PETROLOGY AND STRATIGRAPHY OF THE KIOWA

AND DAKOTA FORMATIONS (basal Cretaceous),

NORTH-CENTRAL KANSAS

by

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ABSTRACT

The Kiowa Formation (formerly Kiowa Shale) of Early Cretaceous age and the Dakota Formation of Early (?) and Late Cretaceous age have been studied and mapped on a detailed reconnaissance basis in an area encompassing some 3500 square miles (9100 km^2) in north-central Kansas. Mapping was initiated as a means of unravelling the stratigraphy, an understanding of which is essential to sedimentary petrographic studies. Neither formation had previously been mapped extensively despite long standing as rock-stratigraphic units. The Kiowa Formation is not present in the northern part of the area mapped. Both formations have an involved nomenclatural history.

The Kiowa Formation is a heterogeneous assemblage composed largely of olive-weathering gray illitic shale and abundant sandstone. The formation rests on the eroded surface of Permian rocks. Along the eastern fringes of its outcrop belt, the Kiowa Formation contains a diagnostic sequence of siltstone underlain by a heterogeneous assemblage of red-mottled and carbonaceous gray to black mudstone and siltstone. The mudstone contains variable amounts of montmorillonite and kaolinite. The siltstone and the underlying assemblage are designated the Longford Member (new name) of the Kiowa Formation. Above the Longford Member, the Kiowa Formation contains numerous fossils of marine or brackish-water invertebrates. As in the Dakota Formation above, fossil deciduous leaves locally are abundant.

The Dakota Formation is subdivided into two members, the Terra Cotta Clay Member below and the Janssen Clay Member above. The Terra Cotta is made up largely of light-gray kaolinitic mudstone and claystone showing abundant red mottles, but it also contains appreciable sandstone. The

Janssen is composed chiefly of gray and dark-gray kaolinitic mudstone and claystone, locally abundant sandstone, and scattered beds of lignite. It contains marine and brackish-water fossils near its contact with the overlying Graneros Shale, into which its upper part grades laterally.

The Kiowa Formation was deposited in, and near the margins of, the Early Cretaceous sea that transgressed from southwest to northeast across Kansas. Part of the Longford Member of the Kiowa Formation is thought to have been deposited on the landward side of the shifting shoreline. The upper part of the formation is thought to include regressive deposits, sedimentation of which heralded deposition of the Dakota Formation. The Dakota Formation is mainly an alluvial plain deposit that developed and extended itself southwestward upon relatively rapid withdrawal of the Kiowa sea. Upward changes in the Janssen Clay Member largely reflect the influence of the transgressing sea in which the Graneros Shale was deposited.

Sandstone in the Kiowa and Dakota formations is mature and contains as much as 95 percent detrital quartz, quartzite, and chert, and locally contains molds and casts of pelecypods. Conglomeratic sandstone in the Dakota Formation is coarser grained than conglomeratic sandstone in the Kiowa and contains numerous pebbles of penecontemporaneously reworked mudstone and claystone. Heavy mineral assemblages in both formations are similar and contain zircon, tourmaline, and staurolite as major components. The proportion of staurolite decreases upward in passing from the Kiowa Formation to the Janssen Clay Member of the Dakota Formation.

Sandstone in both formations is abundantly cross-stratified. Computation of vector-resultant dip bearings of cross-strata in both formations indicates that the regional slope was inclined to the west-southwest. The heavy mineral suite therefore is attributed in part to source areas lying to the east and northeast, mainly Paleozoic or older rocks. The staurolite probably was derived from rocks in the central Appalachian Mountains. Variations in clay mineralogy are attributed to differential transport and sedimentation. Source areas for the clay minerals are thought to have been generally the same for both formations.

The contact selected for mapping the Kiowa and Dakota formations is a sharp, consistent boundary that can be used in most of north-central Kansas and in the type area of the Kiowa Formation in southwestern Kansas. In many places the contact is disconformable.

INTRODUCTION

The Dakota Formation (Cretaceous) of north-central Kansas long has been a source of clay for an important ceramic industry, of water for farms and municipalities, and of construction materials. Subsurface extensions of the Dakota Formation and the underlying Cretaceous Kiowa Formation (formerly Kiowa Shale) have been thought to have potentiality for oil production in the subsurface of western Kansas (Merriam, 1958). Recently, the Kiowa Formation has become a source of raw material for light-weight aggregate, and sandstone within the Kiowa long has been a source of water. In spite of their economic importance, comparatively little intensive geologic work has been done on these basal Cretaceous units in the broad outcrop belt extending from central Kansas (Fig. 1), across Nebraska, and into southwestern Iowa.

In 1958, a study of cross-stratification in the Dakota Formation in Ottawa and Ellsworth counties, Kansas, was started (Franks and others, 1959). As work progressed from Ottawa County into Ellsworth County, it became apparent that study of the Dakota in north-central Kansas could not be divorced from work on the underlying Kiowa. Moreover, study of both formations required that they be differentiated in the field. With impetus provided by plans for the State Geological Survey of Kansas to prepare a new edition of the geologic map of the State (Jewett, 1964), Norman Plummer and the writer started mapping the Kiowa-Dakota contact in the summer of 1960 in Rice County (Fig. 1). Rice County is one of the few areas in Kansas where serious attempt had been made to map the Kiowa and Dakota formations (Fent, 1950) as independent stratigraphic units although they have been classed officially as formations in Kansas since 1942 (Waite, 1942, p. 137). Since the summer of 1960, mapping has been extended

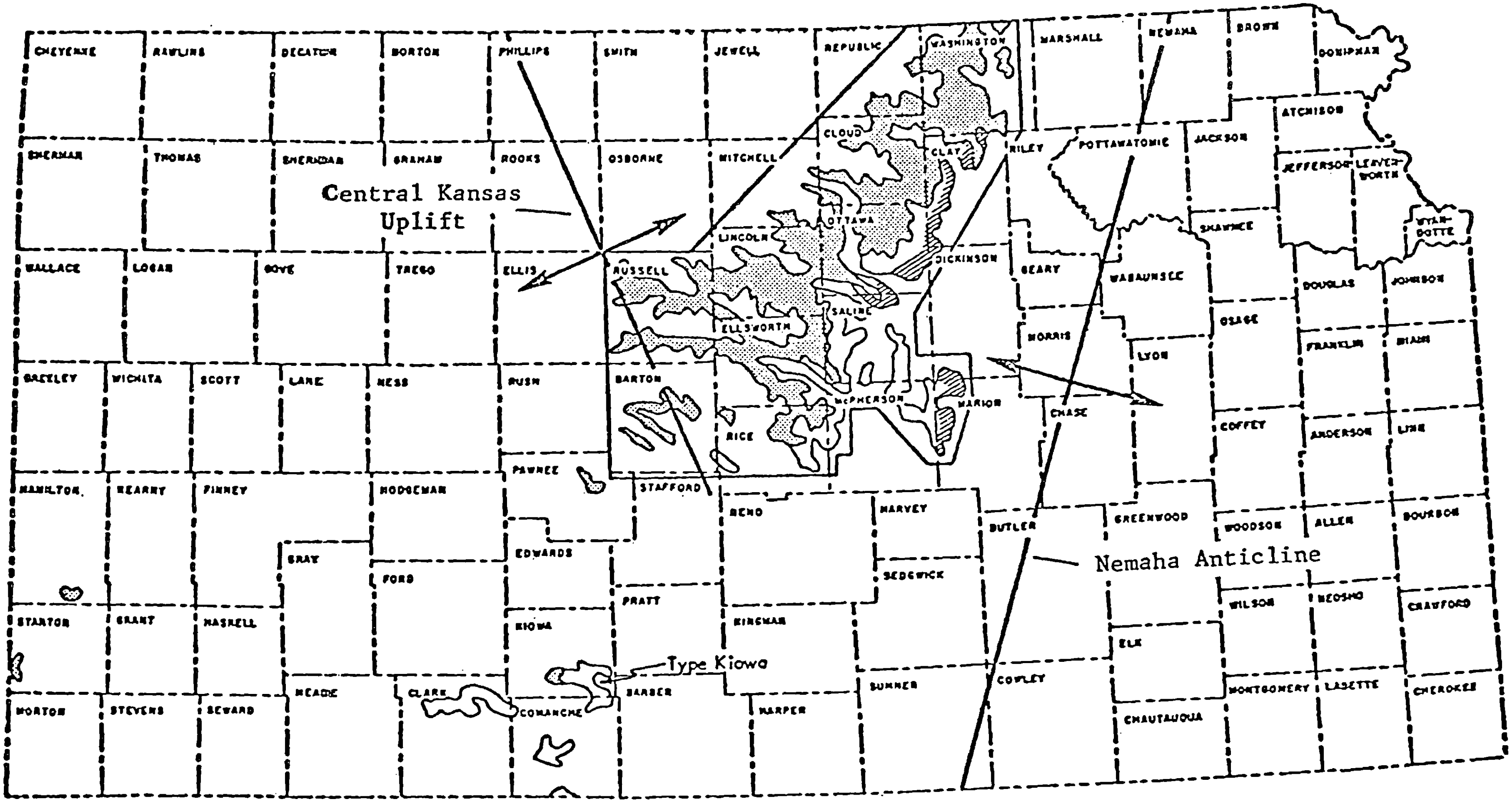

Fig. 1.--- Map of Kansas showing generalized areas of outcrop of the Kiowa and Dakota formations. Area of this report is bounded by solid lines. Stipples indicate Dakota Formation; hachures indicate the general area of outcrop of the Longford Member of the Kiowa Formation (white) in north-central Kansas.

from Rice County northward to Washington County and the Nebraska line in an area encompassing about 3,500 square miles (9,100 km^2) in north-central Kansas.

Concurrently with mapping, samples were collected for analysis of clay minerals, for petrographic and heavy mineral studies, and for size analyses of sandstone. Measurements of dip bearings of cross-stratification also were made and stratigraphic sections (Appendix II) were measured. X-ray diffraction studies of clay minerals were made with nickel-filtered copper radiation and heavy minerals were separated with bromoform. Details of sampling programs and laboratory techniques are given in Appendix I.

Studies of the Kiowa and Dakota formations should increase our basic understanding of the rocks and aid in their exploitation. Increased knowledge of these rocks on the outcrop may be helpful in evaluating whatever potential their extensions in the subsurface of western Kansas may have as reservoirs for oil or natural gas.

Previous Work

The general stratigraphy of the basal Cretaceous Cheyenne Sandstone, Kiowa Formation, and Dakota Formation was worked out by Plummer and Romary (1942). Earlier reports that deserve special mention include the study of the Kiowa by Prosser (1897), the excellent paleontologic work by Twenhofel (1924), and the pioneering petrologic investigation by Tester (1931). Latta (1946) studied the stratigraphy of the Cheyenne, Kiowa, and Dakota formations in the vicinity of the type area of the Kiowa and summarized the nomenclature of the Kiowa Formation. Waite (1942) reviewed the nomenclatural history of the Kiowa and the Dakota formations.

Fent (1950) made one of the first serious attempts at mapping the formations in Kansas.

Various special features have been investigated by several workers. Cementation of Kiowa and Dakota sandstone has been studied by Swineford (1947). Plummer and Romary (1947), Plummer and others (1954), Plummer and others (1960), and Plummer and others (1963) considered ceramic and clay mineralogic aspects of the Kiowa and Dakota. Schoewe (1952) examined coal resources of the Dakota Formation but also reported on lignite beds classed here as Kiowa. Rubey and Bass (1925) studied cross-stratification of the Dakota Formation in conjunction with their work on the so-called "Rocktown channel sandstone" in Russel County. Preliminary studies of cross-stratification were made by Franks and others (1959) in Ottawa County, Kansas. Subsurface studies of the Kiowa and Dakota include those by Lee and others (1948), Merriam (1957a, 1957b), Merriam and others (1959), and Swineford and Williams (1945). Hattin (1964) commented on the significance of fossils in the upper part of the Dakota Formation.

Important papers dealing with the stratigraphy and petrology of rock units overlying and underlying the Kiowa and Dakota formations in Kansas include those by Hattin (1965b) and Swineford (1955).

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Geologic Setting

Stratigraphy

The basal sequence of Cretaceous beds in Kansas includes from bottom to top the Cheyenne Sandstone, the Kiowa Formation (formerly Kiowa Shale), and the Dakota Formation. The Cheyenne Sandstone is composed almost wholly of fine-grained sandstone and is of Early Cretaceous age (Berry, 1922). The overlying Kiowa Formation is noted for its abundance of shale, but it also contains abundant beds and thick lenses of sandstone as well as other rock types. The Kiowa Formation is of Early Cretaceous age (Twenhofel, 1924; Loeblich and Tappan, 1950). The Dakota Formation is composed largely of mudstone and claystone but it also contains appreciable siltstone and abundant lenses of sandstone. The formation has been subdivided into two members, the Terra Cotta Clay below and the Janssen Clay above (Plummer and Romary, 1942). The lower parts of the Dakota Formation are referred questionably to the Early Cretaceous, but the upper parts are of Late Cretaceous age (Eicher, 1965; Hattin, 1965a). Overlying Cretaceous rocks are referred to the Colorado Group, the base of which is marked by the Graneros Shale of Late Cretaceous age (Hattin, 1965b).

In the immediate vicinity of the type area of both the Kiowa Formation and the Cheyenne Sandstone in Kiowa County, Kansas (Fig. 1), the Cheyenne marks the base of the Cretaceous System and rests unconformably on the Whitehorse Formation (Latta, 1948), which is assigned to the Middle Permian of Kansas (Jewett, 1959). West of there, the Kiowa Formation rests directly on Permian rocks and the Cheyenne Sandstone is absent. Exposures of the Dakota Formation are scarce in southwestern Kansas.

In north-central Kansas, the outcrop area of the Kiowa and Dakota formations constitutes the southern end of a belt that extends southward from western Iowa and the type area of the Dakota in northeastern Nebraska into central Kansas. Throughout much of north-central Kansas (Fig. 1; Plate 1), the Kiowa Formation rests directly on Middle Permian rocks, mostly of the Sumner Group. Near the Kansas-Nebraska border where the Kiowa Formation is absent, the Dakota Formation overlies the lower parts of the Sumner Group. From Kansas northward across Nebraska, the Dakota rests on progressively older rocks until it rests on lower Pennsylvanian rocks in its type area, as has been shown by information obtained from oil wells (Condra and Reed, 1959). In northwestern Iowa and southeastern South Dakota, extensions of the Dakota overlap Pre-cambrian rocks of the Sioux Uplift. What seem to be extensions of the Dakota are found in Minnesota, Wisconsin, and western Illinois (Stauffer and Thiel, 1941; Andrews, 1958; Frye, Willman, and Glass, 1964).

