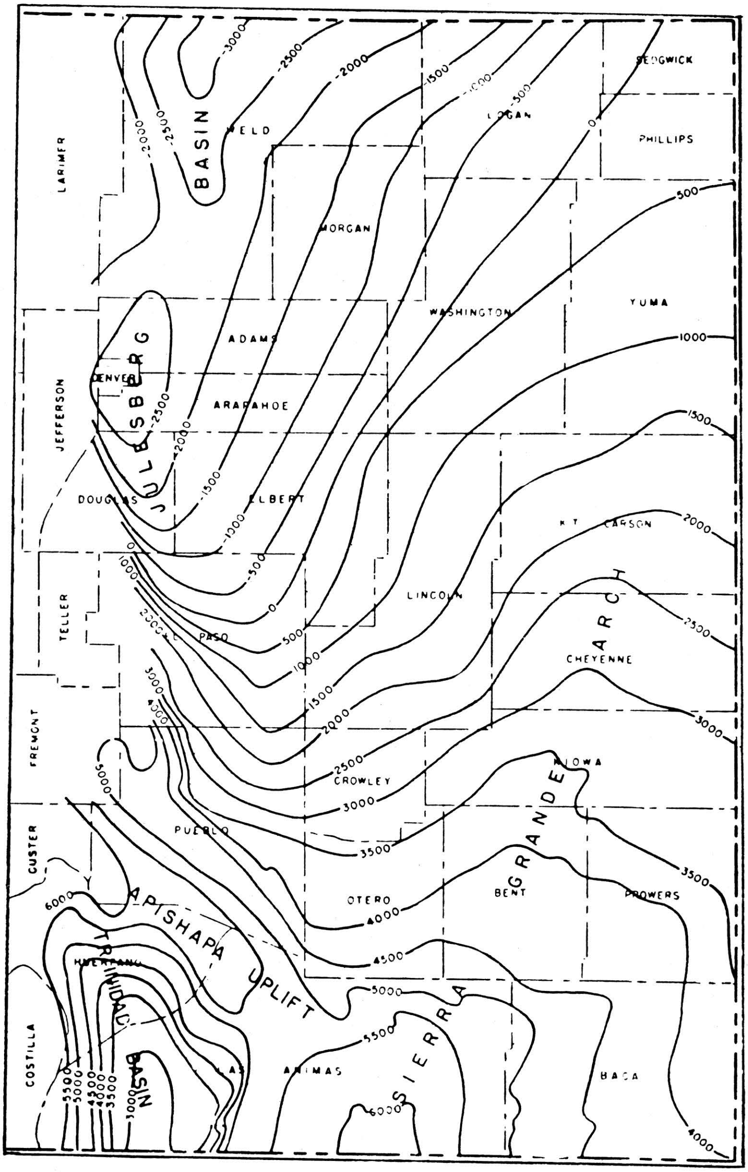

Fig. 21. Structural contour map on the top of the Dakota sandstone in eastern Colorado, by F. M. Van Tuyl, B. H. Parker, and W. H. Fenwick. Contour interval 500 feet. (Reprinted from the Guidebook for the 12th Annual Field Conference of the Kansas Geological Society.)

Purgatoire river. There is no need to search that far for a source of Dakota water, however. On the broad slopes of the Sierra Grande dome the Dakota crops out in an extensive area, and conditions are undoubtedly favorable for the infiltration of an important proportion of the rainfall. The structural slope toward the east and northeast accounts for the artesian pressure. On the lower flanks of the dome, the Dakota is overlain by the Ogallala formation, and may possibly receive some water from it. Possibly there is some recharge from a similar source farther east in Kansas, at places where the eroded edges of the Dakota are overlain by Ogallala and dip away from it (fig. 16).

GROUND WATER IN THE TERTIARY OF THE UPLAND AREAS

In the upland or High Plains portions of the area, the Ogallala constitutes the principal aquifer. The Rexroad formation may be important locally, also, and if pre-Ogallala Tertiary beds are present, they also make up a part of the ground-water reservoir. The depth to water ranges from about 75 feet to 210 feet, and varies with surface topography, bedrock topography, and other factors. The depth of deep wells of large capacity ranges from 200 to 500 feet and probably averages about 300 feet. The amount of water available shows wide variations from place to place, and, for any specific well, depends on the depth from the water table to the bedrock floor (or bottom of the well), and on the lithology of the beds in this zone. Gravel and coarse sand yield water most readily, and are most lenticular and uncertain in distribution. These materials, however, are relatively more abundant in the lower part of the Ogallala.

For domestic and stock-watering purposes, where windmills are used for pumping, the pumping level departs but little from the static water level in the well, and generally the depth of the well below the water table need not be great. For wells of larger pumping capacity, such as those used for municipal supplies and for irrigation, the factor of draw-down must be considered, for the pumping level for maximum discharge may be as much as 150 feet below the static water level. Well construction is also an important factor in determining the yield of water, and gravel-walled wells of large diameter are generally found to be most satisfactory where the water must be obtained from fine-grained materials, as is commonly the case. Pumping capacity of wells in the upland areas is as much as 600 gallons a minute or even more. In the following paragraphs, ground-water conditions are discussed for each physiographic district.

Information on ground-water relations in the uplands of the Kearny area is meager, and no deep irrigation wells were reported. The depth to water is said to exceed 100 feet in much of the district, and in parts of northwestern Kearny county it is reported that no water is found in the Ogallala. These barren spots probably represent bedrock hills, where wells cannot reach the water table, or cannot tap beds that are sufficiently pervious to yield appreciable water.

In the southern part of the Scott-Finney depression, abundant water is obtained at moderate depth, and a large acreage is under irrigation. Some wells exceed 300 feet in depth. The depth to the main water-bearing beds is reported to be as much as 200 feet, but the static water level in wells lies only 50 to 80 feet below the surface. The pumping capacity of individual wells is reported to be as much as 1,700 gallons a minute, and draw-downs range from 40 to 120 feet.

Eastward in the Kalvesta area the supply of ground water is meager. The Ogallala is thin, and its ground water leaks out along the deeper valleys that trench the area. At Spearville, the main source of water is a dug well 7.5 feet in diameter and 85 feet deep. The well bottoms in Cretaceous rock. The static water level is about 75 feet. The pumping capacity is rated at 80 gallons a minute, but it is reported that the well can be pumped dry. At Wright, the depth to water is reported to be about 85 feet.

South of the Arkansas valley, ground-water conditions are equally variable. In the Syracuse upland, no water is to be had in the Ogallala. In the Stanton area, however, the supply is greater. The depth to water ranges from about 60 feet at Richfield to 165 feet at Johnson. In Ulysses, at the eastern edge of the area, the city wells are reported to be about 290 feet deep, and the static water level about 57 feet. The draw-down is reported to be about 50 feet at a pumping capacity of 200 gallons a minute. About 2 miles east and 1.5 miles south of Ulysses, a feebly flowing well occurs in the valley bottom. It is reported to be 220 feet deep. For additional information on the hydrology of the Stanton area, the reader is referred to forthcoming reports by T. G. McLaughlin and by Bruce Latta, and to the older work of Darton (1920) for information on those parts of the area not included in these reports.

In the Cimarron Bend area, the depth to water ranges from about 80 feet in the central part of the area to slightly more than 200 feet at the east, west, and south. At Liberal, there are several deep wells, the depths ranging to 500 feet. The depth to water in different parts of town is reported to range from 100 to 150 feet. In 1937, a new well to test irrigation possibilities was completed. The depth is 356 feet. This well is reported to yield 600 gallons a minute at a draw-down of 115 feet. At Hugoton, the main city well is reported to be slightly more than 300 feet deep, and the static water level 85 feet. On a 28-hour test, this well is reported to have yielded 245 gallons a minute, at a draw-down of 160 feet. The Heger irrigation well, located 8 miles east and 2 miles south of Hugoton (SE¼ sec. 26, T. 33 S., R. 36 W.), is reported to have a static water level of 135 feet, and a pumping level about 30 feet lower for a discharge of 600 gallons a minute. Twelve miles north of Hugoton (sec. 9, T. 31 S., R. 37 W.), a well 256 feet deep is used for irrigation on a small scale. The reported water level is 87 feet. A cylindrical pump set at 131 feet was reported to deliver 20 gallons a minute. Elsewhere in the area, the depth to water is generally greater. At Moscow, it was reported to be 135 feet, at Rolla, 200 feet, and at Elkhart, 200 feet. At many places in this area, the farmers who were interested have had opportunity to reclaim water wells that were originally drilled for water to supply steam for the drilling of gas wells. The abundant supply of natural gas provides ideal fuel for power-pumping equipment.

In the Haskell area, the depth to water ranges from about 150 feet at Plains to 200 feet at Satanta. At Copeland, the reported depth is 120 feet. The city wells there are about 250 feet deep, and one well is reported to have yielded 250 gallons a minute with negligible draw-down. At Sublette, the depth to water is 200 feet. The deeper of the city wells is 348 feet. It is reported to yield 160 gallons a minute with a draw-down of 26 feet. At Satanta, the water level is reported to lie at a depth of 190 feet in the municipal well and 220 feet in the railroad well. The former is reported to yield 200 gallons a minute with a 40-foot draw-down.

Data for the Finney sand plain are meager, but topographic relations suggest that the water table should be nearer the surface than in adjoining upland areas. This is true for the Engler well, located 8 miles south and 5 miles west of Garden City (sec. 32, T. 25 S., R. 33 W.). This well is about 80 feet deep and the water level is about 60 feet. It is reported to yield 600 gallons a minute, and the water is used for irrigation.

In the Minneola area, ground-water relations are variable. The depth to water is reported to be 95 feet at Minneola, 100 feet at Bucklin, and about 165 feet at Ensign (Lohman, 1938). The larger of the municipal wells at Minneola is reported to be about 145 feet deep, and to yield 100 gallons a minute with a 15-foot draw-down. Additional data on the northern part of the section are given in S. W. Lohman's report, and in a forthcoming report by H. A. Waite.

The rate and nature of ground-water recharge in the Ogallala formation is of great importance in any consideration of future possibilities for more widespread deep-well irrigation. The conditions of recharge in this area are essentially similar to those outlined by Schoff (1939, pp. 147-159) for Texas county, Oklahoma, and the reader is referred to Schoff's paper for a detailed discussion of the factors involved. In short, four possible sources may be considered for the ground water in the Ogallala: (1) infiltration of local rainfall; (2) inflow of ground water derived from rainfall on the formation in other areas; (3) recharge from influent streams; and (4) discharge from the eroded edges of the underlying Dakota sandstone.