The Kiowa Formation extends southward into western Oklahoma where it is found mainly as scattered outliers (Bullard, 1928). The Cheyenne, Kiowa, and Dakota formations have facies equivalents in the subsurface of western Kansas (Merriam, 1957a), but in parts of the subsurface of western Kansas, equivalents of the fundamentally nonmarine Dakota Formation are largely marine (Merriam and others, 1959). In the Denver Basin area of Colorado, in northeastern New Mexico, and along the Colorado Front Range, approximate time-stratigraphic equivalents of the basal Cretaceous sequence of Kansas are found. These rocks, which are referred to variously as the Purgatoire and Dakota formations and as the Dakota Group, mostly had different source areas from those of the Cheyenne, Kiowa, and Dakota formations of Kansas (Chisholm, 1963; Haun, 1963; MacKenzie and Poole, 1962; Waagé, 1953, 1955). The rocks in Colorado and New Mexico were deposited in and on the western side of a seaway that extended into the Western Interior of the United States from the Gulf Coast region and also from the north during late Early Cretaceous time and again during Late Cretaceous time (Haun, 1963; Reeside, 1957).

Approximate time-stratigraphic and perhaps partial rock-stratigraphic equivalents of the Cheyenne, Kiowa, and Dakota formations are found in the Black Hills of southwestern South Dakota and eastern Wyoming as well as in the subsurface of surrounding areas including western Nebraska (Gries, 1962; Haun, 1963; MacKenzie and Poole, 1962; Waage, 1959). Some of the basal Cretaceous rocks in these areas, however, may be older than the Cheyenne Sandstone of Kansas. Moreover, the Precambrian quartzite of the Sioux Uplift in southeastern South Dakota and adjacent parts of Nebraska separated the lower part of the sequence deposited in South Dakota from sediments deposited in Kansas and Nebraska (Gries, 1962; MacKenzie and Ryan, 1962; Reeside, 1957).

Distribution of Outcrops and Physiography

The outcrop belt of the Kiowa and Dakota formations in north-central Kansas ranges from 15 miles (24 km) wide near the Kansas-Nebraska border to 100 miles (160 km) wide near its southern limit in central Kansas. The belt underlies that part of the eastern Plains Border region (Fenneman, 1931, p. 25-26) known as the Smoky Hills (Schoewe, 1949, p. 309-311). Outcrops of underlying Permian rocks mark the western edge of the Central Lowlands physiographic province. The southern edge of the outcrop belt coincides with the margins of the Great Bend Lowland (Fenneman, 1931, p. 27). There the Kiowa and Dakota formations are truncated and pass beneath an extensive cover of Pleistocene deposits (Plate 1). In north-central Kansas, the Kiowa and Dakota formations are characterized by the relatively rugged, generally mature topography of the Smoky Hills. Eastfacing dissected escarpments and scattered outliers, some flat-topped, others rounded and dissected, are mostly capped by sandstone beds of the Kiowa and Dakota formations.

The area of this report is transected by four major east-flowing streams. From south to north they are the Smoky Hill, Saline, Solomon, and Republican rivers. The divides between these and other streams generally are mantled by deposits of loess and the major valleys contain thick deposits of Pleistocene alluvium. In places, terrace deposits of sand and gravel blanket the gentle slopes of the valleys. The northern parts of the area shown on Plate 1 are much covered by glacial outwash and by loess, particularly parts of Washington, Republic, Cloud, and Clay counties. Kansan till is found in Washington County.

Thick deposits of Pleistocene along the valley of the Republican River thoroughly blanket the area in which the Kiowa Formation thins and pinches out (Plate 1). The most northerly identifiable rocks of the Kiowa are the nearly white siltstones that mark the top of the Longford Member (new name), which is restricted to the eastern fringes of the Kiowa outcrop belt (Fig. 1).

Structural Geology

Regional dip on top of the Dakota Formation west of the outcrop belt in north-central Kansas approximates 7 feet per miles (1.3 m/km) to the north or northwest (Lee and others, 1948, p. 146; Merriam, 1957b). Within the outcrop belt of the Kiowa and Dakota formations, various structural features have obliterated any readily detectable regional structural pattern although the area shown on Plate 1 lies largely within the Salina Basin. Locally, faults and gentle folds can be detected along the Permian-Cretaceous boundary, but the unconformity at the base of the Cretaceous rocks largely has diluted the influence of pre-Cretaceous structural patterns. The Salina Basin is limited on the west by the Central Kansas Uplift and on the east by the Nemaha Anticline (Fig. 1). The southern end of the Salina Basin is poorly expressed but is in southeastern Saline and northern McPherson counties. The gentle west flank of the Nemaha Anticline underlies much of Washington County and accounts in part for the narrowness of the belt of basal Cretaceous outcrops in that area.

According to Lee and others (1948, p. 146-147), a southwesterly dip of about 10 feet per mile (1.9 m/km) was imparted to Permian rocks in north-central Kansas prior to deposition of the basal Cretaceous beds. Post-Dakota deformation tilted the Permian rocks in the Salina Basin "...to a somewhat variable dip of 6 to 10 feet per mile to the northwest." (Lee and others, 1948, p. 147). Structures superimposed on this regional pattern include the Ellsworth Anticline and the Ellsworth-Kanopolis Anticline. The Kiowa and Dakota formations are flexed over the Ellsworth Anticline, a gentle north-plunging fold on the northeast flank of the Central Kansas Uplift in southern Ellsworth and northern Rice counties. The Ellsworth-Kanopolis Anticline is part of a line of folds extending southeasterly from Russell County on the northwest across Ellsworth and McPherson counties (Jewett, 1951, p. 133-134). In Ellsworth County, the breached crest of the Ellsworth-Kanopolis Anticline is followed approximately by the Smoky Hill River and is expressed in the differences in upstream extent of the Kiowa-Dakota contacts on the north and south banks of the river (Plate 3). In the general area shown on Plate 1, other major drainages are seen to follow approximately the same trend that the Smoky Hill follows across Ellsworth County. Moreover, similar differences in upstream position of the Kiowa-Dakota contact are seen along the Saline River in southern Ottawa County (Plates 1 and 2).

Other structural features that have influenced the outcrop patterns of the Kiowa and Dakota formations include the Lindsborg Anticline (Merriam, 1963, p. 283), which trends northward from McPherson County into central Saline County. The north-flowing reach of the Smoky Hill River in McPherson and Saline counties generally follows the trend of the structure. The anticline coincides approximately with the expanse of Permian rock separating the Smoky Buttes in southwestern Saline County from the outlier of Kiowa in southeastern Saline County (Plate 1). The Lindsborg Anticline is mentioned here inasmuch as it seems to have exerted some control on Kiowa and Dakota sedimentation.

Several small faults are plotted on Plate 1. The fault paralleling the south bank of the Solomon River in southern Ottawa County (Plates 1 and 2) was mapped previously by Mack (1962) and the fault near the southwest corner of sec. 21, T. 16 S., R. 7 W., Ellsworth County (Plates 1 and 3) has been described previously by Ver Wiebe (1937). Movement of the latter fault was penecontemporaneous with deposition of beds in the basal part of the Dakota Formation. All the faults shown on Plate 1 involve minor displacements probably not exceeding 50 feet (15 m) of stratigraphic throw.

NOMENCLATURE, DEFINITION, AGE, AND CORRELATION OF KIOWA AND DAKOTA FORMATIONS

General

Many of the problems of the stratigraphy of the Kiowa and Dakota formations of Kansas stem from problems of nomenclature, but the reverse also is true. Figure 2 emphasizes the complexity of nomenclature applied to these rocks. The variations in terminology shown in the figure would be increased manifoldly if classifications used in other sources (as

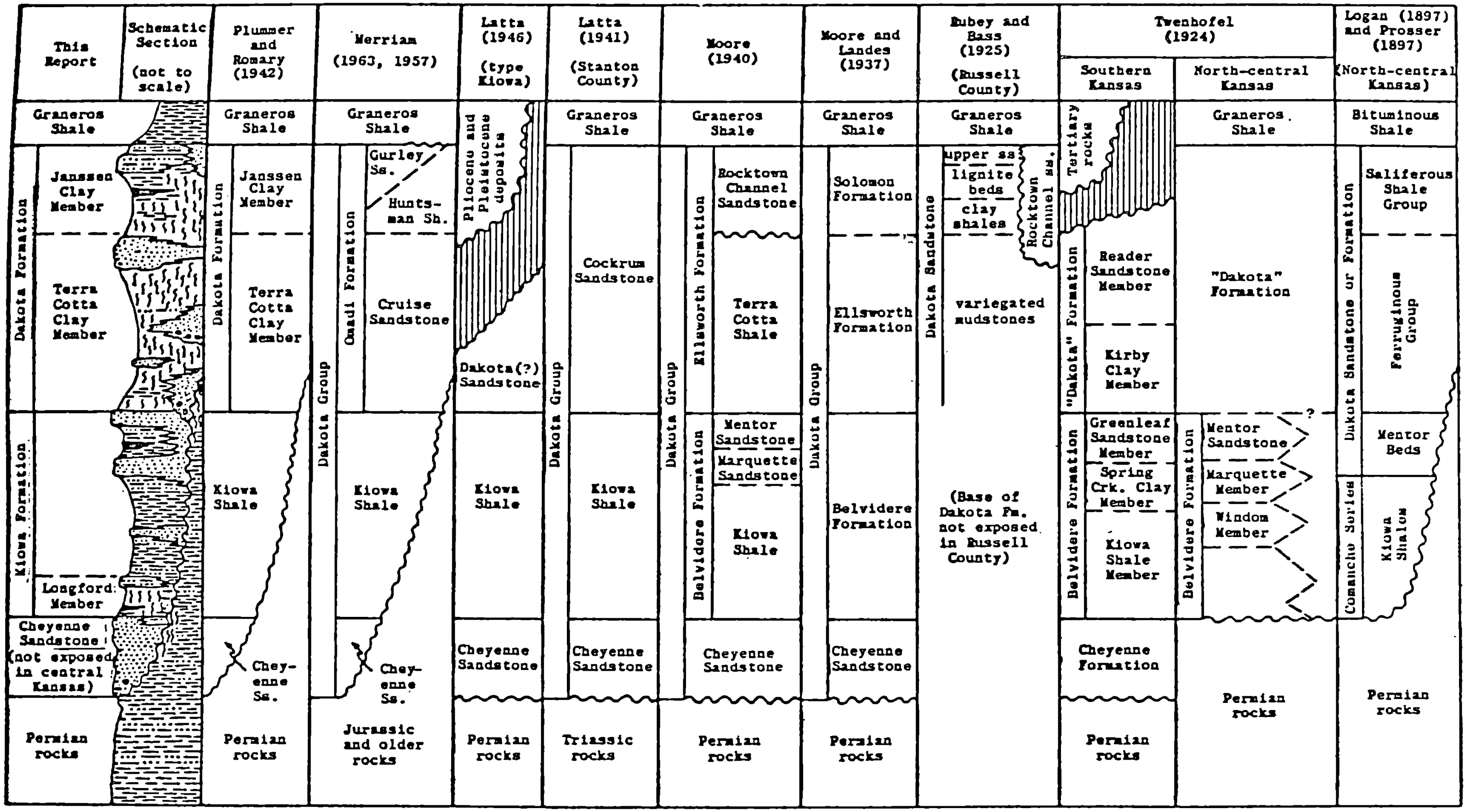


Fig. 2 .--- Chart showing generalized section of basal Cretaceous rocks in Kansas and some of the variations in nomenclature and interpretations of stratigraphic relationships.

Cragin, 1885, 1886, 1890, 1894, 1895b; Gould 1898; Twenhofel, 1920; Tester, 1931) were added to the compilation. The Cheyenne Sandstone is included in Figure 2 for completeness, but it does not crop out in north-central Kansas.

Although the nomenclatural history of the Kiowa and Dakota Formations is complex, excellent summaries have been given by Bullard (1928), Latta (1946), and Waite (1942). More recently, Merriam (1963, p. 135-137) has discussed additional innovations in terminology. Discussions of nomenclature in the Colorado Front Range and in the Black Hills by Waagé (1955, 1959) also are pertinent to problems of nomenclature in Kansas.

One aspect of the stratigraphic-nomenclatural problems of the Kiowa and Dakota formations warrants special mention. Since introduction of the name "Dakota" in the broad belt of outcrops that extends from western Iowa to the type area in northeastern Nebraska and thence southward into central Kansas, rocks variously referred to as Dakota Group, Dakota Formation, and Dakota Sandstone have been studied and described in Kansas, Nebraska, Iowa, Minnesota, Colorado, Wyoming, South Dakota, Utah, Arizona, and New Mexico. The name "Dakota" also has been applied in British Columbia in time-stratigraphic sense (Dawson, 1901, p. 77-89). All the exposures except those in Kansas, Nebraska, Iowa, and Minnesota are in outcrop belts that are separated from the type region by hundreds of miles of younger and older rocks. Moreover, ideas and inferences, observations, and classifications based on rocks in these outlying areas have been extrapolated backwards to the type area, even to the extent that nomenclature developed for units having either different source areas or different stratigraphic ranges has been applied in the type area of the Dakota in northeastern Nebraska. On occasion, disconformities or unconformities detected in some of the outlying areas have been inserted into the type section of the Dakota.

In discussing the stratigraphy and nomenclature of the Kiowa and Dakota formations, it must be remembered that much of the nomenclature of these rocks developed before modern concepts of stratigraphic nomenclature and principles. Of particular importance is the lack of distinction made by early workers between rock-stratigraphic and time-stratigraphic units and the degree to which recognition and extension of rock units as we think of them now were dependent upon paleontologic rather than lithologic criteria. Hence, many of the comments that follow are not intended as strong criticism of either the men or of their publications, but rather as providing background for evaluation of various points of view now held concerning the stratigraphy and nomenclature of Kiowa and Dakota rocks.

Definition of Kiowa and Dakota Formations

Dakota Formation

The Dakota Formation has its type area in northeastern Nebraska where it was defined as the Dakota Group by Meek and Hayden (1862). They described it (p. 149) as "Yellowish, reddish and occasionally white sandstone, with at places, alternations of various colored clays and beds and seams of impure lignite...." and referred to its distribution as follows:

> Hills back of the town of Dakota; also extensively developed in the surrounding country in Dakota County below the mouth of Big Sioux River, --- thence extending southward into Northeastern Kansas[1/] and beyond.

1/ Reference to "Northeastern Kansas" stems from the time when the Kansas Territory encompassed the eastern half of what is now Colorado. The area would be described as north-central and central Kansas today.

They also stated (p. 420):

> Below the mouth of the Big Sioux River, this formation is seen at some localities resting directly upon the limestones of the Coal Measures; but in north-eastern Kansas it usually reposes on a series of reddish and various colored clays, probably of Jurassic age.

Since the time of introduction of the name, "Dakota" it has been shown that the rocks referred to as Jurassic in Kansas by Meek and Hayden mostly are Permian, but Prosser (1897, p. 188-189, 192-193) has offered good evidence that rocks now classed as part of the Kiowa Formation in north-central Kansas (particularly in the vicinity of Smoky Buttes in Saline County) were included in the Jurassic by Meek and Hayden (1859a, 1860) (Fig. 3). But other Kiowa rocks in Saline County were included in the Dakota Group or "Formation No. 1" by Meek and Hayden largely because of the presence of imprints of dicotyledonous leaves in indurated sandstone.

The classification used in this report ranks the Dakota as a formation. The term Dakota Group (cf. Merriam, 1957a), which also includes the Cheyenne Sandstone and the Kiowa Formation, is not used. Ranking of the Dakota as a formation is and has been official usage of the State Geological Survey of Kansas since 1942. Although age considerations entered into acceptance of the Dakota as a formation in 1942 (Waite, 1942, p. 137), application of the name "Dakota Formation" stems directly from the work of Plummer and Romary (1942). Their classification was lithologic and was not founded on age considerations. They also recognized that the underlying Kiowa Formation thinned northward in north-central Kansas and did not extend into Nebraska along the outcrop (p. 326). Hence Plummer and Romary's study showed that rocks classed as "Dakota Formation" in Kansas as "Dakota Group" in Nebraska (Condra and Reed, 1959) are rock-stratigraphic extensions one of the other.

Fig. 3.--- Exposure of shale and sandstone in Kiowa Formation, Coronado Heights, NW¼ SW¼ sec. 31, T. 16 S., R. 3 W., Saline County, Kansas. Typical gray Kiowa shale (2) grades upward into interlaminated siltstone, fine-grained sandstone, and shale (3) that in turn grades upward into fine-grained sandstone (4). Numerals correspond to units in Measured Section 9, Appendix and Plate 4. Sandstone capping hill is basal part of Dakota Formation. The Kiowa exposed here is part of the general sequence referred to the Jurassic or Triassic by Meek and Hayden (1859a, 1860).

Terra Cotta Clay Member.---

Plummer and Romary (1942) subdivided the Dakota Formation into two members on lithologic and economic grounds, the Terra Cotta Clay Member below and the Janssen Clay Member above. Both members have their type localities in Ellsworth County, Kansas. The Terra Cotta Clay Member is named from the old Terra Cotta school district near the abandoned town of

Terra Cotta along the north line of sec. 23, T. 15 S., R. 6 W. The Terra Cotta Clay is characterized by light-gray to light greenish-gray mudstone and claystone showing numerous red to reddish-brown mottles. The amount of sandstone and siltstone present in the member differs from place to place. The Terra Cotta approximates the lower two thirds of the Dakota Formation in north-central Kansas (Plummer and Romary, 1947, p. 38, 41).

Janssen Clay Member.---

The Janssen Clay Member of the Dakota Formation is defined from exposures near Janssen Station (now abandoned) near the cen. S. line, sec. 3, T. 16 S., R. 9 W., Ellsworth County. According to Plummer and Romary (1942, p. 336) "...the Janssen member consists largely of gray to dark-gray clay and silt, some beds of fissile shale, and commonly a bed of lignite or highly lignitic clay." Sandstone generally is a minor component. The contact between the Janssen Clay and the Terra Cotta Clay members (Plummer and Romary, 1942, p. 336) was "...drawn at the top of a marker concentration of concretionary 'iron'." However, the concentrations of concretionary iron oxide used by Plummer and Romary to separate the two members of the Dakota Formation do not constitute a persistent datum and the stratigraphic position of the contact differs from place to place. In many places the Janssen Clay Member also contains beds characteristic of the Terra Cotta Clay Member. The Janssen Clay approximates the upper one-third of the Dakota Formation. The member generally corresponds to those parts of the Dakota Formation previously designated as "saliferous shale group" (Logan, 1897), "Rocktown channel sandstone" (Rubey and Bass, 1925), and "Solomon formation" (Moore and Landes, 1937).

Kiowa Formation

Recognition of beds of Cretaceous age in the type area of the Kiowa Formation near Belvidere, Kiowa County, Kansas (Fig. 1) goes back to Mudge (1878, p. 47, 55). In 1883, St. John (p. 571) recorded the occurrence of marine fossils of Cretaceous age in rocks near the base of the Dakota Group of Meek and Hayden (1862) not only in Kiowa County, but also in western Saline County, north-central Kansas. He also noted (p. 588) that the fossil assemblages were similar to those found in the Cretaceous of north-Texas Coastal Plain. Both the Cheyenne Sandstone and the Kiowa Formation in southwestern Kansas were correlated variously with the Fort Benton and Dakota groups of Meek and Hayden (1862) by Cragin (1885) and St. John (1887).

In 1889 Cragin (p. 35-37) published the first relatively detailed description of the rocks exposed in the vicinity of type Kiowa, where the Kiowa Formation locally is overlain by erosional remnants of the Dakota Formation. Cragin also observed the similarity of the fossils in the Kiowa Formation to those described from the Comanche Series of Texas and seems to have been the first to realize that the rocks now assigned to the Kiowa Formation were older than the Dakota Group of Meek and Hayden (1862). Hay (1893, p. 108-109) concurred in the assignment of Kiowa rocks to older parts of the Cretaceous although he had been tempted to equate the rocks with the Dakota and Fort Benton group of Meek and Hayden (1862).

Cragin (1894, p. 49) first used the name "Kiowa shales" to designate

> ...the inferiorly dark-colored and superiorly light-colored shales that outcrop in several of the counties of southwestern Kansas, resting upon the Cheyenne sandstone in their eastern, and upon the 'red-beds' in their middle and western exposures, and being overlaid by brown

> sandstones of middle Cretaceous age, or Tertiary or Pleistocene deposits, according to locality....

With publication of Prosser's (1897) excellent study of the so-called Comanche series of Kansas, the name "Kiowa shales" seems to have come into fairly general use in approximately the same sense that the name "Kiowa" is used now in southwestern Kansas. However, the names "Belvidere beds" and "Medicine beds" have been applied to the same rocks in whole or in part from time to time (cf. Cragin, 1895b; Twenhofel, 1924, p. 20-34; Latta, 1946, p. 222, Fig. 2).

Although LeConte found marine fossils in sandstone in the basal parts of what was then included in the Dakota Group near Bavaria, Saline County, as early as 1868, Cragin (1889, p. 37) seems to have been the first to recognize that shale lithologically and paleontologically equivalent to the Kiowa of southwestern Kansas also was present in north-central Kansas. Prosser (1897), Twenhofel (1924), and Plummer and Romary (1942) have established that the Kiowa Formation of north-central Kansas not only correlates in time with the Kiowa of southwestern Kansas, but also constitutes a lithologic and genetic extension of rocks exposed in southwestern Kansas.

Traditionally the lithic term "shale" has been used with the geographic term "Kiowa," but the name "Kiowa Formation" is used in this report in recognition of the lithologic heterogeneity of the unit. Mapping in north-central Kansas, as well as in Clark County in southwestern Kansas (Swineford, unpublished manuscript) demonstrates that the Kiowa commonly is not the relatively monotonous sequence of dark-gray to medium-gray shale seen in the type area (cf. Latta, 1946, measured sections, p. 251-256). Rather the Kiowa Formation shows amazing lateral and vertical lithologic variation: in many areas it is composed largely of sandstone that interfingers laterally with more typical shale. Locally abundant carbonaceous shale, claystone, and mudstone as well as light-colored mudstone and siltstone also are present in the Kiowa and a distinctive sequence of siltstone and argillaceous rocks is found along the eastern fringes of the Kiowa outcrop belt in north-central Kansas.

In north-central Kansas, Cragin (1895a) studied Kiowa sandstone beds that contain marine fossils and introduced the name "Mentor beds" for them. He also correlated these beds with the higher parts of the Kiowa of the type area and proposed a type locality for the "Mentor beds" near the common corners of secs. 15, 16, 21, and 22, T. 15 S., R. 2 W., about 3 miles east of Mentor, Saline County. The type locality consisted then as now mainly of fossiliferous sandstone rubble scattered about plowed fields and grader ditches. Some bedrock is exposed just east of the NW cor. sec. 22 but it contains few fossils and dips steeply to the southwest (Plate 1). Partly or largely because of the association of sandstone containing marine fossils with sandstone containing imprints of dicotyledonous leaves, Prosser (1897) grouped the "Mentor beds" with the Dakota of Meek and Hayden (1892). Twenhofel (1920, 1924) attached great importance to the beds of fossiliferous sandstone and ranked the "Mentor" as a member of his "Belvidere formation" (Kiowa of this report). In describing his usage of the name "Mentor" as well as the names of various other members he had proposed, Twenhofel (1924, p. 31) said: "It is not to be understood that these terms are given any significance other than that they conveniently serve to designate the occurrence of fossils and the stratigraphic position of exposures." However, Twenhofel (1924, p. 31) did attempt to use the "Mentor horizon" as a dividing line between his "Belvidere formation" and the Dakota. The "Mentor beds" constitute varied assemblages (R.W. Scott, 1965, oral communication) of facies fossils in sandstone beds, but the fossiliferous sandstone does not form a zone within the Kiowa Formation. Rather, the sandstone is found as separated beds and lenses in various parts of the Kiowa Formation in north-central Kansas and "Mentor" fossils range nearly from the base of the formation to its top.

Longford Member (new name).---

In parts of Marion, Dickinson, Saline, Ottawa, and Clay counties, mapping of the Permian-Cretaceous contact has revealed the presence of a distinctive sequence of siltstone at or near the base of the Kiowa Formation. The siltstone sequence rests directly on weathered Permian rocks belonging to the Wellington Formation in places, but more commonly it lies on a heterogeneous assemblage of siltstone, mudstone, claystone, and carbonaceous or lignitic beds of variable thickness that locally contains lenses of characteristic gray Kiowa shale. In most places the distinctive siltstone is overlain by Kiowa shale, but the rocks below the siltstone have been confused with the Dakota Formation in the past. Schoewe (1952, p. 108-112) assigned lignitic material in the Longford Member to the Dakota Formation. Walters and Bayne (1959) mapped these rocks as part of the Dakota Formation in Clay County and consequently overlooked appreciable thicknesses of overlying Kiowa rocks, as did Mack (1962) in Ottawa County.

The name "Longford Member" is proposed for this distinctive basal part of the Kiowa Formation. The name is taken from exposures north of the town of Longford, Clay County, Kansas. The type section is along the west line SW 1/4 sec. 9, T. 10 S., R. 1 E., Clay County, (Measured Section 12, Appendix and Plate 5) in cutbanks and roadcuts along the black-topped road linking Longford to Oak Hill. The topmost few feet of the member are not exposed in the immediate vicinity of Longford, but are well exposed together with the contact with the overlying shale in sec. 32, T. 9 S., R. 1 E., Clay County (Measured Section 13, Appendix and Plate 5). A reference section also was measured near the cen. SE 1/4 sec. 23, T. 16 S., R. 1 E., Dickinson County where somewhat different aspects of the lower parts of the Longford Member are expressed (Measured Section 10, Appendix and Plate 5).

Excellent exposures of the Longford Member also are seen in sec. 27, T. 9 S., R. 1 E., Clay County, east of Oak Hill, and near the cen. sec. 8, T. 6 S., R. 2 E., Clay County, in the cut behind the Northern Natural Gas Company pumping station. Figure 1 shows the generalized distribution of the Longford Member in north-central Kansas.

The siltstone marking the top of the Longford Member (Fig. 4) mostly is between 3 and 15 feet (0.9 and 4.5 m) thick. Characteristically it is nearly white but commonly is light gray to light yellowish gray or grayish orange depending upon concentrations of limonitic stain. In most places it is very thin to thin bedded and individual beds are made up of thin laminae. The laminae are either even or rippled. Locally bedding surfaces show imprints of or carbonized remains of abundant plant debris. Although the siltstone commonly is indurated, calcite cement is erratically distributed. The cement follows bedding locally but also is concentrated in discoidal to spherical concretionary masses (Fig. 4).

The sequence beneath the capping siltstone is highly varied both in thickness and lithology. In places it is composed largely of red-mottled gray mudstone and claystone (Fig. 5-A) that is superfically similar to red-mottled mudstone and claystone in the Dakota Formation. The plasticity generally is greater than mudstone and claystone found in the Dakota

Fig. 4.--- Thin-bedded siltstone marking top of Longford Member, Kiowa Formation, about 0.15 mile (o.24 dm) north SE cor. sec. 8, T. 10 S., R. 1 E., Clay County, Kansas. Upper parts contain numerous discoidal concretionary masses of calcite cement. Handle of pick is about 2.5 feet (0.8 m) long.

Formation, however, due to the presence of appreciable amounts of montmorillonite or mixed-layer illite-montmorillonite. Locally the sequence contains considerable thicknesses of nearly white siltstone with unusually coarse red mottles and streaks (Fig. 5-B). In nearly all exposures examined, gray mudstone and claystone were seen. Commonly the clay rocks are highly carbonaceous and beds of lignite and lignitic shale occur locally. To the south and west carbonaceous brownish-gray argillaceous siltstone and dark-gray to black plastic claystone increase in abundance.

Fig. 5.--- Exposures of Longford Member, Kiowa Formation, north-central Kansas. A) Red-mottled mudstone near base of Longford Member near cen. W line SW¼ sec. 9, T. 10 S., R. 1 E., Clay County (unit 5, Measured Section 12, Appendix and Plate 5), about 1.25 miles (2 km) north of Longford. The mudstone is superficially similar to mudstone in the Terra Cotta Clay Member, Dakota Formation, but the puffy nature of the slope indicates the montmorillonitic character of the rock. Handle of pick is about 2.5 feet (0.8 m) long.