Infiltration from local precipitation is undoubtedly small. In areas covered by the silt and clay of the Kingsdown formation, and by the widespread mantle of loess, the downward movement of rain water is greatly retarded, and the calcareous beds in the upper part of the Ogallala probably have relatively low permeability also. Furthermore, dry-farming methods aim at maximum utilization of rainfall for crop production. Under these conditions, the proportion of water returned to the atmosphere by evaporation and transpiration is large, and the proportion that reaches the water table is small. In areas of sandy soil, as in the Cimarron Bend area and the Finney sand plain, however, additions to the ground-water reservoir are probably somewhat larger in proportion. For the region as a whole, Theis (1937) estimates that of the total annual rainfall only about 0.5 inch actually reaches the water table, on the average. There is no reason to doubt that this estimate is of the correct order of magnitude for southwestern Kansas.

The possibility of subsurface inflow of water derived from precipitation on other areas may next be considered. The principal area involved is the outcrop zone of the Ogallala in southeastern Colorado, which is considerably smaller than the outcrop area in southwestern Kansas, and lies in a belt of still less rainfall. Although it is probable that some water does enter the area from this direction, it is doubtful whether it is very important quantitatively, except in the Stanton area. Within the area, however, there is probably appreciable migration of ground water down dip in the Ogallala from higher to lower ground. This applies particularly to the Finney basin, which is so disposed structurally as to receive the inflow from a large gathering ground to the north and northwest. The abundant supply of water at moderate depth in the southern part of the Scott-Finney depression and along the Arkansas valley is undoubtedly a result of these conditions.

The possibilities of recharge from stream channels are as yet difficult to estimate. Of the streams to be considered there are only Arkansas river, Whitewoman creek, Bear creek, and Cimarron river and its few tributaries. The nature of any interchange between these streams and the water table can be determined only when it is known whether the water table slopes toward or away from their channels, which is best worked out through the construction of water-table contour maps. These are in preparation for Ford, Morton, and Stanton counties, and conclusions drawn from them will be presented in the forthcoming reports on these counties. Available data for other parts of the area indicate that the water table slopes toward both Cimarron and Arkansas rivers, suggesting that these streams receive water from the ground-water reservoir rather than contribute to it.

The possibility of recharge from the underlying Dakota sandstone is limited to those parts of the area where that formation wedges out down dip beneath the Ogallala, or where the cover rock has been stripped off as a result of pre-Ogallala erosion. This condition is believed to exist mainly in the southwestern part of the area, and may result there in significant contributions to the water of the Ogallala. Detailed estimates, however, must await knowledge of water levels in the Ogallala and of hydrostatic head in the Dakota. Chemical analyses of well waters may be of assistance, also, in distinguishing places where this source of recharge is in effect. On the whole, it seems that infiltration of local rainfall is the main process of ground-water recharge in the Ogallala. Intake from other sources, although possibly of local importance, is probably of very minor significance for the region as a whole. Certainly in the Kalvesta area, the likelihood of any water entering from the west is slight, for it is probable that the Finney basin diverts any water moving from that direction. The same is true of the greater part of the Minneola area, which is cut off from areas to the west by the valley of Crooked creek. Therefore, it may be concluded that the recharge of the ground-water reservoir is very slight, amounting only to a very small fraction of the annual precipitation, and that conservation of the ground-water supply is very desirable.

ARTESIAN WATER OF THE MEADE BASIN

The presence of artesian water in the Meade basin has long been known, and was described at length by Johnson (1901, pp. 712-728). Flowing wells are numerous in the west side of the topographic basin north of Meade, and water rises to shallow depths in the wells in other parts of the valley. When Johnson wrote (1901, p. 718), the maximum height of artesian rise was 22 feet above ground level.

The ground water of the Meade basin occurs primarily in Ogallala and Rexroad beds, and possibly also in Pleistocene sands and gravels. The artesian conditions are due to the presence of a broad downwarp in these beds, complicated in places by faulting. Quaternary clay beds probably constitute the confining cover, although it is possible that clay beds in the Rexroad may function in this capacity also.

A preliminary report on the Meade artesian basin by John C. Frye is to be published by the Geological Survey soon. Consequently, no attempt will be made here to outline hydrologic conditions fully.

GROUND WATER OF THE VALLEY AREAS

Buckner Creek.—Along Buckner creek, ample water is obtained at shallow depth from wells in the alluvium (Moss, 1932, p. 45). These wells range to 50 feet in depth. Jetmore and other towns along the valley derive their water supply from this source, and well water is used also for irrigation at many places.

Arkansas Valley.—Along the bottom lands of the Arkansas valley, ground water is obtained from Quaternary alluvium west of Hartland, and from both the alluvium and the Ogallala formation east of that point. The depth to water ranges from about 5 to 30 feet, increasing away from the river. Wells drawing water entirely from the alluvium have depths of 30 to 50 feet. The volume of water is more than ample for present requirements. Detailed discussions of hydrologic conditions along the western part of the Arkansas valley are given by Slichter (1906) and by Darton (1920) and data for Ford county are contained in a report by H. A. Waite, to be published by the Geological Survey.

The ground water in the alluvium is reported to be considerably harder than that in the Ogallala, and, according to Slichter (1906, chap. 3), the hardness decreases somewhat with depth, and is greater under the floodplain than under the 8-foot terrace, or "second bottoms".

> The tendency of the ground water near the surface in the bottom lands of the river to run high in solids seems to indicate that this increased hardness is due to the loss of the ground water by evaporation. The water plane in these bottom lands lies close to the surface of the ground and is subject to frequent fluctuations due to rain and changes of conditions in the river itself. These changes are sufficient to account for a large excess of dissolved solids in the surface waters, and it is believed that no other explanation is necessary. (Slichter, 1906, p. 48.)

The concentration of dissolved solids as a result of surface-water irrigation upstream may be an additional contributing factor. In some places, the water on the south side of the river is reported to be softer than that on the north side. This may be due to an influx of softer water from the bordering sand hills. Where Ogallala water is available, it is greatly preferred for domestic use, and in wells intended for that purpose the "first" water is generally cased off.

As to the origin of the "underflow" in the alluvium of the Arkansas valley, Slichter concluded that it was derived mainly from rainfall within the valley area, rather than from river waters originating in Colorado, as popularly supposed. He found that (1906, pp. 5-6, 34):

> (1) The water plane slopes to the east at the rate of about 7.5 feet per mile, and toward the river at the rate of 2 to 3 feet per mile.
>
> (2) The moving ground water extends several miles north from the river valley. No north or south limit was found. . . . The rate of movement is very uniform.
>
> (3) The elevation of the water plane is very sensitive to the amount of rainfall, the rise in the water plane (due to a rain) in the first bottoms being greater than can be accounted for by the localized precipitation. . . . The underflow has its origin in the rainfall on the sand hills south of the river and on the bottom lands and plains north of the river. . . . The sand hills constitute an essential part of the catchment area. . . . On the sandy bottom lands 60 percent of an ordinary rain reaches the water plane as a permanent contribution.
>
> (4) High water in the river has much less effect upon the level of the ground water than the rainfall, its influence being confined to a distance of a few hundred feet from the river channel. . . . A heavy rain contributes more water to the underflow than a flood.
>
> (5) The water plane falls at a very rapid rate after its elevation has been increased by rainfall or by a flood in the river.
>
> (6) The fact that the water plane lies for a considerable distance at a level lower than the river channel, even when there is water in the river for an extended length of time, and the rapid way in which the ground water sinks after its rise due to heavy rain, establishes the fact that the underground

drainage through the sands and gravels beneath the river valley is more than sufficient to carry off all of the rainfall without runoff into the river channel.

Near Hartland, the base of the Ogallala passes under the valley floor, and to the east the Ogallala formation constitutes an important additional source of water in the valley area. The water in the Ogallala is considerably softer than that in the overlying alluvium, and in some places it is reported to be under a different hydrostatic head. Wells in the Ogallala are generally more than 180 feet deep.

The source of the ground water in the Ogallala of the Arkansas valley undoubtedly is mainly the precipitation on a broad intake area lying to the north, northwest, and south. The structural basin serves to concentrate waters coming in from several sides. Some recharge may be effected also from the Quaternary valley fill, at the west where it crosses the eroded edges of dipping pervious beds in the Ogallala. Supplied thus from the subsurface drainage of a much larger area, the volume of water within the limits of the valley area is very large.

The ground water of the Arkansas valley is extensively used for irrigation (pl. 34C). In many places, only the water of the alluvium is drawn upon, and a battery of shallow wells, connected to a single centrifugal pump, is used. Such a battery consists of a linear series of wells, spaced about 50 feet apart, and preferably aligned transverse to the axis of the valley. Such pumping units deliver 1,000 to 2,500 gallons a minute. It is believed by some persons, however, that a single deep well, fed from both the alluvium and the Ogallala, and pumped by a turbine pump, might be more efficient in areas where the Ogallala underlies the alluvium. During the season of heavy pumping (July and August), it is reported that the level of the "first" water is lowered a few feet, but recovers before the next pumping season.

In the sand-hill belt bordering the Arkansas valley, moderate supplies of soft water may be had in relatively shallow wells. These are used mainly for watering stock.

Cimarron Valley.—Ground water lies at shallow depth along the Cimarron valley, but is little used except for domestic and stock water. It is probably derived in part from precipitation within the valley area, and in part from floodwaters of Cimarron river, particularly along the persistently dry stretches.

OIL AND GAS

Oil and gas production in southwestern Kansas have been summarized by Ver Wiebe (1938, 1939). Most important is the Hugoton gas field, which had produced 146,170,000,000 cubic feet of gas to the end of 1938.

VOLCANIC ASH

The volcanic-ash resources of southwestern Kansas have been described by Landes (1928, 1937). Most of the deposits listed by him were revisited by me and I found several additional deposits, not previously recorded. A list of the deposits inspected by me is given below (see fig. 13).

Locations of volcanic ash deposits in southwestern Kansas

Clark County.

Secs. 11 and 12, T. 30 S., R. 23 W.: Ash deposits occur along the sides of three small valleys tributary to Bluff creek. There has been virtually no exploitation.

Sec. 19, T. 30 S., R. 23 W.: One small exposure was found on the side of a small draw in the northwestern corner of the section. It has not been opened.

Sec. 24, T. 30 S., R. 24 W.: Small exposures occur on both sides of a small draw in the north-central part of the section. These are unexploited.

Sec. 23, T. 30 S., R. 24 W.: A pit has been opened in dipping beds of ash, in the southeastern corner of the section.

Meade County.

Sec. 33, T. 30 S., R. 26 W. (about 1 mile east of Fowler): A large pit was opened, but has been abandoned.

Sec. 2, T. 31 S., R. 28 W. (about 6 miles north of Meade): The pit here is the largest in the area, and is being actively quarried for the Cudahy Packing Company.

Secs. 11 and 12, T. 31 S., R. 28 W.: Several small abandoned pits were found in these sections.

Sec. 33, T. 31 S., R. 28 W.: Abandoned workings occur in the southeastern corner of the section.