B) Siltstone near top of Longford Member near NE cor. sec. 1, T. 6 S., R. 1 E., Clay County. Hematitic red mottles are exceptionally coarse and form irregular vertical streaks. This red-mottled siltstone is about 5 feet (1.5 m) below thin-laminated resistant siltstone marking the top of the member and grades downward into nearly white poorly sorted sandstone also showing red mottles. Mottling on this scale generally is not seen in the Dakota Formation.

C) Permian-Cretaceous contact at base of Longford Member near cen. SE¼ sec. 23, T. 16 S., R. 1 E., Dickinson County. Red-mottled gray to brownish-gray mudstone and claystone at base of Longford Member contains abundant mixed-layer clay having kaolinite as a major component (Fig. 28). Underlying variegated top of Permian Wellington Formation contrasts with normally olive Wellington mudstone and shale and contains abundant kaolinite as well as white nodules composed of both kaolinite and halloysite (Fig. 9 and 10). See Measured Section 10, Appendix and Plate 5. Pocket knife is about 6 inches (15 cm) long.


C
B
A

The Longford Member ranges in thickness from 0 to about 100 feet (0 to 30 m). Maximum thickness is in the vicinity of Longford and Oak Hill in southwestern Clay County. The member thins and grades westward and southwestward into more typical Kiowa shale. It also thins northward and cannot be identified north of secs. 33 and 34, T. 5 S., R. 3 E., Washington County (Plate 1). The siltstone marking the top of the Longford Member is the northernmost Kiowa lithology that can be identified with certainity beneath the Dakota Formation. Distribution of the Longford Member and its area of disappearance beneath the Dakota Formation show coincidence with the dip slope of the Nemaha Anticline and with the increased width of the anticline in Clay and Washington counties.

Age of Kiowa and Dakota Formations

The Early Cretaceous (Albian) age of the Kiowa Formation has not been questioned since the work of Hill (1901). Twenhofel's (1924) paleontologic work leaves no doubt that the Kiowa Formation of north-central Kansas correlates paleontologically with the Kiowa of the type area in southern Kansas, and that type Kiowa can be correlated with the Lower Cretaceous Comanche Series of the Texas Coastal Plain. Although Twenhofel (1924, p. 45) noted a Fredericksburg aspect in much of the Kiowa fossil assemblage, he correlated the Kiowa with the overlying Washita Group of Texas. Studies by Loeblich and Tappan (1950) of foraminifers found in shale in the type area of the Kiowa Formation indicate that the Kiowa correlates with the Kiamichi Formation of the Fredericksburg Group of northern Texas. Inasmuch as fossil assemblages in the Kiowa seem to have properties of fossil assemblages in both the Fredericksburg and Wahsita groups in Texas, and in light of the facies aspects of most Kiowa fossils, it may be that the Kiowa correlates in part with each of the groups in Texas and that it was deposited over a considerable span of time during the later stages of the Early Cretaceous. The idea is not new: Cragin (1895b) suggested that the "Kiowa shale represents a group of sediments intermediate between the Fredericksburg and the Washita."

The Dakota Formation of Kansas more-or-less traditionally was considered to be of Late Cretaceous age, largely because of the voluminous work on fossil deciduous leaves by Lesquereux (1874, 1883, 1892). After Hill's (1895) discovery of fossil leaves in the Cheyenne Sandstone, which underlies the Kiowa Formation in southwestern Kansas, and following Gould's (1900) discovery that extensions of the Kiowa Formation in central Kansas also contained fossil leaves similar to those in the Dakota Formation, serious question about the Late Cretaceous age of the Dakota Fromation was raised by Twenhofel (1920, 1924). As was emphasized by Berry (1920) in a short paper to which insufficient attention seemingly has been given, the plant fossils in the Cheyenne Sandstone and probably also those in the Kiowa do not constitute assemblages identical to those in the Dakota Formation. Moreover, Berry (1922) showed the Early Cretaceous age of the fossil flora of the Cheyenne Sandstone.

Meek and Hayden (1862) noted and described marine fossils in the upper parts of the Dakota in its type area in Nebraska, and Logan (1897) reported marine or brackish-water fossils in the upper parts of the Dakota Formation in central Kansas. Following Logan, Twenhofel (1920) not only thought that the forms near the top of the Dakota Formation were similar to fossils in the Kiowa, but argued that at least part of the Dakota as then defined in Kansas must be of Early Cretaceous age. Stanton (1922), however, doubted the Early Cretaceous age assigned to the fossils near the top of the Dakota Formation in central Kansas. More recently, McLaughlin (1943, p. 108) reported finding a fossil of Early Cretaceous age near the top of the Dakota Formation in Baca County, southeastern Colorado, and Tester (1952) reported discovery of early Cretaceous foraminifers near the top of the Dakota in its type area in northeastern Nebraska. In light of this information, the Dakota Formation of Kansas was tentatively classified as Lower (?) Cretaceous (Jewett, 1959).

Hattin (1965a) re-examined the fossil assemblages found near the top of the Dakota Formation in north-central Kansas and confirmed Stanton's (1922) belief that the assemblages have affinities with the basal Upper Cretaceous (Cenomanian) Woodbine fauna of Texas. Eicher (1965) not only assigned the overlying Graneros Shale to the Upper Cretaceous, but indicated (p. 888) that the entire Graneros section in Kansas is equivalent to the Trochamminoides apricarius zonule, the upper part of the Graneros in its type area in Colorado. Thus, it would appear that the upper part of the Dakota Formation in north-central Kansas grades westward into and interfingers with the Graneros Shale and is of Late Cretaceous age.

Eicher's (1965) work also indicates that the base of the Upper Cretaceous lies within the upper part of the Dakota Sandstone near type Graneros in southeastern Colorado (Fig. 5, p. 887) and that the Dakota Formation of Kansas is in part younger than the Dakota Sandstone of Colorado. Although the Late Cretaceous age of the upper part of the Dakota Formation in Kansas seems well established, the stratigraphic position of the boundary separating Lower Cretaceous rocks from Upper Cretaceous rocks in north-central Kansas remains problematic. That boundary either coincides with the top of the Kiowa Formation or is within the Dakota Formation. Subsurface studies summarized by Haun (1963) indicate that the Lower Cretaceous-Upper Cretaceous boundary is within the Dakota

Formation. In this report, therefore, the Kiowa Formation is classed as Early Cretaceous in age and the Dakota Formation is classed as Early (?) and Late Cretaceous in age.

Problems of Nomenclature and Correlation

Problems of correlation of the Kiowa and Dakota formations and variations in nomenclature applied to these rocks have been intimately related. Although the Dakota was defined as a "group" by Meek and Hayden (1862), it has been ranked both as a group and as a formation in Kansas, and the stratigraphic span of rocks encompassed by the name "Dakota" has varied with usage (Fig. 2). It has been argued that the Dakota should have rank as a group including both the Cheyenne and Kiowa formations because original definition was as a "group." However, the terms "group" and "formation" were used indiscriminately at the time of definition. Meek and Hayden themselves had previously referred to the Dakota as "Formation No. 1" in their general description of the Cretaceous rocks along the Missouri River in Nebraska (1857) and in their discussions of the Dakota section in the Kansas Territory (1859a, 1860). In the report in which the Dakota was defined as a group, the same rocks also are referred to as a formation (1862, p. 417, 418, 420). Hence it is obvious that original definition as a "group" has little bearing on the rank given the Dakota today. The following quotation from Meek and Hayden (1862, p. 420) should emphasize the point:

> Although we still retain this Dakota Group as a distinct rock, our present impression is, that it is probably only a subdivision or member of the Fort Benton Group. Still, until more fossils can be obtained from it in the region of the typical localities, the question whether or not it should rank as a distinct formation must remain an open one.

In the years subsequent to its introduction, the name "Dakota" was used in a combined formational and time-stratigraphic sense until relatively recently. For example, in 1942 considerations of the ages of the Kiowa and Dakota formations were factors in redefinition of terminology applied to these rocks by the State Geological Survey of Kansas (Waite, 1942, p. 135-137). The Cheyenne and Kiowa formations were separated from the so-called "Dakota group" used at that time and the name "Dakota" was restricted in usage to correspond to modern Survey classification in the sense set forth by Plummer and Romary (1942). Part of the basis for the decision to restrict application of the name "Dakota" stemmed from the belief that the Upper Cretaceous-Lower Cretaceous boundary actually separated the Kiowa and Dakota formations. Age assignments, however, played no part in the lithologic classification outlined and used by Plummer and Romary, and their classification is as workable today as it was in 1942.

The argument has been advanced that the Dakota should have group status because, as orginally proposed by Meek and Hayden (1862), it was intended to span all rocks in the Western Interior from the base of the Benton (Graneros) to the base of the Cretaceous. Remarks published subsequently by Meek (1876, p. 26-28) do indicate that the intent was to use the Dakota as the basal subdivision of the Cretaceous in the western United States. The concept of Late Cretaceous age of the Dakota was extended with the name to the several parts of the Western Interior where sandstone was found near the base of the Cretaceous System, for as Hill (1901, p. 319) has pointed out, no older Cretaceous rocks were recognized at that time in the western parts of the United States. In fact, Meek (1876, p. 26), citing Shumard and making use of leaf fossils in sandstone, correlated the Dakota of Nebraska and Kansas with the basal parts of the section now assigned to the Early Cretaceous in Texas.

Once the presence of fossils of Early Cretaceous age was recognized, the rapidity with which workers in the latter parts of the 19th century separated rocks of Early Cretaceous age from the Dakota leads one to suspect that Meek and Hayden might have done the same. The thinking of the times is illustrated by Hill (1901, p. 319) who pointed out that Meek (1876, Plates 1 and 2) published two plates of fossils

> ...from the alleged Dakota formation, one of which was from the type locality...and the other from Salina, Kansas. These two plates are now known to represent fossils from two entirely distinct formations, the first representing the fauna of the typical locality in Nebraska, the other the fauna of the Denison beds of the Comanche series in Kansas. Thus it will be seen that the author of the term 'Dakota formation' himself included within it the equivalent of at least two distinct, unrelated formations and faunas of the Texas section.

Precedence for restriction of the name Dakota to the upper parts of sections formerly assigned in whole or in part to the Dakota is well established.

Between 1890 and 1900 discovery of fossils of Early Cretaceous age in the lower parts of rocks classed as Dakota led to restriction of the name to the upper parts of the basal Cretaceous sequence in Kansas and led to introduction of the name "Kiowa" for the lower parts. With publication of the excellent study by Prosser (1897), the name "Kiowa" became established in north-central Kansas and the practice of restricting the name "Dakota" to the upper parts of the basal Cretaceous section both in north-central and southern Kansas became accepted. However, restriction was not complete inasmuch as the "Mentor beds" (Cragin, 1895a), which contain marine fossils of Early Cretaceous age, were assigned to the "Dakota sandstone" by Prosser largely because it was thought that they were closely associated with leaf-bearing sandstone of the "true Dakota." Prosser (1897, p. 184) also recognized the possible impact of the close association of marine fossils of Early Cretaceous age with leaf fossils of supposed Late Cretaceous age:

> If these Mentor shells and part of the Dakota fossil plants occur at the same horizon then the position of that part of the Dakota sandstone in the Cretaceous system will need reconsideration.

Early paleontologic or time-stratigraphic connotations of the name Dakota are implicit in the above quotation. Extension of the name to the several parts of the western United States stems directly from paleontologic or time-stratigraphic connotations. The importance of leaf fossils in sandstone in application of the name "Dakota" is apparent in the reports of Meek and Hayden (1859a, 1859b, 1860, 1862), Newberry (1860), and Tester (1931). As noted by Berry (1922, p. 200), "Any yellowish or reddish sandstone with impressions of dicotyledonous leaves was Dakota in age, and for a large number of species 'Dakota group of Kansas,'...."

At about the same time that Cragin was working on the "Mentor beds" of north-central Kansas, Hill (1895) reported the occurrence of leaf fossils similar to those in the Dakota in the Cheyenne Sandstone, which underlies the Kiowa Formation in the type area in southwestern Kansas. Excellent insight into the confusion generated by this discovery can be gained from Prosser (1897, p. 179-184), Twenhofel (1920), and Berry (1920, 1922).

Following the work by Cragin (1895a) and Prosser (1897), Gould (1900) found that the "Mentor beds" locally were stratigraphically higher than beds carrying supposedly typical Dakota flora. Gould's discovery paved the way for later work by Twenhofel (1920, 1924), Twenhofel and Tester (1926), and Tester (1931) in which it was held that intercalation of leaf-bearing sandstone with fossiliferous sandstone of the so-called "Mentor" type and with more typical Kiowa shale demonstrated intertonguing of the Kiowa and Dakota formations (Fig. 30-A). Leaf fossils still were considered an important guide to the Dakota, largely owing to the copious work by Lesquereux (1874, 1883, 1892). Moreover, brackish water and marine fossils found near the top of the Dakota Formation in various parts of Nebraska and north-central Kansas were erroneously interpreted as "Mentor" assemblages and hence were taken as evidence of wholesale intertonguing and essential contemporaneity of Kiowa and Dakota sedimentation.

In spite of pertinent comments by Stanton (1922) and by Berry (1920, 1922), the concept of wholesale intertonguing and essential contemporaneity of Kiowa and Dakota sedimentation seems to have taken hold and led to expanded use of the name "Dakota" and to reintroduction of the term "Dakota Group" in classifications in Kansas.

In the outlying areas where supposed extensions of the Dakota of northeastern Nebraska crop out (e.g., Colorado, South Dakota, and Wyoming), discovery of fossils of Early Cretaceous age in the basal parts of the so-called Dakota near the turn of the century gradually led to restriction of nomenclature similar to the process of restriction in Kansas. Higher parts of the sequences were assigned to the Dakota and the lower parts to other formational units (Waagé, 1955, 1959). Eventual discovery of a paleontologic miscorrelation led to abandonment of the name "Dakota" in the Black Hills in 1927 (Waagé, 1959, p. 23). In some parts of Colorado, however, restriction of the name "Dakota" was followed by use in an expanded sense, and the name "Dakota" as formal group terminology came into use somewhat earlier along the Colorado Front Range (Lee, 1927) than it did in Kansas. At the same time, the Dakota was retained as a formation in southern and southeastern Colorado where the underlying Purgatoire Formation was not reincorporated into a Dakota group (Waagé, 1953, 1955). The two classifications persist side by side even though the Dakota of one spans only part of the stratigraphic interval of the other.