Sec. 9, T. 32 S., R. 28 W. (2 miles west of Meade): Two large abandoned pits are found on both sides of a small valley.

Sec. 18, T. 32 S., R. 28 W.: A small pit has been opened in the northwestern part of the section.

Sec. 13, T. 32 S., R. 28 W.: Volcanic ash crops out along a road cut in the southwestern part of the section. It has not been opened.

Sec. 26, T. 32 S., R. 28 W.: Ash was being regularly hauled from a pit of moderate size at the time of my visit in 1937.

Sec. 3, T. 33 S., R. 28 W.: Ash crops out along a road cut on the northeastern edge of the section. It has not been opened.

Sec. 21, T. 33 S., R. 28 W.: A small deposit occurs just below the edge of the upland. It is unexploited and probably unexploitable, owing to overburden and inaccessibility.

Seward County.

Sec. 13, T. 33 S., R. 32 W. (a few miles southwest of Kismet): A large pit at this locality has been abandoned.

Sec. 35, T. 34 S., R. 31 W.: An exposure of ash was discovered in a field in the southeastern quarter of the section. It is a new locality, and unexploited.

Sec. 7, T. 31 S., R. 34 W. (northwestern corner of the county): A very small pit was opened along the road in the southeastern part of the section. When visited, it seemed to have been untouched for some time.

Sec. 19, T. 31 S., R. 34 W.: A fair-sized pit has been opened in the northeastern quarter of the section, but has not previously been placed on record.

Grant County.

Sec. 24, T. 30 S., R. 35 W.: A pit of moderate size was found at this locality, but there were no indications of recent activity.

Hamilton County.

Sec. 13, T. 26 S., R. 41 W.: An ash deposit of probable Tertiary age occurs on the west side of a small valley near the center of the section. Although once opened, it is no longer worked.

Virtually all of the workings listed as abandoned still contain large tonnages of volcanic ash, and could probably be reopened if market conditions warranted.

At present, the uses of the volcanic ash in the area are confined mainly to the making of scouring powder and other abrasives, and to use as a constituent of the oil-mat type of highway surfacing. Potential uses, as yet undeveloped, lie in the manufacture of cement and heat-insulation material (Landes, 1928), and in the preparation of ceramic glazes (Plummer, 1939).

SAND AND GRAVEL

Sand and gravel used locally for road surfacing and in concrete are obtained from three sources: (1) stream channels, (2) terrace deposits, and (3) the Ogallala formation. Along Arkansas river, sand and gravel are obtained directly from the stream channel by the use of centrifugal pumps. Along some small dry stream courses, minor amounts of sand and gravel are excavated directly by shoveling. A more important source, however, is found in the terrace deposits. Along both the Arkansas and Cimarron valleys, these constitute the main source of supply. The location of the more important dry pits is shown in figure 22. In a very few places, sand

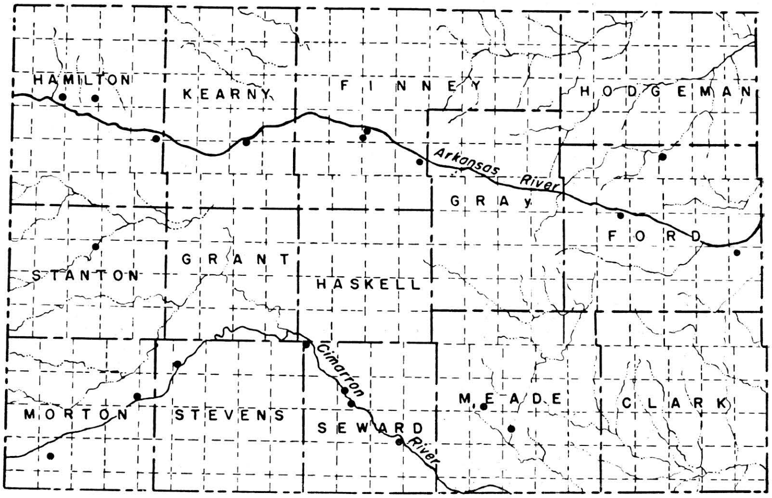

FIG. 22. Map showing location of principal gravel pits.

and gravel are taken directly from the Ogallala, but this is generally impracticable, owing to the heavy overburden.

"CALICHE"

Hard calcareous beds in the upper part of the Ogallala are used in some places as road-surfacing material. The material is generally excavated in shallow upland pits.

CLAY

Large deposits of clay occur in the upper Pliocene and Pleistocene beds of Meade county and adjoining areas. Although tests have not yet been made, it is possible that some of this material might be of suitable quality for commercial use. Clay and shale are abundant also in the Cretaceous formations.

BUILDING STONE

Rock ranging in age from Permian to Pliocene has been used in various places as building stone. The most important, however, is the limestone of the Greenhorn formation. The harder sandstone beds of the Dakota are also used to some extent (Darton, 1920, p. 8; Bass, 1926, pp. 81-82). In southeastern Seward county, the lower Pliocene (?) chalk beds have been used locally for the construction of farm buildings, and, being easily cut with a saw, are well adapted for that purpose.

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PLATE 3. The channel of Arkansas river: A. At Kendall, July, 1938. B. At Cimarron, more than 70 miles to the east, August, 1937. (pp. 18, 173-174.)

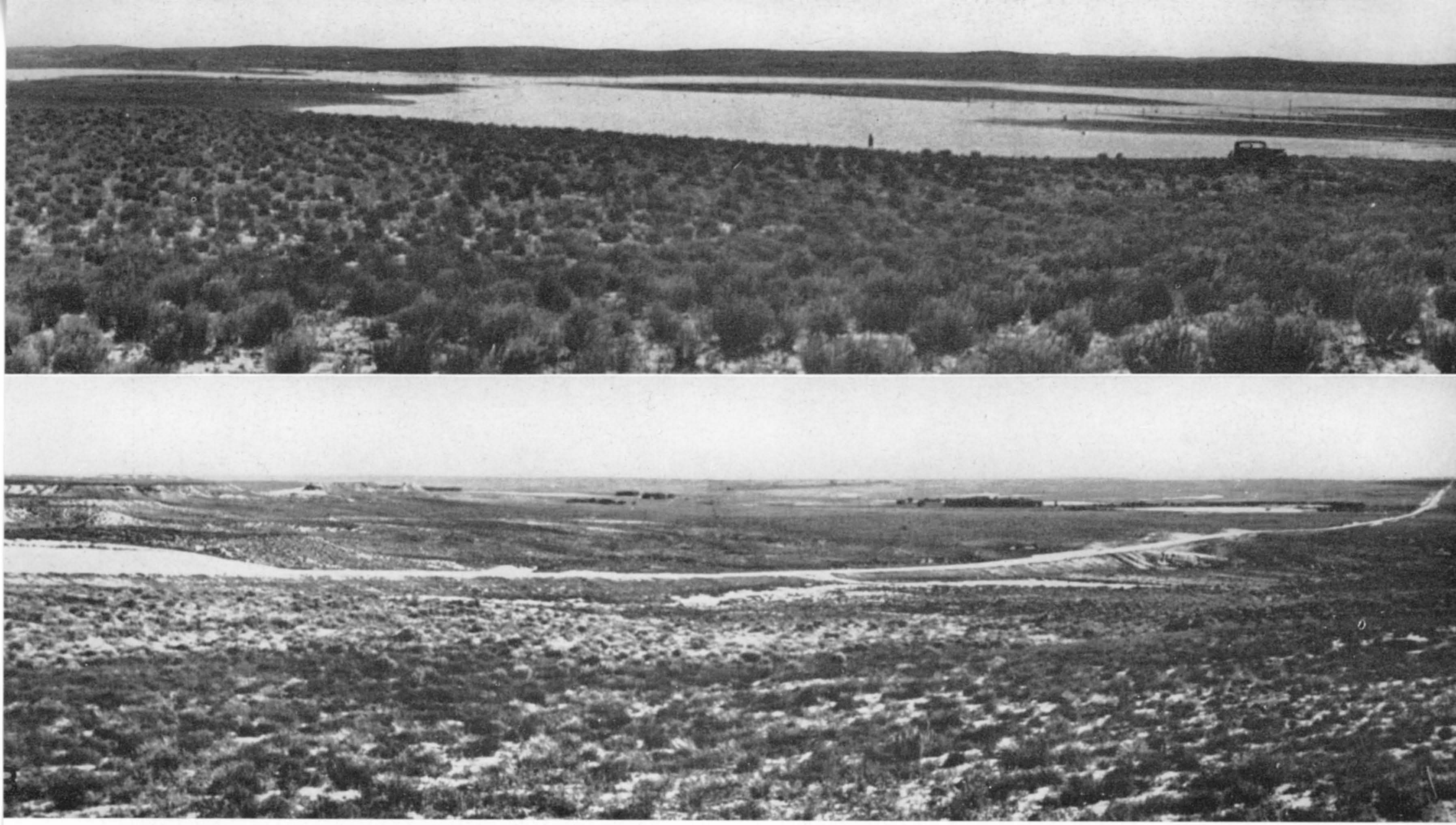

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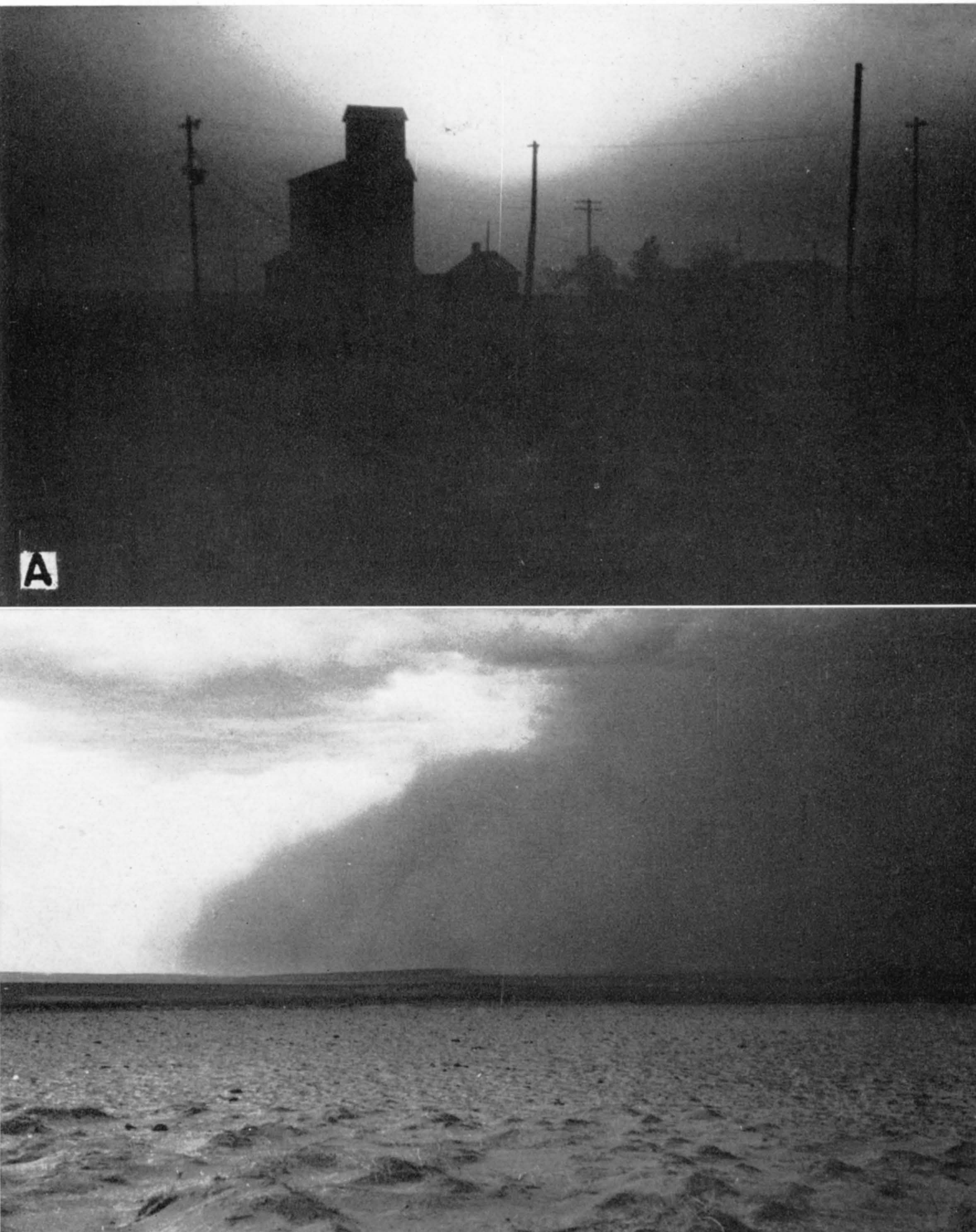
PLATE 6. Bluff creek valley, just north of Clark County State Lake. The bluffs on the far side expose Kiowa shale up to the line of trees, which marks the base of the Ogallala formation. (pp. 23, 34, 72.)



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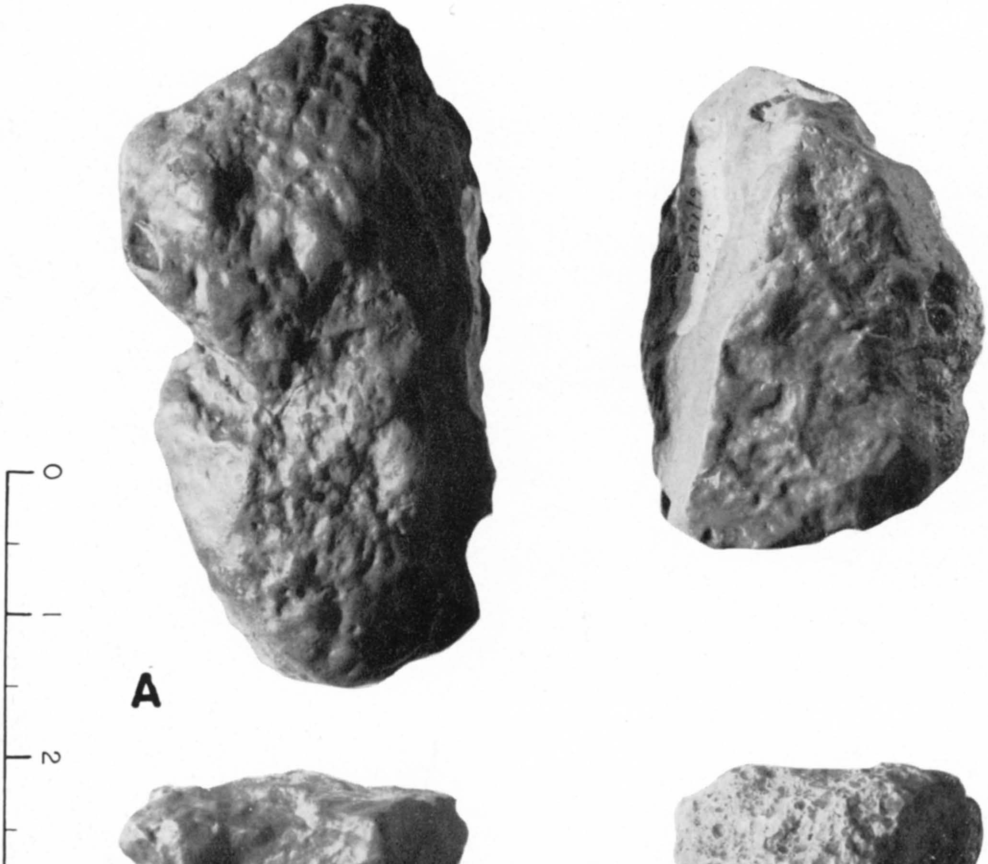

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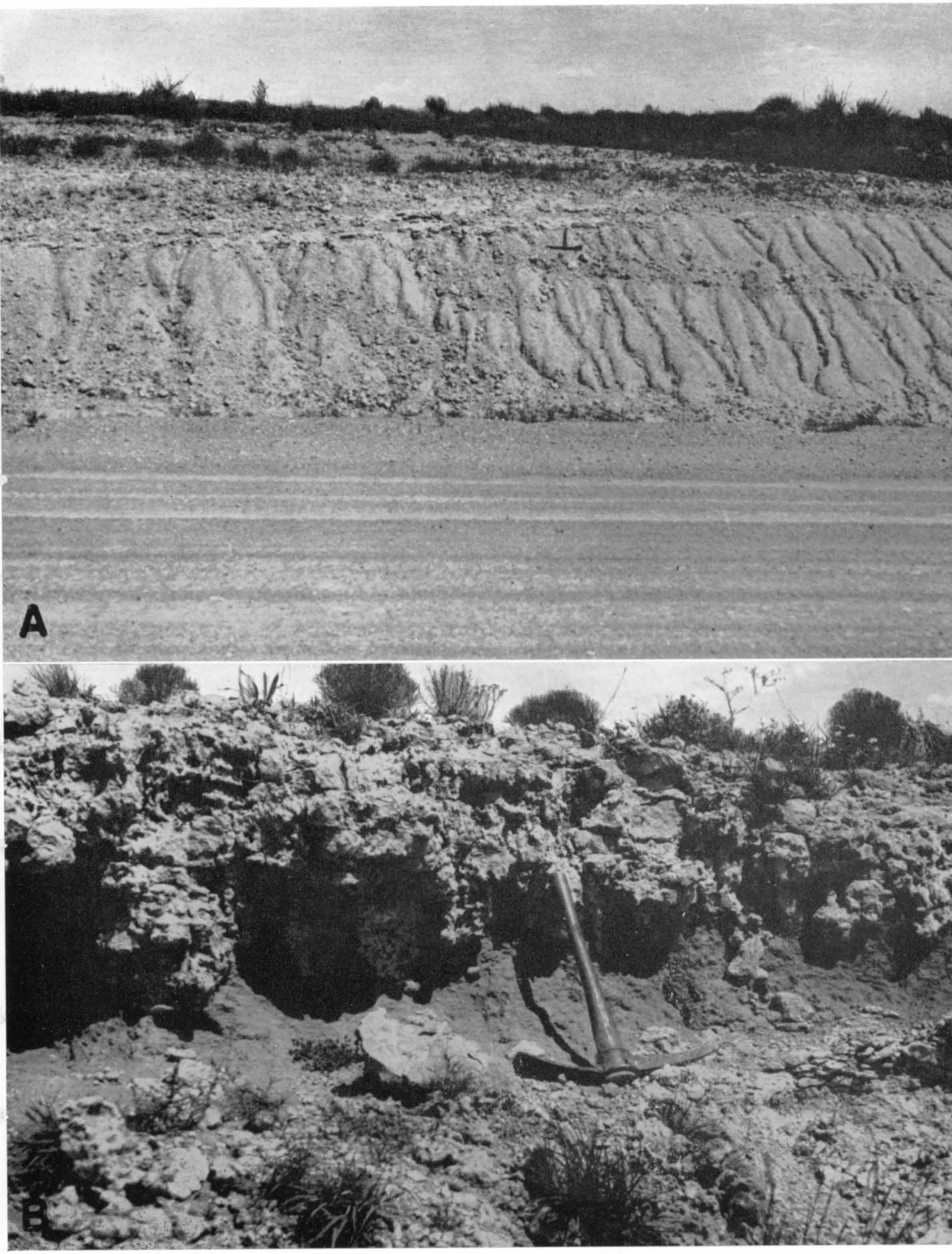

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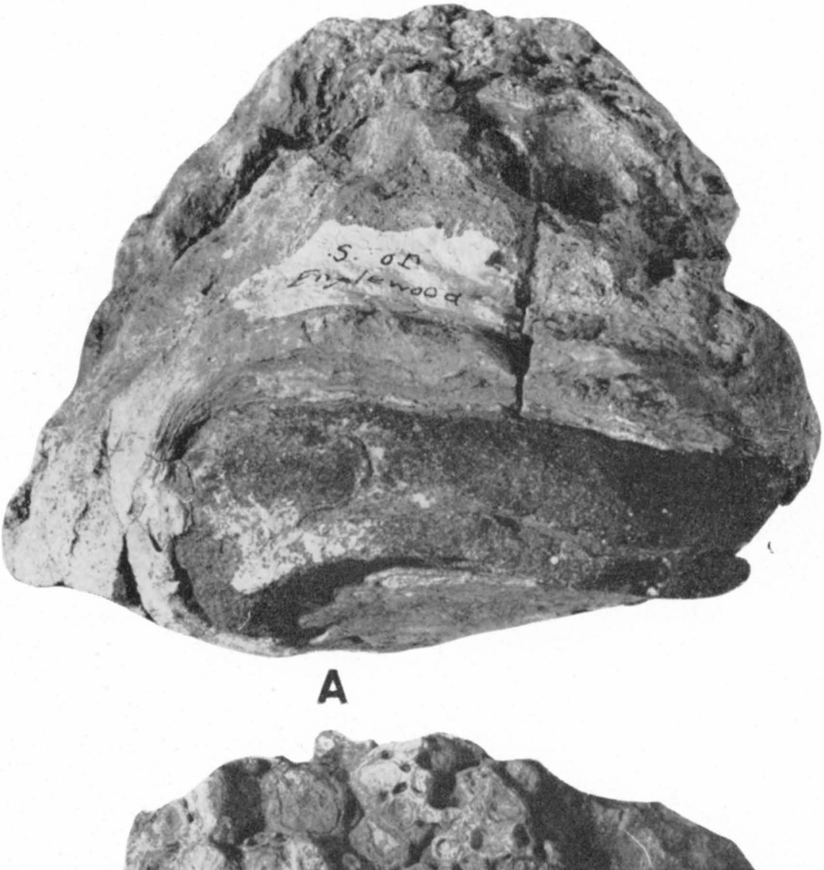