Distinct differences in classification also exist between Kansas and Nebraska (Fig. 6). Classifications proposed for the Dakota of the type area and throughout the outcrop belt of eastern Nebraska have been conditioned by work outside the belt of exposures that reaches from northeastern Nebraska into central Kansas. Particular influence can be detected in work from Colorado, southeastern Wyoming, and the Black Hills of South Dakota. Tester (1931, p. 278) stated:

> The occurrence of 50 to 100 feet of sandstone and interbedded shales in one locality, 100 or or more feet of clays and silts in another locality, with 50 to 100 feet of sandstone overlying the clay in several cases, has led some geologists to believe that the Dakota is divisible into three members, and that the thickness is the total of the three divisions. The writer's observations...cause him to be strongly of the opinion that the clay zones are frequently the equivalent of the sandstone zones, either the so-called upper or the lower sandstone.

Evidently, terminology in Nebraska at that time was influenced by terminology used by Gilbert (1896) and Hills (1899) in parts of Colorado where the Dakota was subdivided into an upper sandstone, middle shale, and lower sandstone.

Later, Condra and Reed (1943, p. 18) correlated the section at the type area of the Dakota with Lee's (1927) five-fold subdivision of the

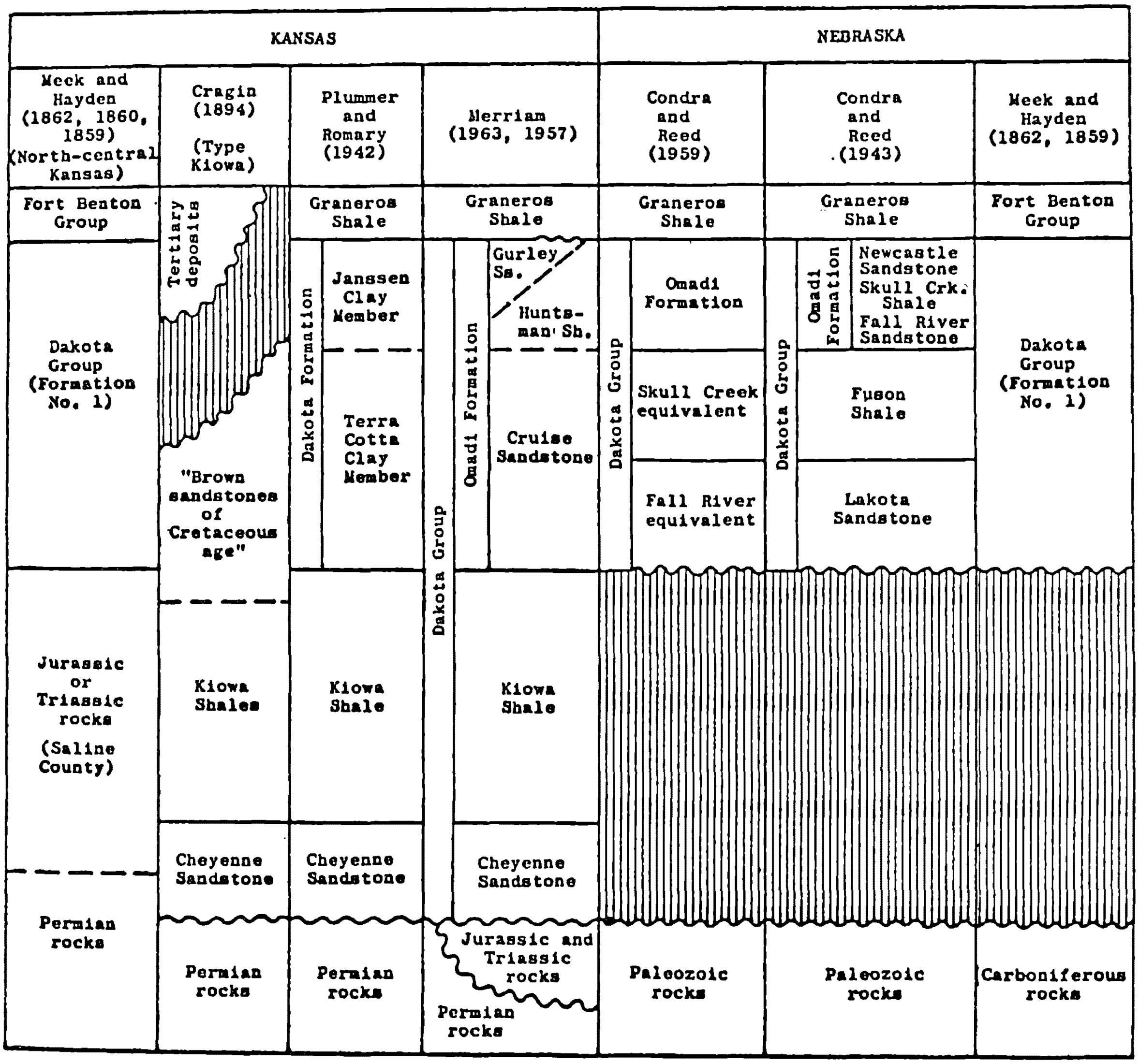


Fig. 6.--- Chart showing variations in terminology applied to basal Cretaceous rocks in Kansas and Nebraska. Rocks assigned to the Jurassic or Triassic by Meek and Hayden in Saline County, Kansas, actually include the Kiowa Formation.

Dakota in the Laramie Range of Wyoming and introduced a modified three-fold or five-fold division of the Dakota of Nebraska (p. 15, Fig. 7). They stated (p. 18):

> Our study of the Dakota group in the Laramie Range, Black Hills, in the outcrop areas across Nebraska, and from cuttings and logs from many wells in the area between has led us to the conclusion that the New Castle sandstone, Skull Creek shale, and the Fall River sandstones correlate collectively with the so-called Dakota sandstone or top formation of the Dakota group in eastern Nebraska, which means that these divisions may be

> members of the upper formation of the
> Dakota Group.

They also correlated the Fuson Shale of the Black Hills and Laramie Range with the supposed middle shales of the Dakota of eastern Nebraska and the Lakota Sandstone with the supposed basal sandstone unit of the Dakota. Moreover, they adopted the names "Fuson" and "Lakota" for formational units in eastern Nebraska (Fig. 13).

In order to do away with the conflict in terminology engendered by use of the name Dakota for both a group and the topmost formation in that group in eastern Nebraska, Condra and Reed (1943, p. 18) also proposed the name "Omadi" for a formation corresponding to the "Dakota sandstone" of earlier usage. The names "New Castle," "Skull Creek," and "Fall River" were used for members of the "Omadi sandstone" in eastern Nebraska and elsewhere in the state (Fig. 6). Although the name "Omadi" has not been accepted generally, it has received some use in the subsurface of southwestern Nebraska and adjoining areas. Merriam (1957a) introduced the name into Kansas literature pointing out (p. 7) that difficulties in correlation of rocks between the Kiowa Shale and the Graneros Shale necessitated use of some sort of "unofficial terminology." In the same paper, Merriam also introduced the names "Gurley sandstone," "Huntsman shale," and "Cruise sandstone," for members of his "Omadi formation" (Fig. 6). In his 1957 paper and in subsequent papers (Merriam and others, 1959; Merriam, 1963), the names have not only been used in a formal sense, but have been applied and correlated throughout the state. Haun (1963, p. 121) has observed that no type localities have been suggested for the "Gurley," "Huntsman," and "Cruise," and that "These names should probably be considered as informal...." He also noted (p. 121) that "Omadi," as used by Merriam, may not be the lithogenetic equivalent of the Omadi at the type locality in Dakota County, Nebraska...."

Since reclassification of the Dakota section in Nebraska in 1943, a further revision has been made (Condra and Reed, 1959). Although it is not clearly specified, the names "Newcastle," "Skull Creek," and "Fall River" seemingly have been dropped for members of the Omadi in Nebraska and the "Fuson shale" and "Lakota sandstone" deleted as formational units of the lower parts of the Dakota section in eastern Nebraska (Fig. 13). In the section entitled "Current Revisions" Reed stated:

> In the Dakota Group the Omadi formation of eastern Nebraska is now recognized as equivalent to the Mowry sandstones of western Nebraska including the oil productive Gurley ('D') and Cruise ('J') sandstones; the 'Fuson' shale of eastern Nebraska is now correlated as equivalent to the Skull Creek, and the 'Lakota' sandstone of eastern Nebraska is equivalent to the Fall River sandstone of western Nebraska and the Black Hills. The Fuson shale and Lakota sandstones seem to be represented only in western Nebraska, principally in the northern part of the Panhandle, but may have thin equivalents in the Denver-Julesburg Basin of the southern Panhandle.

The more recent changes in nomenclature and correlation advanced by Condra and Reed (1959) and Merriam (1957a, 1963) do little to bring about resolution of the discrepancies in classification and correlation between Kansas and Nebraska. The Skull Creek Shale of the Western Interior and the Kiowa Formation are thought to be close lithostratigraphic and time-stratigraphic correlatives (Cobban and Reeside, 1952; Haun, 1963). As was shown by Plummer and Romary (1942, p. 326), the Kiowa Formation thins northward and disappears south of the Kansas-Nebraska line (Plate 1); examination of numerous exposures in Nebraska, including the type area, and in western Iowa indicates that lithogenetic equivalents of the Terra

Cotta Clay Member of the Dakota Formation of Kansas extend into Nebraska. Yet units correlative with the Skull Creek Shale and the underlying Fall River supposedly are found on the outcrop in eastern Nebraska. Moreover, the Omadi of eastern Nebraska and the Janssen Clay Member of the Dakota Formation in north-central Kansas seem to be essentially coextensive and lithogenetic equivalents. The writer's concept of the stratigraphic relationships seen along the outcrops in Kansas and Nebraska is shown diagrammatically in Figure 7.

Waagé (1955, p. 19; 1959, p. 13-14) has noted a persistent transgressive disconformity in the Lower Cretaceous rocks of the Colorado Front Range, southern Colorado, and the Black Hills. In 1959 (p. 13), he indicated that the same disconformity also is present in southwestern Kansas, presumably between the Kiowa and Cheyenne formations, and stressed its regional significance in terms of marking the first transgression of the Cretaceous sea into the Western Interior (p. 18). MacKenzie (1963, p. 145-146) has discussed the occurrence of the regional transgressive disconformity in much of the subsurface of the Western Interior and Franks and Plummer (in Merriam and others, 1959, p. 79, 87) cited evidence for a disconformity separating the Kiowa Shale of the subsurface in northwestern Kansas from the underlying so-called Cheyenne Sandstone. Latta (1946, p. 234) judged the Cheyenne-Kiowa contact to be conformable in their type area although, citing a communication from R.C. Moore to Twenhofel (1924, p. 21), he suggested that it may locally be unconformable. Waagé (1959, p. 13-14) reported that the same regional transgressive disconformity is present in the type area of the "original Dakota formation" in northeastern Nebraska. If the stratigraphic relationships shown in Figure 7 are true, it seems unlikely that any disconformity separating

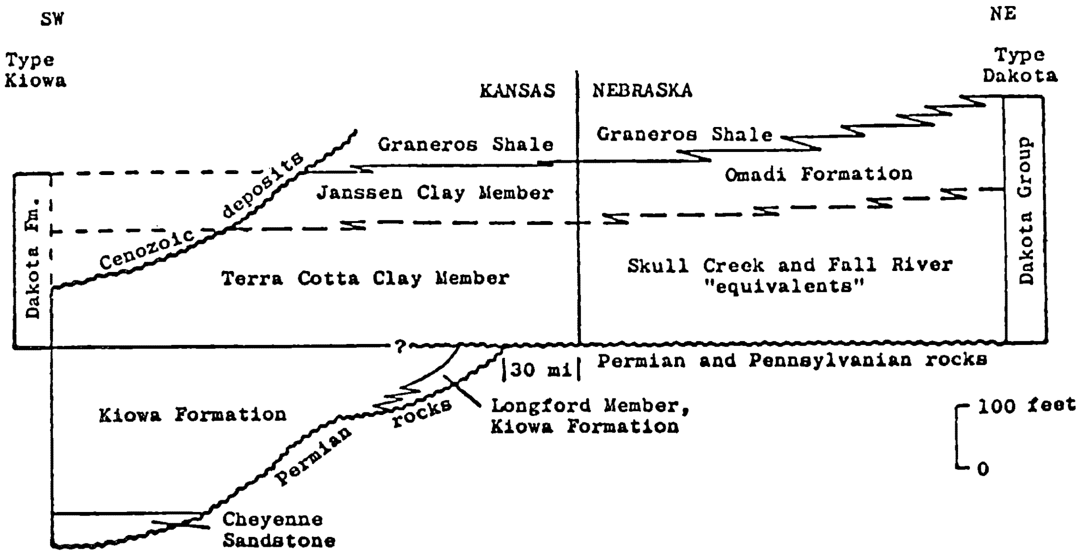


Fig. 7.--- Schematic cross-section showing stratigraphic relations of basal Cretaceous rocks in Kansas to those in Nebraska, and corresponding differences in terminology. At least locally, the Dakota Formation rests disconformably or unconformably on the Kiowa Formation; query indicates that the extent of the unconformity is uncertain. Omadi Formation and Janssen Clay Member of the Dakota Formation are approximate lithologic extensions one of the other; the same is true of the Terra Cotta Clay Member of the Dakota Formation and the supposed Skull Creek and Fall River equivalents in Nebraska. The Skull Creek Shale of the Black Hills area of South Dakota and Wyoming and the Kiowa Formation of Kansas are close rock-stratigraphic and time-stratigraphic equivalents.

the Kiowa and Cheyenne formations, or their equivalents, and marking the transgression of the Early Cretaceous sea into the Western Interior extends into the type area of the Dakota Formation.