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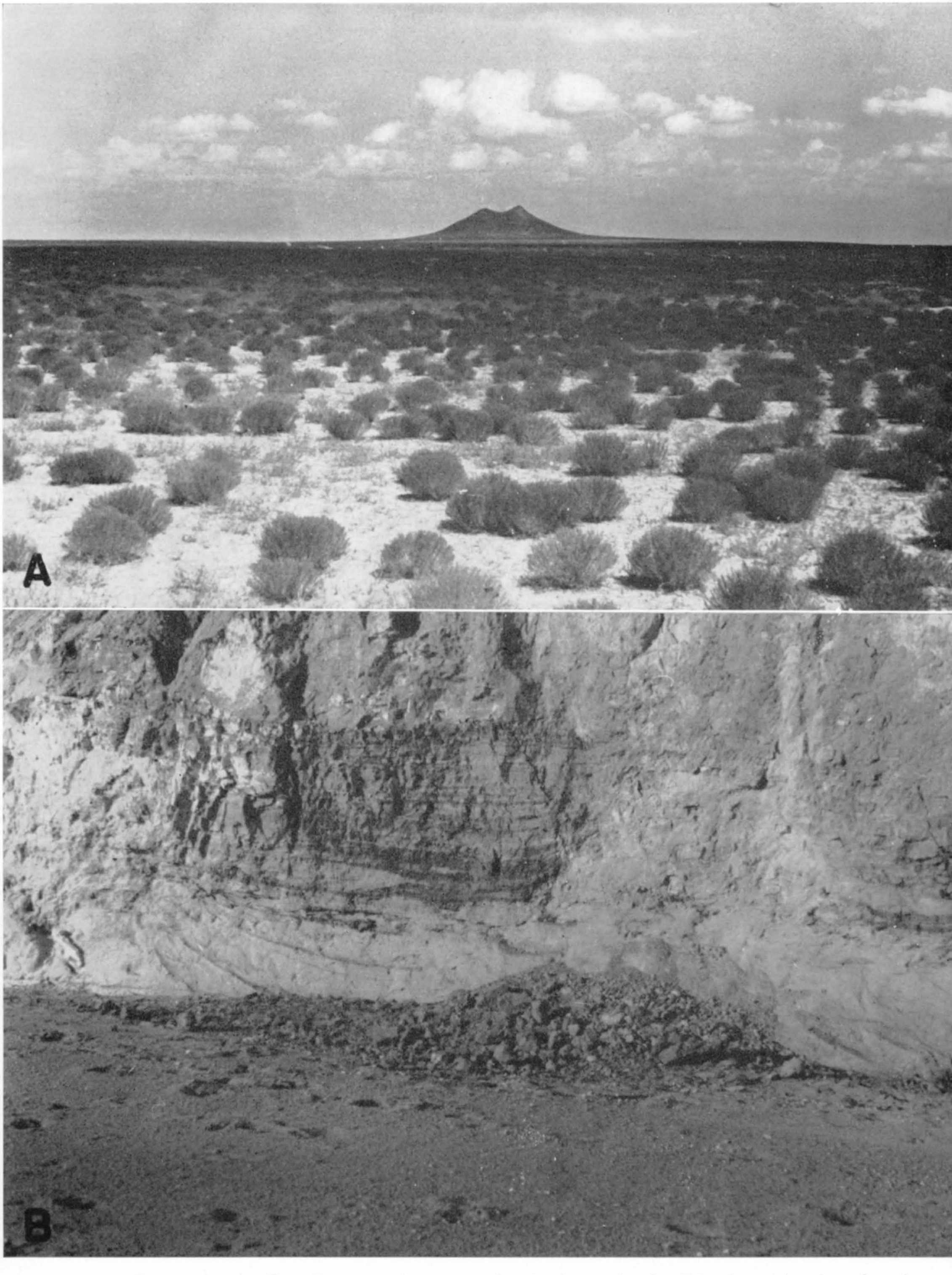

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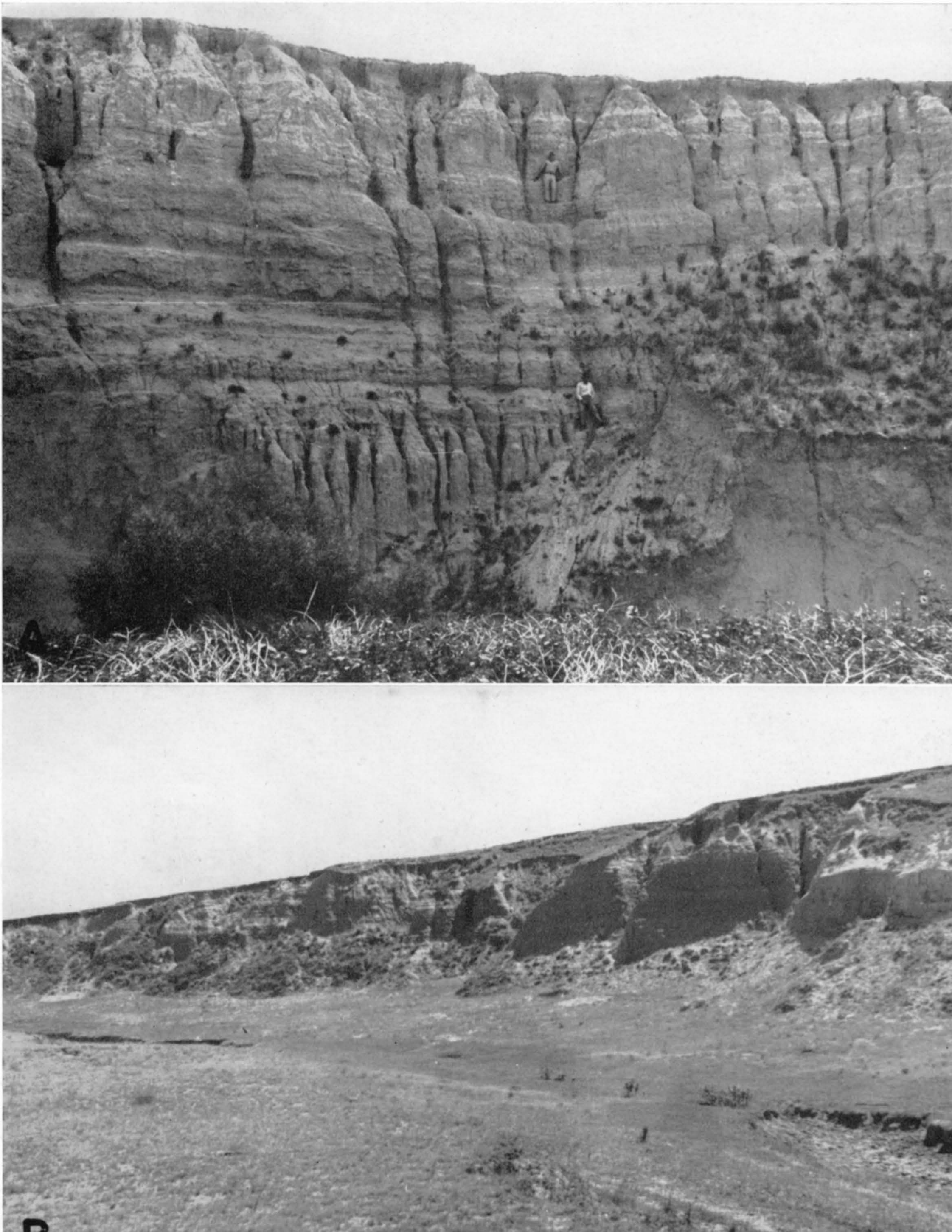