PERMIAN-CRETACEOUS UNCONFORMITY

The contact between Permian rocks and the overlying Cretaceous beds in north-central Kansas is part of an extensive regional unconformity that transects rocks as young as Jurassic in the subsurface of southwestern Kansas (Merriam, 1963, p. 67) and as old as the Wellington Formation in north-central Kansas. The same erosion surface separates the Dakota of the type area from Pennsylvanian rocks. In northernmost Nebraska, southeastern South Dakota, northwestern Iowa, and in Minnesota the Cretaceous rocks overlap on Precambrian basement rocks (MacKenzie and Ryan, 1962). The unconformity also merges with unconformities separating Jurassic from Triassic (?) rocks and Triassic (?) from Permian rocks in the subsurface of western Kansas (Merriam, 1963, p. 67). Within the area shown on Plate 1, the basal Cretaceous beds overlap progressively older Middle Permian rocks. From southwest to northeast, the Permian rocks are the Harper, Stone Corral, Ninnescah, and Wellington formations. In much of north-central Kansas, the surface between Permian and Cretaceous rocks is a mature erosion surface that commonly shows as much as 50 feet (15 m) of local relief and in places as much as 75 to 100 feet (23 to 30 m) of relief (Mack, 1962, p. 25; Greene, 1910).

Pebbles and granules of various sorts of chert, quartzite, and "vein" quartz are concentrated locally in the basal parts of the Cretaceous beds above the unconformity. Their occurrence in the basal parts of the Cheyenne, Kiowa, and Dakota formations, whichever rests directly on the Permian in Kansas, indicates that the pebbles and granules are related more to the erosion surface than to the overlying Cretaceous units. The pebbles and granules are mostly well rounded and measure as much as 2.5 inches (6 cm) in long diameter. The nonporous pebbles and granules are highly polished. The enclosing matrix ranges from sandstone to mudstone. Pebbles in sandstone locally occur several feet above the actual base of the Cretaceous, from which they commonly are separated by argillaceous rocks. Permian rocks beneath the pebble zone generally are intensely altered.

The results of counts of pebbles from two localities at the base of the Kiowa Formation are given in Table 1. Fusulinids and productid brachiopods present in some chert pebbles demonstrate that much of the

Table 1.--- Composition of pebbles in pebble zone along unconformity separating Permian and Cretaceous rocks in north-central Kansas. Collections at both localities were taken from the base of the Kiowa Formation. Percentages based on a count of 132 pebbles from Rice County locality and of 180 pebbles from Clay County locality.

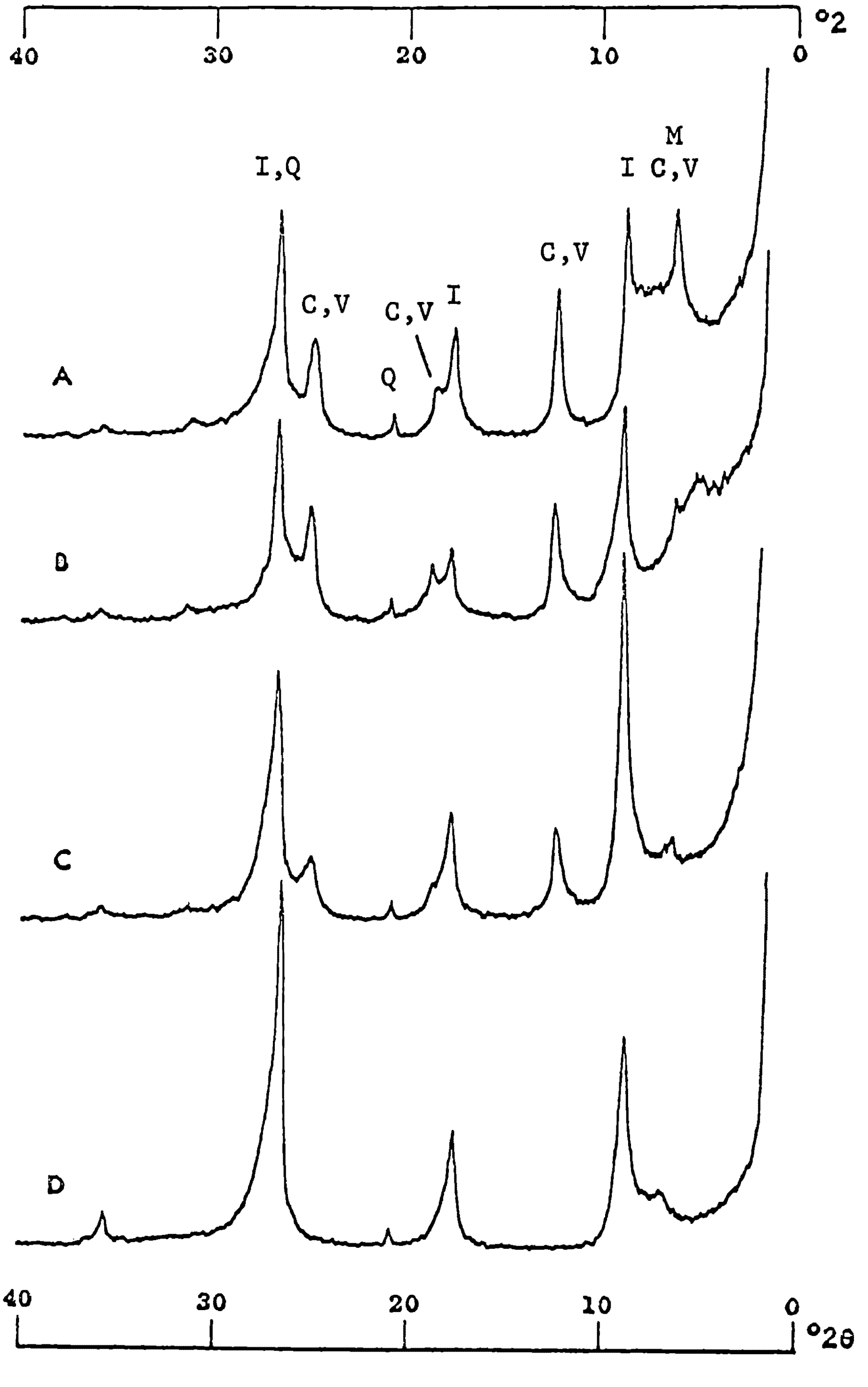
LOCALITY	LITHOLOGY	PERCENTAGE
W$\frac{1}{2}$ SW$\frac{1}{4}$ sec. 16 T.20S., R.6W., Rice County	Chert	62
	white, porous	26
	white, dense	22
	black to brown, fine-grained	5
	black to brown, coarse-grained	9
	Silicified wood	2
	Silica-cemented sandstone	2
	Quartzite	19
	"Vein" or pegmatitic quartz	20
NW$\frac{1}{4}$ sec. 27 T.8S., R.2E., Clay County	Chert	69
	white, porous	39
	white, dense	6
	black to brown, fine-grained	14
	black to brown, coarse-grained	10
	Silica-cemented sandstone	1
	Quartzite	15
	Quartz schist	1
	"Vein" or pegmatitic quartz	14

chert is derived from late Paleozoic limestone. Pebbles of quartzite and "vein" quartz indicate that Precambrian terrains ultimately furnished part of the gravel. The varied matrices enclosing the pebbles, association of the pebbles with intensely altered topmost Permian rocks, and their presence on the flanks of or on top of pre-Cretaceous topographic highs developed on Permian rocks, together with local incorporation of pebbles in rocks several feet above the actual base of the Cretaceous section, implies that the pebbles are reworked and winnowed relicts of an originally widespread mantle of gravel. The gravel accumulated during the development of the erosion surface, but prior to erosion that preceded or partly coincided with deposition of the overlying Cretaceous beds. The fossiliferous chert pebbles, the "vein" quartz, and the quartzite indicate that the pebbles were derived from the east and northeast. A northeasterly source for either the pebbles or the Cretaceous beds would not seem to be in agreement with the north-draining river system that Merriam (1963, p. 67) inferred was the agent that cut the topography on top of Permian rocks in Kansas.

The clay mineralogy of Permian rocks underlying the Cretaceous beds is considered in some detail because the clay minerals have been weathered, reworked, and incorporated into some of the basal Cretaceous rocks. The ancient weathering profiles preserved locally at the top of the Permian in north-central Kansas also allow insight into conditions that prevailed during the interval of nondeposition and erosion preceding Kiowa and Dakota sedimentation.

Swineford (1955) has noted the illitic and chloritic character of Middle Permian argillaceous rocks in Kansas. Relatively fresh samples from the Wellington and Ninnescah formations examined for this report are composed largely of illite and chlorite, but commonly contain appreciable vermiculite as well. The diffraction patterns shown in Figure 8 are from a fresh sample of Ninnescah mudstone that exemplifies the clay fraction of many Permian samples studied (Plates 4, 5, and 7). The clay fraction of the rock contains abundant illite, minor amounts of quartz and montmorillonite, and little or no kaolinite. Much of the 14-Angstrom reflection can be attributed to chlorite, but partial expansion of the peak toward 16.3A on glyceration indicates the presence of vermiculite inasmuch as Walker (1961, p. 316) reported expansion of vermiculite to about 16A "if the interlayer cations are Ca, Sr, or Ba." The presence of

Fig. 8.--- Diffractometer patterns of fraction finer than 2 microns of a sample of fresh Ninnescah mudstone from NE¼ NW¼ SW¼ sec. 1, T. 17 S., R. 6 W., Ellsworth County, Kansas (unit 1, Measured Section 7, Appendix and Plate 5), illustrating illitic (I) and chloritic (C) or vermiculitic (V) character of Permian mudstone and shale. A) air-dried, B) glycerated, C) heated to 450°C, D) heated at 575°C for one-half hour. Small amounts of quartz (Q) are present. Strong reflection near 25.1°2θ indicates that the prominent reflection at 6.3°2θ (14A) in Pattern A is due either to chlorite or vermiculite, as does the 003 chlorite spacing at 18.6°2θ. Pattern B shows partial expansion of the 14-Angstrom spacing to 5.4°2θ (16.3A) and beyond, and left a small peak at 14A, indicating that both chlorite and vermiculite as well as montmorillonite (M) are present. Persistence of the 14-Angstrom peak on heating verifies the presence of chlorite. Skewing of the 10-Angstrom reflection toward 14A in Patterns C and D may mean that partly collapsed vermiculite, mixed-layer chlorite-montmorillonite, or mixed-layer vermiculite-montmorillonite is present.


°2
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10
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I C,V
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40
30
20
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0
°2θ

montmorillonite and perhaps mixed-layer chlorite-montmorillonite or mixed-layer vermiculite-montmorillonite also can be inferred from the x-ray traces.

Permian rocks underlying the unconformity show sign of differing degrees of weathering prior to deposition of overlying Cretaceous rocks. Least altered Permian mudstone and shale, in which the clay minerals show nearly negligible conversion to expansible mixed-layer clay, is found in Pre-Cretaceous topographic lows. Where the elevation of the top of the Permian seems higher than in surrounding areas, weathering prior to depostion of the overlying Cretaceous rocks produced not only extensive variegation of the upper few feet of Permian rock (Fig. 5-C), but extensive changes in clay mineralogy as well. In the SE 1/4 SW 1/4 SW 1/4 sec. 9, T. 10 S., R. 1 E., Clay County, the top of the Wellington Formation is about 18 feet (5.4 m) higher than it is nearby at Measured Section 12 (Appendix and Plate 5) near the cen. W line sec. 9. The topographically low mudstone at the top of the Wellington Formation in the measured section is reddish brown and contains only sparse laminae that have been bleached yellowish gray. The clay minerals show only partial alteration to montmorillonite. Illite, chlorite, and vermiculite are major components. In contrast, mudstone at the top of the Wellington Formation in the SW 1/4 sec. 9 is intensely variegated and ranges from yellowish green to pale red. Weathering prior to deposition of overlying Cretaceous rocks generated abundant kaolinite as well as montmorillonite.

In an area encompassing parts of T. 16 and 17 S., R. 1 and 2 E., southwestern Dickinson County and northwestern Marion County, the upper few feet of the Wellington Formation commonly have been converted from generally olive-gray mudstone and shale to intensely variegated claystone

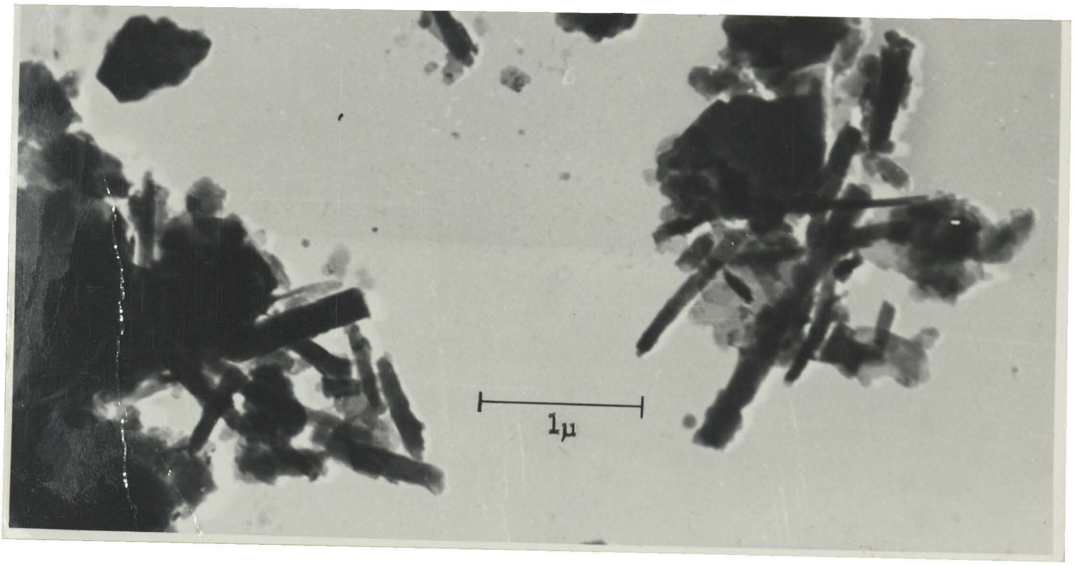


Fig. 9 .--- Electron micrograph of fraction finer than 2 microns from kaolinitic and halloysitic nodule from weathered top of Wellington Formation (Permian) in SW¼ SW¼ sec. 29, T. 17 S., R. 2 E., Marion County, Kansas. Permian at this locality is overlain by Longford Member, Kiowa Formation. Many of the kaolinite flakes show crudely hexagonal outlines and seem to be relatively well crystallized. Halloysite tubes locally show split ends as well as terminal angles near 120°, indicating that the structure approaches one of higher crystallinity, i.e., that of kaolinite.

that is mainly grayish red but also is streaked, mottled, and stained yellowish brown, greenish yellow, dusky red, reddish purple, and even white (Fig. 5-C; see also Measured Section 10, Appendix and Plate 5). The claystone is composed almost completely of kaolinite (diffraction pattern opposite unit 2, Measured Section 10, Plate 5) and contains hard white nodules composed of kaolinite and halloysite. Figure 9 is an electron micrograph of the fraction finer than 2 microns from a nodule collected near the SW cor. sec. 29, T. 17 S., R. 2E., Marion County. It shows numerous flakes of kaolinite, some of which have irregular hexagonal outlines, and tubes of metahalloysite.