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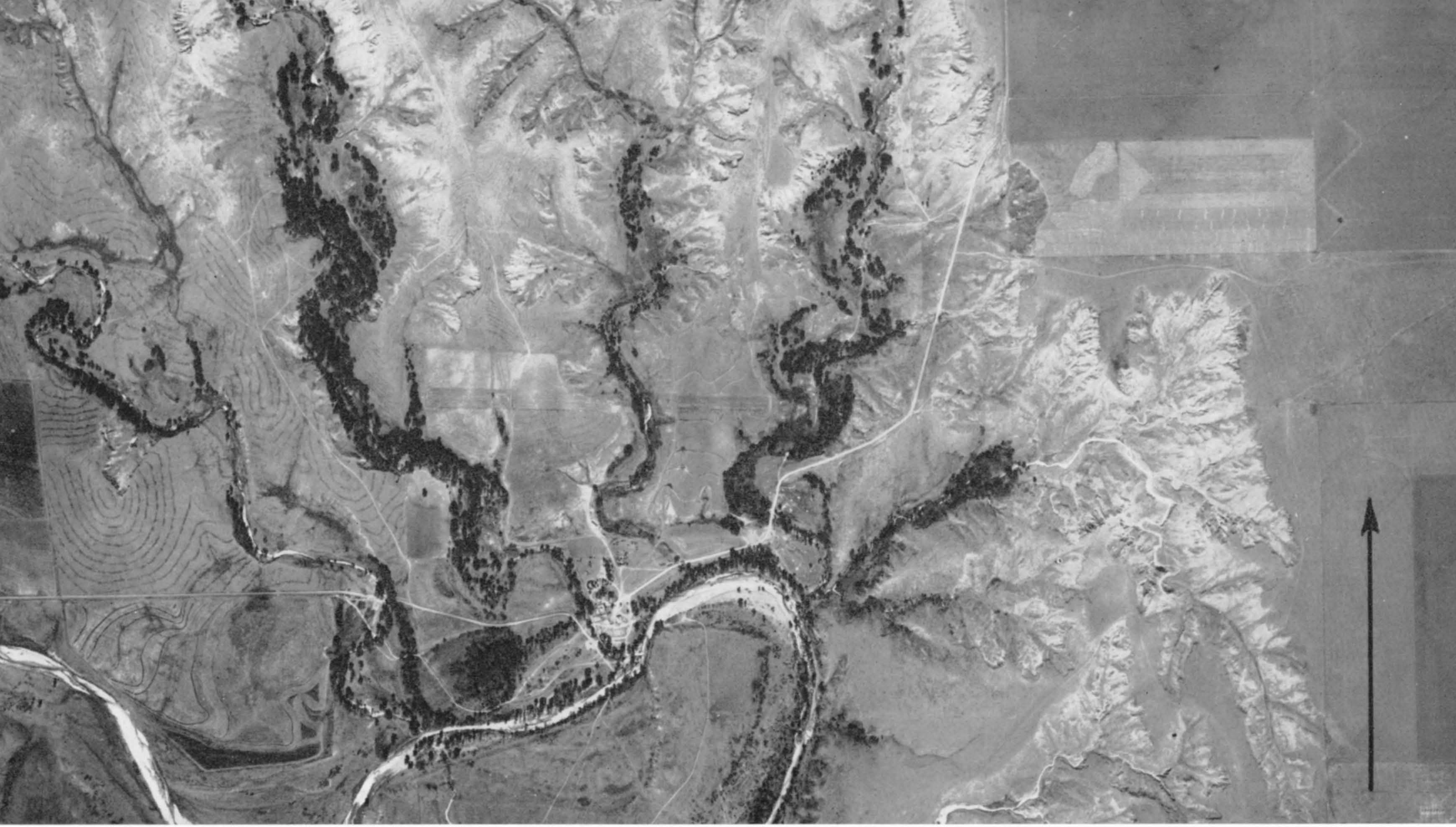
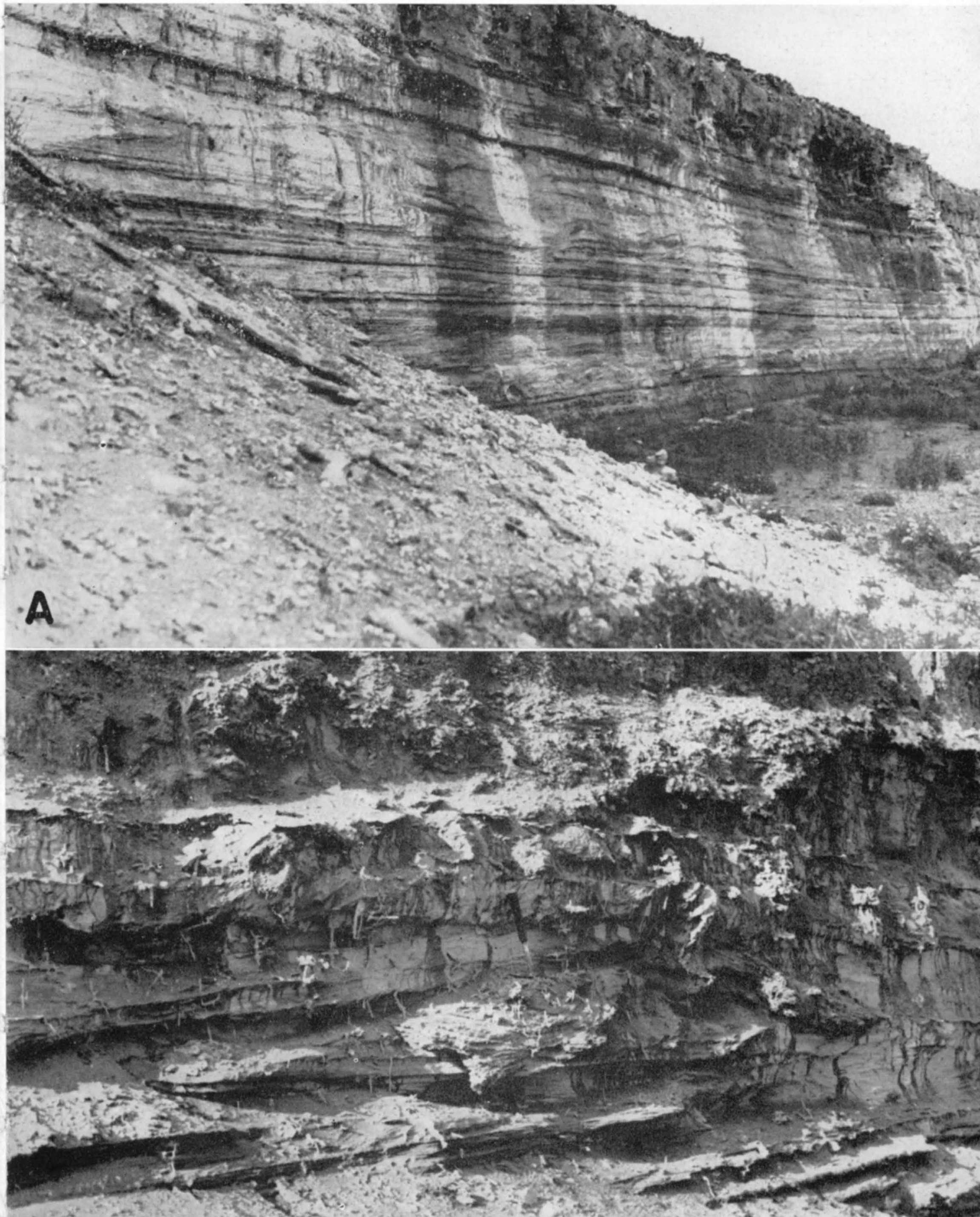


PLATE 16. Aerial photograph of the Bluff Creek Bend area. Note the shallow upland watercourse aligned with Bluff creek in the northeastern corner of the picture suggesting piracy. Note, also, the contour furrowing, and the intricate gullying of the Kingsdown formation. The arrow points north, and is about 0.5 mile long. Photograph from U. S. Agricultural Adjustment Administration, October, 1938. (pp. 111, 150, 178.)



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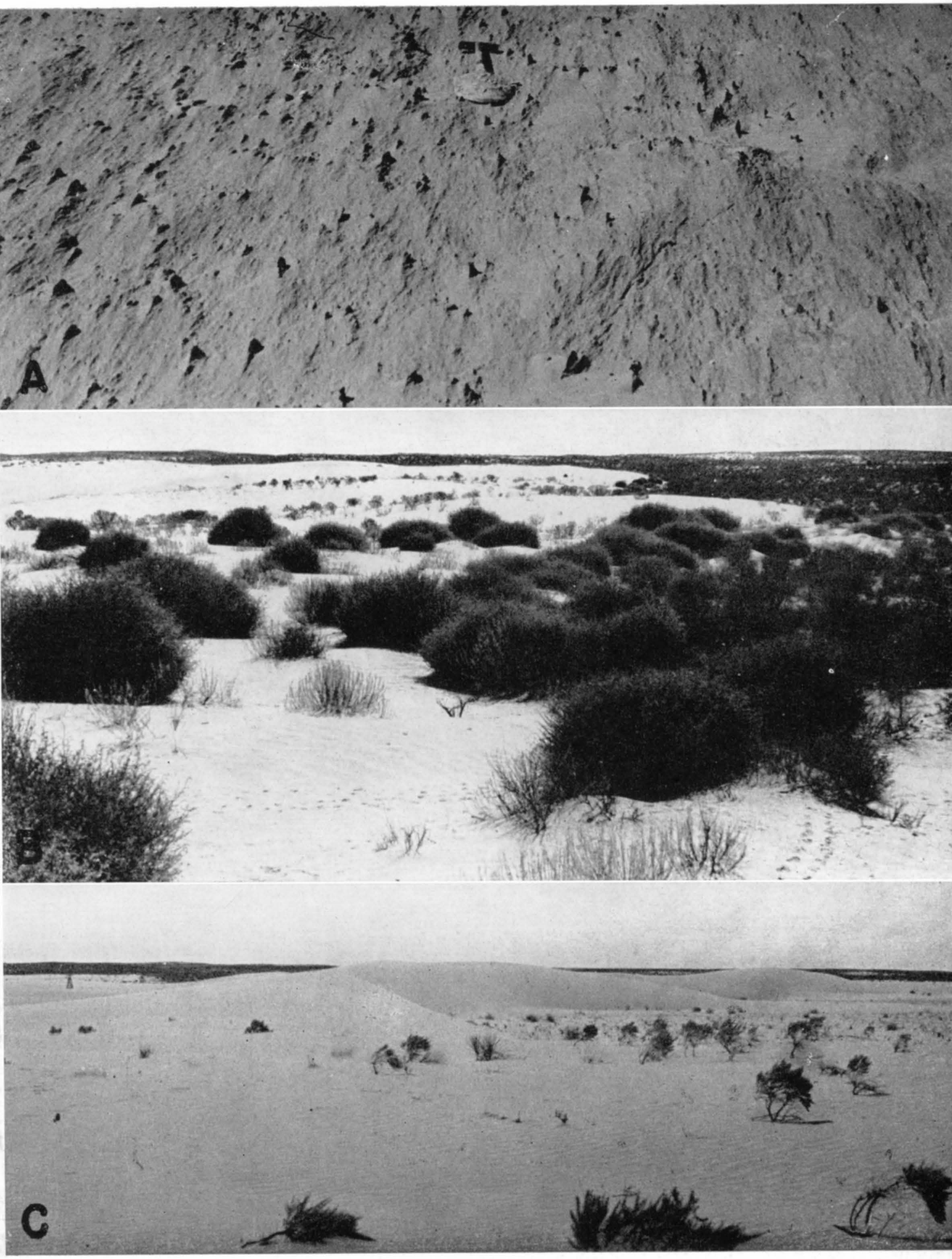

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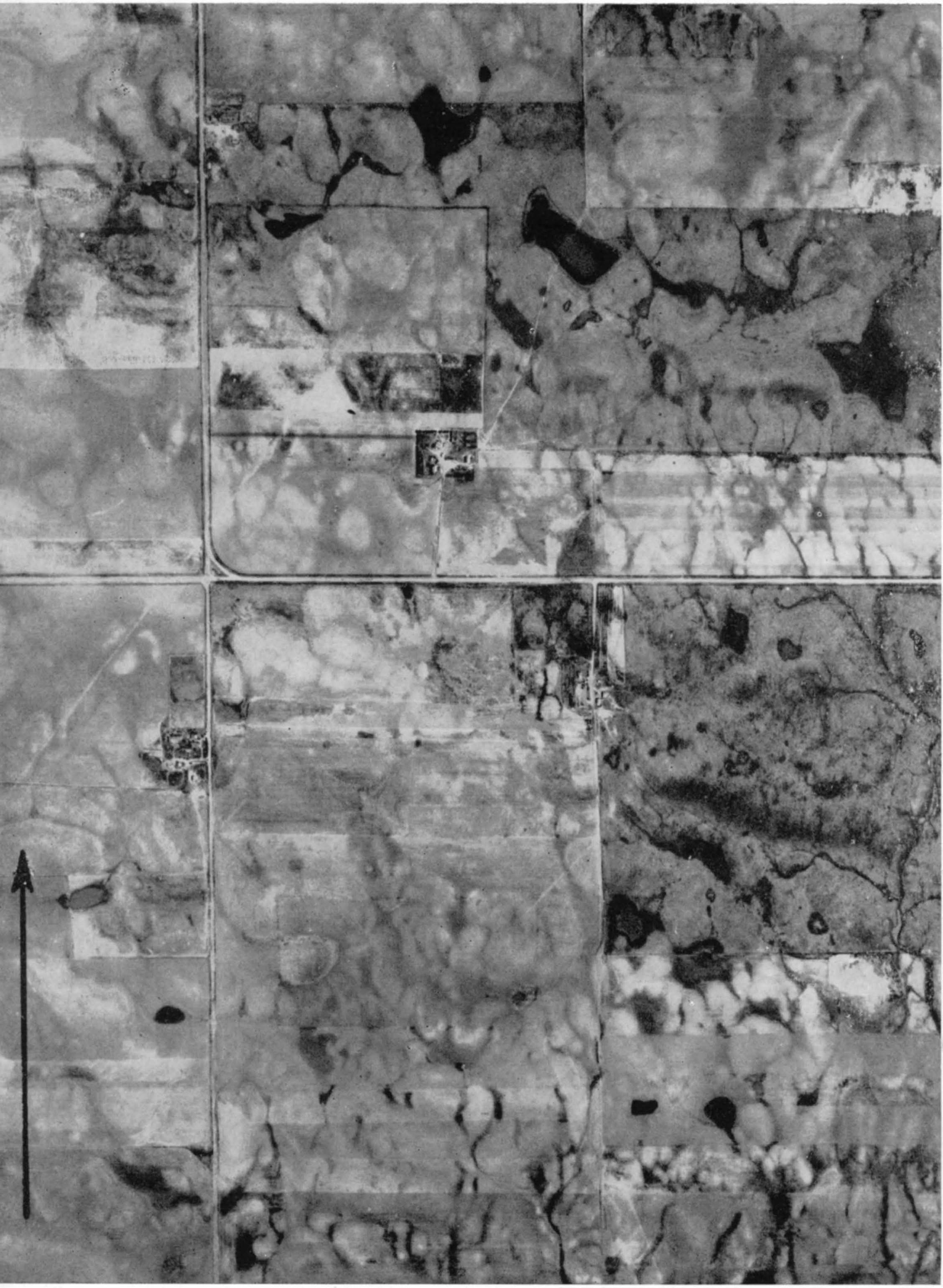

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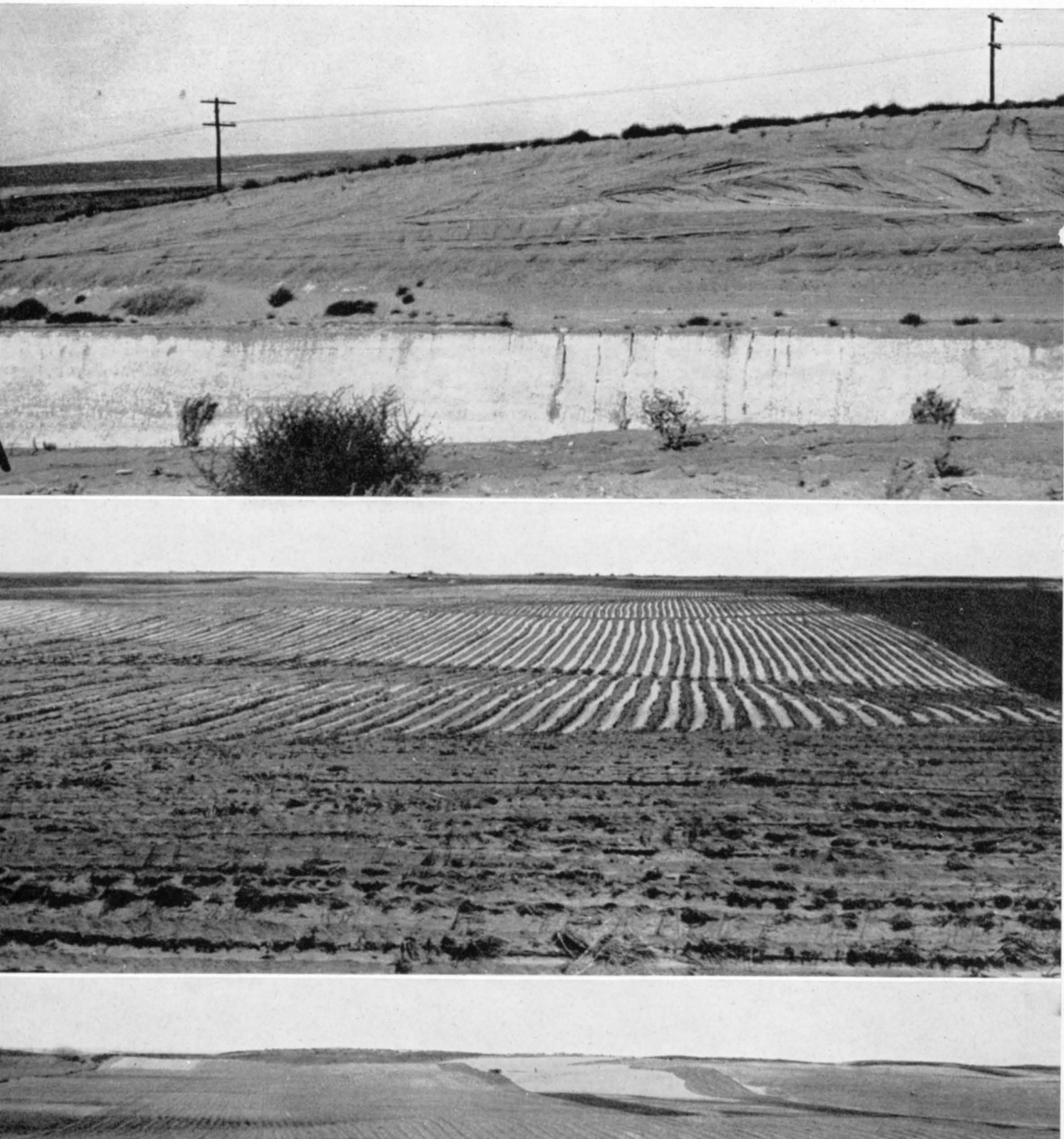

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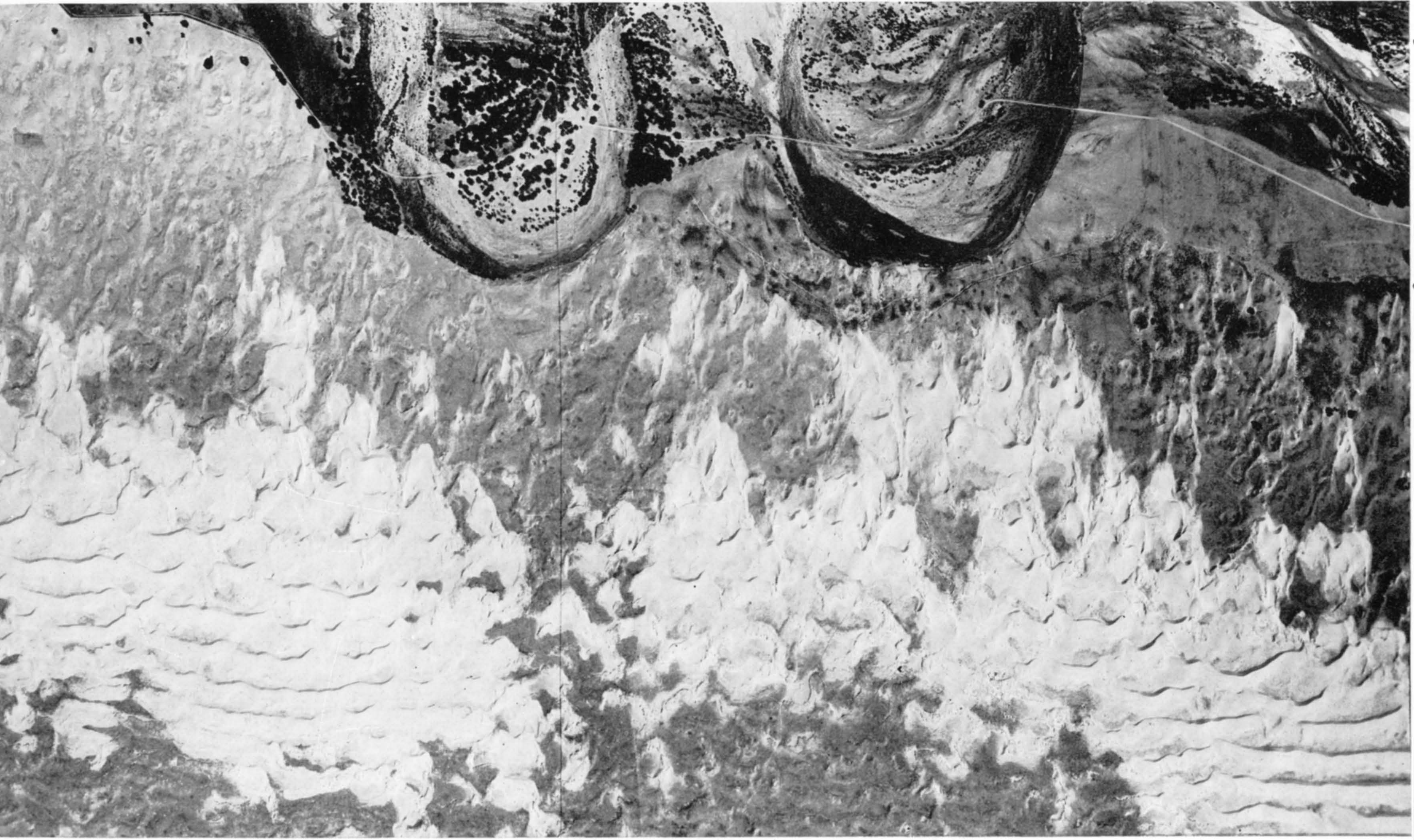