Figure 10-F is a diffraction pattern of a packed sample of the fraction finer than 2 microns from a similar halloysitic nodule from the cen. SE 1/4 sec. 23, T. 16 S., R. 1 E., Dickinson County (unit 2, Measured

Fig. 10.--- Diffractometer patterns of packed samples of fractions finer than 2 microns from kaolinitic rocks in the Graneros Shale, Dakota Formation, and Wellington Formation, north-central Kansas.

A) kaolinite seam in Graneros shale near cen. N½ sec. 6, T. 15 S., R. 10 W., Ellsworth County (unit 15, Measured Section 3, Appendix and Plate 8).

B) shaly claystone, Janssen Clay Member, Dakota Formation, near cen. W½ sec. 19, T. 15 S., R. 9 W., Ellsworth County (unit 7, Measured Section 4, Appendix and Plate 8).

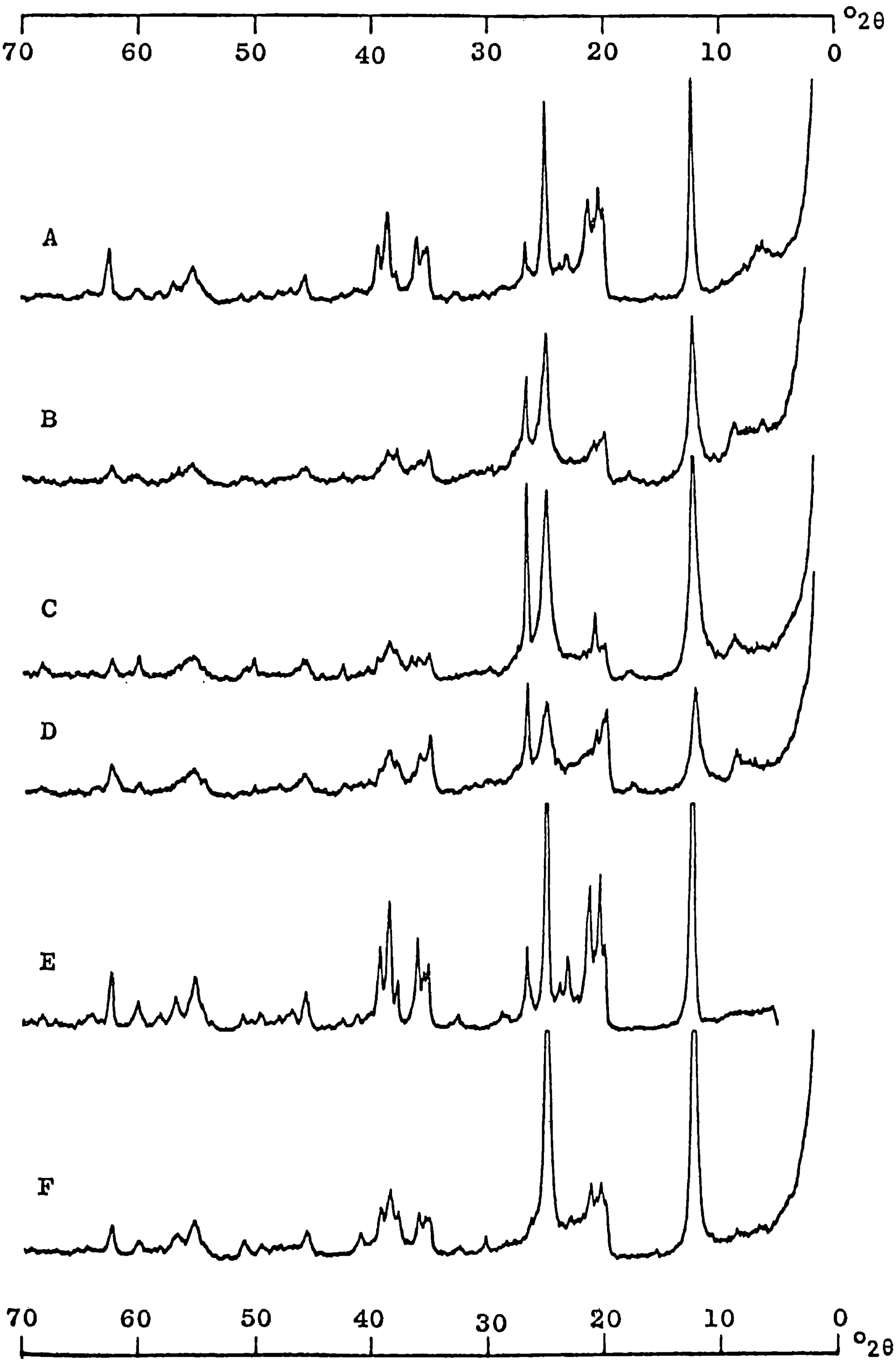
C) light-gray mudstone about 52 feet (16 m) above base of Terra Cotta Clay Member, Dakota Formation, near cen. SW¼ sec. 28, T. 15 S., R. 7 W., Ellsworth County (unit 27, Measured Section 5, Appendix and Plate 4).

D) shaly laminae in brownish-gray siltstone about 73 feet (23 m) above base of Terra Cotta Clay Member, Dakota Formation, near cen. N½ SW¼ sec. 1, T. 16 S., R. 7 W., Ellsworth County (unit 20, Measured Section 6, Appendix and Plate 4).

E) white porcelaneous kaolinite seam about 20 feet (6 m) above base of Terra Cotta Clay Member, Dakota Formation, near cen. NE¼ sec. 25, T. 15 S., R. 7 W., Ellsworth County.

F) halloysitic kaolinite nodule in weathered top of Wellington Formation (Permian) near cen. SE¼ sec. 23, T. 16 S., R. 1 E., Dickinson County (unit 2, Measured Section 10, Appendix and Plate 5).

Pattern E shows best crystallinity as is indicated by the sharpness of the 060 reflection at $62.4^\circ 2\theta$ and by good resolution of *hkl* reflections between 20° and $24^\circ 2\theta$ and between 34° and $40^\circ 2\theta$. Pattern E also shows partial resolution of $11\bar{1}$ and $1\bar{1}\bar{1}$ reflections near 21.2° and $21.5^\circ 2\theta$ although resolution is not apparent at the scale of reproduction. The kaolinite seam probably is an altered bed of volcanic ash. Pattern A is from similar material in the basal part of the Graneros Shale, but the degree of crystallinity is somewhat lower. Patterns B, C, and D show the general *b*-axis disorder characteristic of kaolinite in the Dakota Formation. Pattern F from an halloysitic nodule in the weathered top of the Permian shows good crystallinity although the $11\bar{1}$ and $1\bar{1}\bar{1}$ reflections are not resolved.



°2θ
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A
B
C
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E
F

Section 10, Appendix and Plate 5). The pattern shows the presence of relatively well crystallized kaolinite. However, resolution of the $11\bar{1}$ and $1\bar{1}\bar{1}$ reflections is not seen and a considerable degree of *b*-axis disorder is inferred (Brindley, 1961a, p. 62). The crystallinity of the kaolinite actually may be somewhat better than that indicated by the x-ray trace inasmuch as the sample is diluted by metahalloysite. As is true of other exposures where kaolinitic alteration products abound at the top of the Permian, there is transition downward into normally illitic and chloritic Permian rocks through a zone enriched in montmorillonite, but the transition seems particularly abrupt.

Upward gradation from fresh Permian mudstone and shale through a zone enriched in montmorillonite to a zone enriched in kaolinite suggests partial preservation of ancient soil profiles on topographic highs developed on top of the Permian rocks prior to deposition of overlying Cretaceous rocks. Altschuler, Dwornik, and Kramer (1963) and Altschuler and Dwornik (1964) have shown that kaolinite is generated by weathering of montmorillonite, which in turn is a common weathering product of mica-like and chlorite-like clay materials. Keller (1964, p. 22-23) has observed that montmorillonite is generated under conditions of weathering that differ from those under which kaolinite and related minerals form, although both processes may go on side by side (p. 17). Generation of montmorillonite requires fairly abundant cations in solution and terrain that is relatively waterlogged. Removal of both silica and cations is essential to production of kaolinite (Keller, 1964, p. 17-20). Provided that pH in the soil is low (7 or less), drainage need not be good.

The conditions outlined above for genesis of montmorillonite and kaolinite are in keeping with a mature erosion surface of low relief cut on top of Permian rocks in north-central Kansas. They also indicate that the soil may have been relatively saturated and hence that rainfall may haven been moderate to heavy in this area during Early Cretaceous time. Dialysis and hydrolysis, perhaps aided by plants, may have allowed generation of kaolinite in the upper parts of the weathering profiles whereas more restricted removal of cations in the lower parts of the profiles favored formation of montmorillonite. The compressed nature of the weathering profiles at the top of the Permian rocks may stem from repeated erosion and removal of newly formed weathering products, from the generally impervious character of most of the mudstone and shale, or from the generally saturated conditions and poor drainage that probably prevailed.

Mechanisms by which halloysite forms during weathering seem varied (Sudo, 1954; Bates, 1962; Keller, 1964) and transformation of parent material to halloysite may or may not involve transitory allophane or gel phases, although an acid pH is required. According to Keller (1964, p. 13) halloysite may develop as an intermediate stage in progressive weathering of rocks to kaolinite. Occurrence of halloysite in nodules in a weathering profile ranging from clayey Permian rocks through montmorillonite to kaolinite may mean that a gel phase was involved in formation of the halloysite. That the nodules are unstained by iron oxide whereas the enclosing b-axis disordered kaolinite is variegated, and that the nodules contain relatively well crystallized kaolinite indicates that the halloysite perhaps formed late in a sequence of rock weathering leading to generation of relatively well crystallized kaolinite. The halloysite may have formed as a member or byproduct in conversion of disordered kaolinite to relatively well crystallized material if dissolution of silica and alumina or a transitory gel phase was involved in the reorganization. Nonetheless, generation of halloysite indicates that the soil was not well drained and that an acid pH prevailed (Keller, 1964, p. 16). Inasmuch as the parent material was composed mainly of clay minerals, alkali and alkaline earth cations probably were not overly abundant and contributed little to the process of desilication in the soil profile. Plant activity may have been an agent in removal of silica and establishment of acid pH in the soil system as suggested by Keller (1964, p. 23-26, 58) and Lovering (1959).

KIOWA FORMATION

Lithology

Shale

The Kiowa Formation of north-central Kansas is a heterogeneous unit made up of shale and other argillaceous rocks, siltstone, and sandstone. The shale is medium to dark gray but characteristically weathers olive gray to olive brown. Locally it is dark brownish gray. Most Kiowa shale is thinly laminated and plastic. In many places imprints of small pelecypods measuring as much as 1 inch (2.5 cm) long can be found by careful splitting of the shale along its laminae. R.W. Scott (oral communication, 1965) has found sorted assemblages of fish scales, teeth, and bone fragments associated with glauconite pellets along the bedding surfaces of Kiowa shale in Ellsworth County. The winnowed fish remains and glauconite pellets commonly are associated with imprints of pelecypods. The high plasticity and water adsorbtion of the shale typically give rise to small-scale landslips and slumping even on relatively gentle slopes. The resultant gentle topography of the more argillaceous parts of the Kiowa contrast sharply with the rugged topography developed in areas underlain by thick sequences of Kiowa sandstone.

Plummer and Romary (1942) stressed the illitic nature of most Kiowa shale, but much of the shale contains appreciable montmorillonite and kaolinite. The illite in samples from most exposures of the shale seems to have been converted partly to an expansible montmorillonite-like clay on weathering, so that the 10-Angstrom illite peak is more-or-less strongly skewed in the low-angle direction (so-called degraded illite) in diffraction patterns of air-dried slide mounts. Figure 11, for example, shows a series of diffraction patterns of the fraction finer than 2 microns of a relatively kaolinitic sample of shale. The illite peak not only is skewed in the low-angle direction, but a distinct montmorillonite reflection can be seen at $6.3^{o}2\theta$ (14A) in the trace from the air-dried preparation. Weathered samples of Kiowa shale commonly are composed largely of montmorillonite, as the sample whose diffraction trace is shown opposite unit 6, Measured Section 8, Plate 4, or the two traces from Kiowa shale opposite Measured Section 7, Plate 5. It is the high proportion of montmorillonite that lends weathered Kiowa shale its plasticity and instability on slopes.