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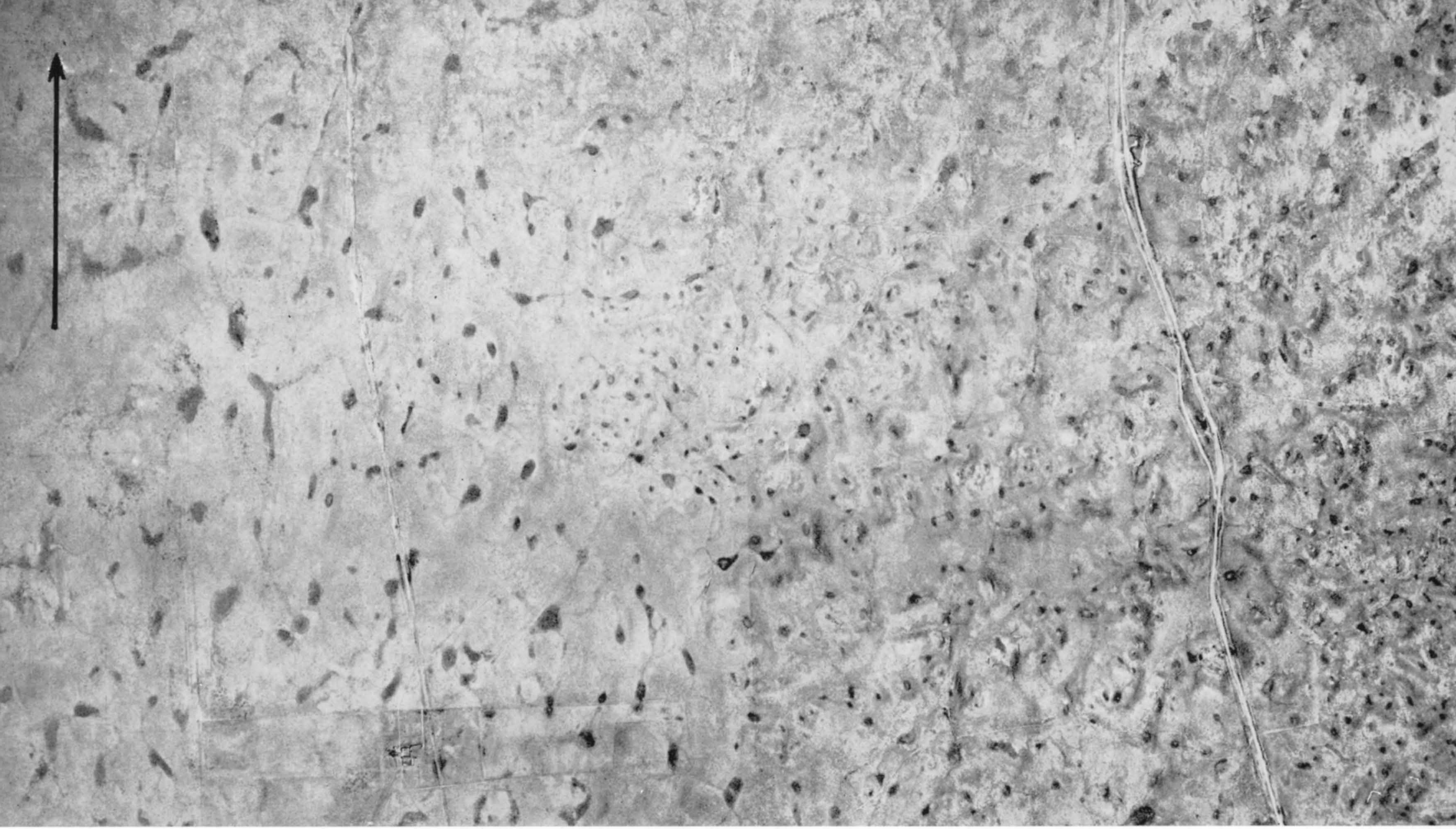

PLATE 28. Multi-cycle dune topography south of Garden City. The recency and extent of rejuvenation increase from left to right. Note changes in the texture of the topography as a result of rejuvenation. The area at the left represents an old-age topography. The dark spots are low places where moisture accumulates and vegetation is denser. Photograph from U. S. Soil Conservation Service. (p. 164.)

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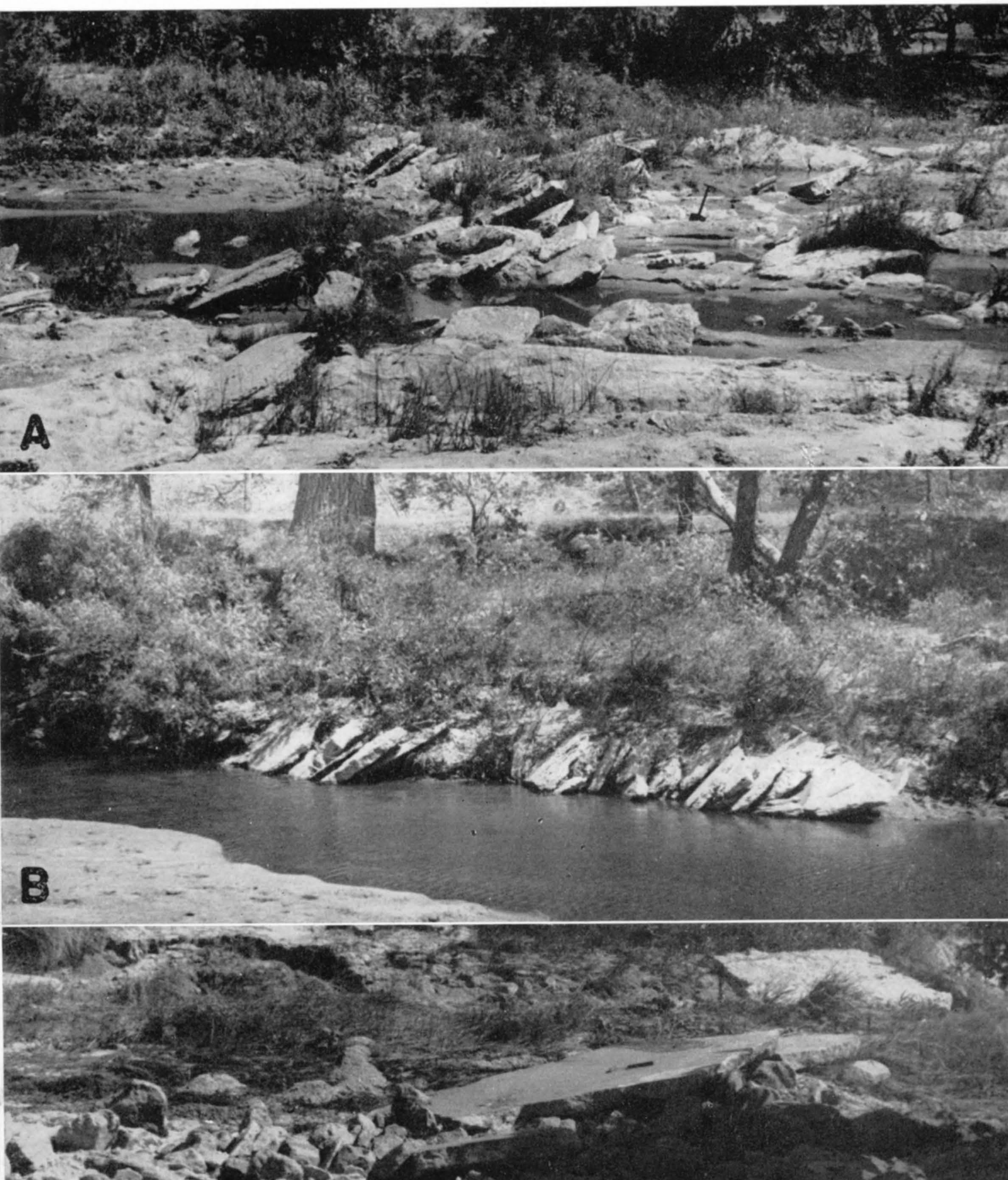

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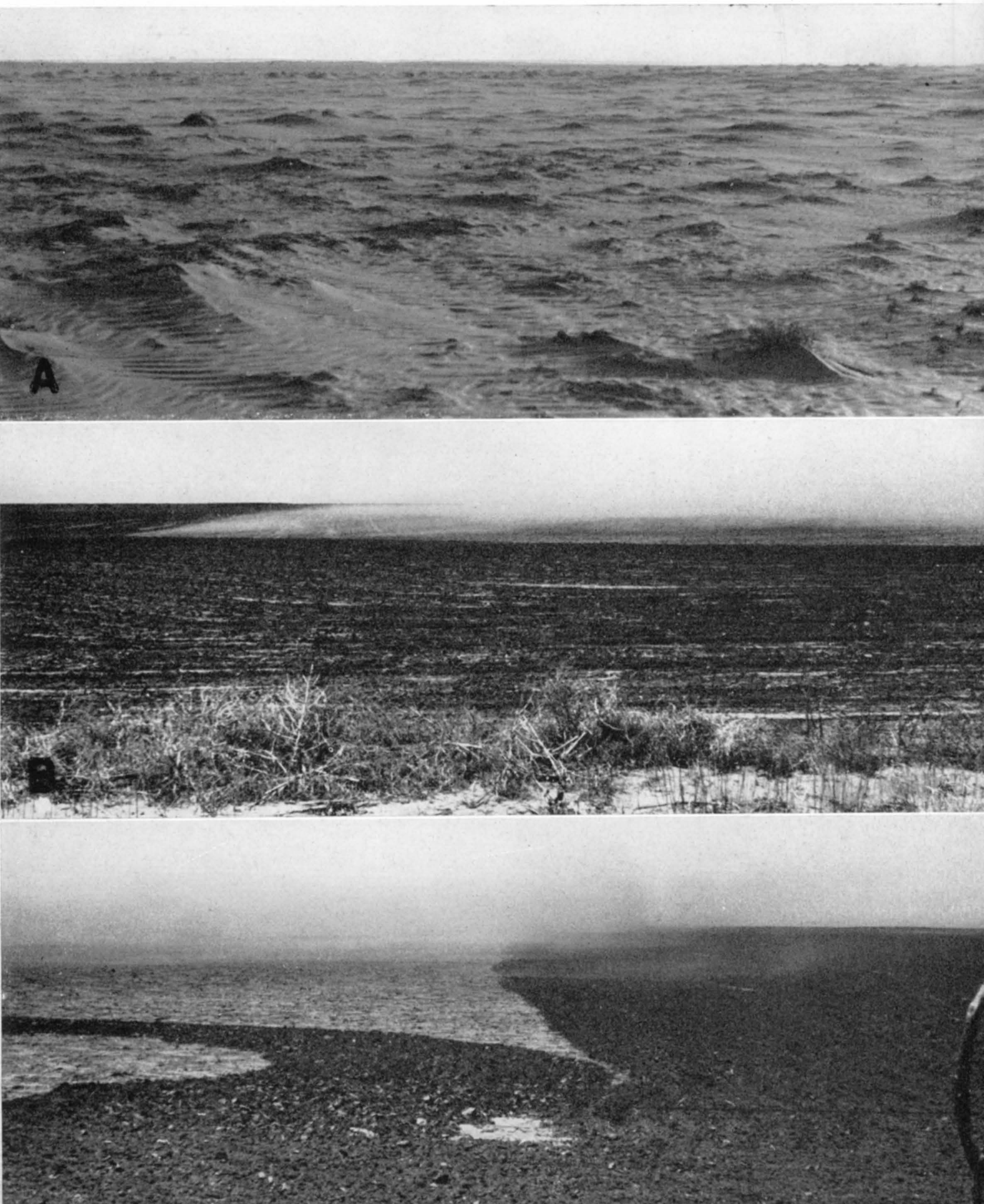

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