The clay fractions of core samples of subsurface equivalents of the Kiowa Formation in northwestern Kansas contain appreciable chlorite and vermiculite (Franks and Plummer, in Merriam and others, 1959), but neither chlorite nor vermiculite was detected in samples of typical gray Kiowa shale from exposures in north-central Kansas, even where the shale rests directly on Permian rocks. The samples studied by Franks and Plummer also showed distinct skewing of the 001 illite diffraction, although the proportions of montmorillonite in mixed-layer structures with illite seem smaller than the proportions in surface samples. Thus, not all of the

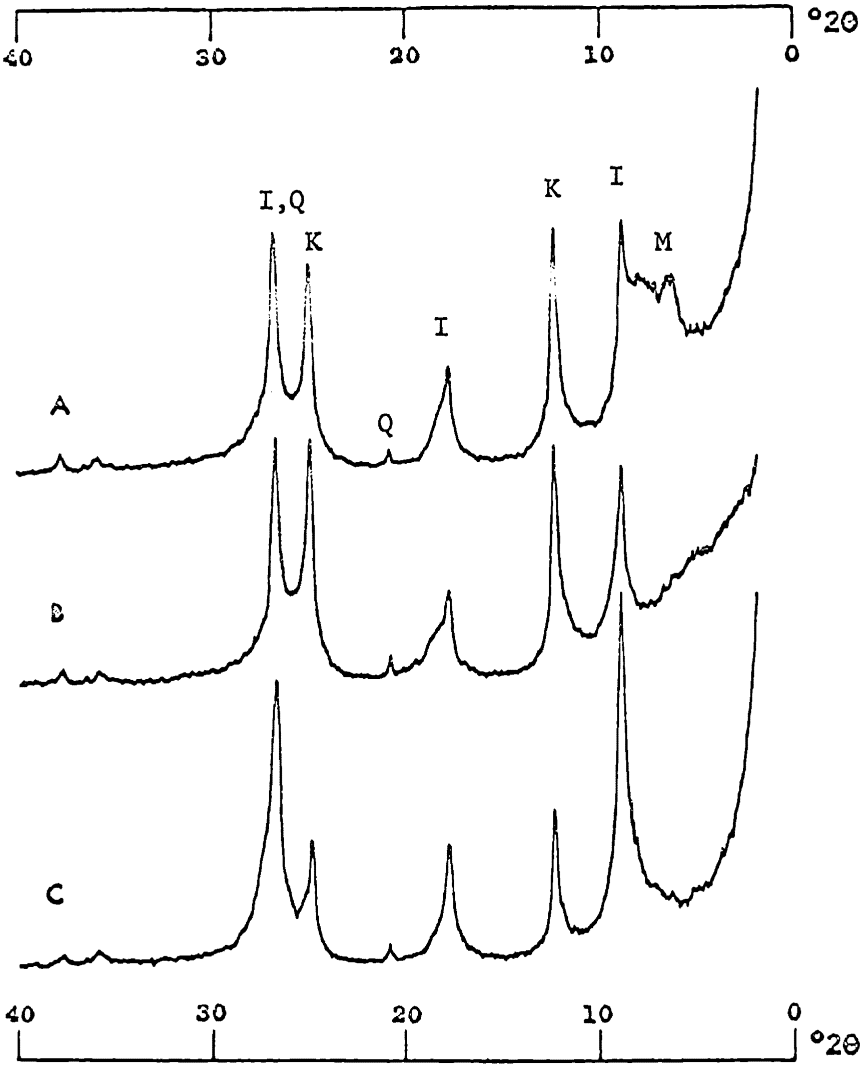


Fig. 11.--- Diffractometer patterns of fraction finer than 2 microns from shale in the Kiowa Formation, NW¼ SW¼ SW¼ sec. 31, T. 16 S., R. 3 W., Coronado Heights, Saline County, Kansas. See Fig.   and unit 2, Measured Section 9, Appendix and Plate 4. A) air-dried, B) glycerated, C) heated to 450°C. Pattern A shows the presence of abundant illite (I) and kaolinite (K), and small amounts of quartz (Q). The illite 001 peak at 8.8°2θ is strongly skewed in the low-angle direction toward the montmorillonite peak (M) at 14A. On glyceration (Pattern B) the montmorillonite peak and the skewed shoulder shift and give a broad, weak reflection centered near 5°2θ (18A) and a weak mixed-layer "superlattice" maximum appears near 3.2°2θ (about 27A). Pattern C shows complete collapse of the montmorillonite spacing and of the skewed mixed-layer diffraction. The small amount of skewing of the 10-Angstrom peak in Pattern C is accounted for by Lorentz polarization and angular effects, and the mixed-layer clay is composed of randomly interstratified illite and montmorillonite.

mixed-layering in surface samples can be attributed to modern weathering of the Kiowa Formation. Some would seem to be a primary feature of argillaceous Kiowa sediments, and in this respect, reference to so-called "degraded" illite may be misleading, but the term is conveniently descriptive.

Much Kiowa shale that is interstratified with sandstone or siltstone contains appreciably more kaolinite than shale that is not interstratified with sandstone or siltstone (Plate 4). Potter and Glass (1958, p. 35-43) observed similar relationships in Pennsylvanian rocks in Illinois, both on the outcrop and in subsurface samples. They attributed the increased amount of kaolinite in sandstone samples to authigenesis of kaolinitic clay by percolation of subsurface waters and to exposure to meteoric water on outcrop. Shelton (1964) has described authigenic kaolinite in numerous sandstone samples. Both authigenesis and selective sorting of coarse-grained kaolinite during deposition may account for the occurrence of kaolinite rich clays with sandstone and siltstone in some parts, particularly the upper parts, of the Kiowa Formation.

Features indicating that Kiowa shale is rich in iron are misleading. The dark color of the shale, disseminated nodules of marcasite, discoidal concretions of impure siderite, and the jarosite stain on weathered exposures seem to be in accord with a high content of iron. Moreover, the reddish-brown and brown firing characteristics, low fusion point, and bloating properties of Kiowa shale (Plummer and Hladik, 1951) suggest fluxing that is aided by iron oxide tied up in the clay lattice. Table 2 gives the averages of seven chemical analyses of channel samples of Kiowa shale collected by Norman Plummer in Ellsworth and Saline counties, Kansas. Total iron reported as Fe_2O_3 ranges from 2.75 to 5.94 percent by weight

Table 2 .--- Chemical composition of composite samples of argillaceous rocks from the Kiowa and Dakota formations. Results for Kiowa Formation based on averages of chemical analyses of 7 channel samples of shale from intervals 5 to 27 feet thick in Ellsworth and Saline counties, Kansas; results for Terra Cotta Clay Member, Dakota Formation, based on analyses of 16 channel samples of mudstone and claystone from intervals 3.5 to 95 feet thick in Cloud, Ellsworth, Lincoln, Ottawa, and Washington counties; results for Janssen Clay Member, Dakota Formation, based on analyses of 16 channel samples of mudstone and claystone from intervals 5 to 16 feet thick in Ellsworth, Lincoln, Ottawa, Russell, and Washington counties. Total iron reported as Fe_2O_3. Samples collected by Norman Plummer and original analyses by Geochemistry Division, State Geological Survey of Kansas.

	KIOWA FORMATION		DAKOTA FORMATION			
			Terra Cotta Clay Member		Janssen Clay Member	
	Mean	Range	Mean	Range	Mean	Range
SiO_2	61.33	57.94-65.35	65.14	59.51-76.43	68.35	59.38-74.69
Al_2O_3*	19.55	16.09-21.64	19.56	14.02-24.53	18.78	11.90-23.01
Fe_2O_3	4.47	2.75- 5.94	4.26	1.38- 8.14	1.68	1.02- 2.34
TiO_2	1.04	0.82- 1.28	1.52	0.95- 2.69	1.42	0.96- 2.24
CaO	0.91	0.11- 2.63	0.45	0.09- 0.97	0.24	0.77- 0.08
MgO	1.33	0.53- 1.91	0.45	0.06- 2.09	0.46	0.11- 0.79
P_2O_5	0.08	Tr - 0.13	0.02	nil - 0.15	0.01	Tr - 0.05
SO_3	0.50	0.09- 0.96	0.18	nil - 0.90	0.11	nil - 0.36
K_2O	2.40	1.50- 3.59	1.12	0.10- 2.58	0.95	0.13- 2.30
Na_2O	0.21	0.12- 0.34	0.16	0.04- 0.42	0.14	0.04- 0.24
Sulfide S	0.20 1/	nil - 0.54 1/	0.01 2/	nil - 0.04 2/	0.10 3/	nil - 0.39 3/
LOI (1000°C)	8.16	7.44- 9.40	6.89	4.83- 9.30	7.77	5.44-12.38
TOTAL	100.18		97.76		100.00	

*Includes MnO_2 and Ga_2O_3 if present.

1/Based on only 5 determinations.

2/Based on only 6 determinations.

3/Based on only 4 determinations.

and the mean of the samples is 4.47 percent. Recognizing that comparison of analyses by different laboratories may not be completely valid, it is interesting to compare the average of the seven channel samples from the Kiowa with Clarke's (1924, p. 547) average of 6.49 percent iron oxide for 75 samples of shale. The average of chemical analyses of Kiowa shale also is somewhat more siliceous and aluminous than Clarke's average.

Two samples of Kiowa shale were examined for determination of the dioctahedral or trioctahedral character of the illitic and montmorillonitic components after destruction of kaolinite by heating the samples at 575° C. One sample was from NE 1/4 NW 1/4 SW 1/4 sec. 1, T. 17 S., R. 6 W., Ellsworth County, the other from near the cen. W line SW 1/4 sec. 31, T. 16 S., R. 3 W., Saline County. Weak reflections from the fraction finer than 2 microns were detected in the range of 060 diffractions near 1.54A and 1.50A to 1.51A. The strength of the reflection near 1.54A probably can be attributed mainly to quartz, but the relative strength of reflections near 1.50A indicates that the illite and collapsed montmorillonite are dominantly dioctahedral in character.

The dioctahedral character of illitic and montmorillonitic clay in Kiowa shale is in keeping with the relatively aluminous character of the rock (Table 2) and with a relatively low iron content in the clay mineral lattices. Little or none of the alumina in the shale can be attributed to feldspar or zeolite inasmuch as neither has been detected in diffraction traces. Feldspar, moreover, is scarce even in Kiowa sandstone. Therefore it seems likely that much of the iron in Kiowa shale is present not only as sulfide and siderite, but also that appreciable amounts of iron may be tied up in organic or clay-organic complexes. The red fired colors, low fusion points, and bloating of Kiowa shale mentioned previously indicate that appreciable proportions of iron in the Kiowa Formation are tied to the clay micelles, perhaps in organic complexes, if the iron is not bound chemically in the octahedral layer of the clay lattices.

Organic matter in Kiowa shale may have distinct bearing on the thin-laminated nature of the shale. Ingram (1953) noted that the organic content of shale showing good fissility was greater than that of mudstone and that preferred orientation of clay flakes paralled to lamination is essential to fissility. He also found that disaggregated and dispersed fissile shale containing organic stain settled out of suspension in pronounced parallel alignment when sedimentation was induced by addition of NaCl to the suspension. On the other hand, suspensions made by dispersion of initially nonfissile rocks showing random orientation of the clay particles and containing little or no organic matter generally gave randomly oriented flakes in the sediment on addition of NaCl.

Red mottles occur locally but are not characteristic of shale in the Kiowa Formation. Medium light gray plastic shale and claystone showing reddish-brown mottles was observed near the SE cor. sec. 13, T. 13, R. 2 W., Saline County, and near the cen. N 1/2 sec. 13, T. 11 S., R. 3 W., Ottawa County. The distribution of red-mottled material could not be determined from the exposures but it forms zones less than 2 feet (0.6 m) thick that are overlain and underlain by characteristic olive-weathering Kiowa shale containing concretions of impure siderite. The red-mottled shale weathers to essentially olive-gray slopes and much of it is plastic, thinly laminated, and fissile. X-ray diffraction studies showed illite and montmorillonite to be the major components of the clay fraction; kaolinite was present in minor amounts. The olive weathering colors, plasticity, and clay mineralogy set the mottled shale or claystone apart from mudstone and claystone in the Dakota Formation.

Weathered slopes of argillaceous Kiowa rocks commonly are littered with euhedral crystals of gypsum measuring as much as 2 inches (5 cm) long. In palces abundant radial aggregates ("sunbursts") of gypsum are found on weathered exposures. The gypsum seems to be a secondary product derived from weathering of disseminated or nodular iron sulfide, mainly marcasite, in the shale rather than the product of marine precipitation in a highly saline sea in an arid climate as suggested by Twenhofel (1924, p. 38-39, 42). Commonly aggregates of gypsum encrust partly oxidized iron sulfide, but are not associated with fresh marcasite. Much of the Kiowa shows yellow stain and films of jarosite along bedding and fracture surfaces. Like the gypsum, the jarosite is a weathering product of iron sulfide. In the NE 1/4 SE 1/4 sec. 34, T. 13 S., R. 4 W., Saline County, in an abandoned clay pit in Kiowa shale, small chips of alunite (identified by x-ray diffraction) weather out of the shale. The alunite probably also stems from decomposition of iron sulfide, but formed under conditions of low pH whereby alumina was released from clay mineral lattices and iron oxide was prevented from reacting to form jarosite.

A thin yellowish-gray layer of apatite about 1 cm thick is enclosed in typical gray Kiowa shale near the common corners of secs. 22, 23, 26, and 27, T. 16 S., R. 7 W., Ellsworth County. The apatite mainly is cryptocrystalline and few of the anhedra measure more than 0.01 mm in long dimension. The rock also contains silt-sized detrital quartz as well as rounded pellets of glauconite. X-ray diffraction data, particularly reflections near 1.794A and 1.722A, indicate that the apatite is carbonate fluorapatite (Silverman, Fuyat, and Weiser, 1951, p. 6, Table 1). McConnel (1965) has indicated that sea water is nearly saturated with respect to carbonate fluorapatite, and rounded nodules or detrital fragments of apatite (mostly carbonate fluorapatite) are common in subsurface equivalents of the Dakota Formation (Merriam and others, 1959, p. 16, 55-58); MacKenzie, 1963, p. 143-147). The layer in Ellsworth County, however, is the only occurrence of sedimentary apatite in the Kiowa of north-central Kansas known to the writer, although apatite is found as fish teeth, bone fragments, and scales.

Concretions (clay-ironstone) in Kiowa shale.---

Thinly laminated illitic Kiowa shale generally contains numerous so-called clay-ironstone concretions (Fig. 12-A). The concretions have discoidal form, are about 0.2 foot (6 cm) thick, and are as much as 4 feet (1.2 m) in diameter. They form discontinuous beds only one concretion thick that closely parallel lamination in the enclosing shale. Both upper and lower surfaces of many of them are marked by structures resembling synaeresis cracks (White, 1961; Burst, 1965). Beneath the outer rind showing more-or-less polygonal fractures are elongate welts that follow the arcuate traces of the fractures and enclose gentle mounds near the center of each polygon (Fig. 12-A).

X-ray diffraction data show that the concretions are composed largely of siderite although some contain detectable amounts of calcite. One sample that was dissolved in 6N HCl contained 11 percent by weight insoluble residue composed chiefly of silt-sized quartz, illite, and kaolinite. Thin section examination also revealed trace amounts of pyrite or marcasite in anhedral aggregates less than 0.02 mm long. Individual siderite anhedra measure less than 4 microns in diameter and form indistinct globular aggregates about 0.01 mm across. Colloidal aggregation about numerous centers of nucleation may account for the internal structure. Synaeresis could have formed the outer cracks into which colloidal siderite flowed to produce the arcuate welts beneath the outer rind. On weathering, the

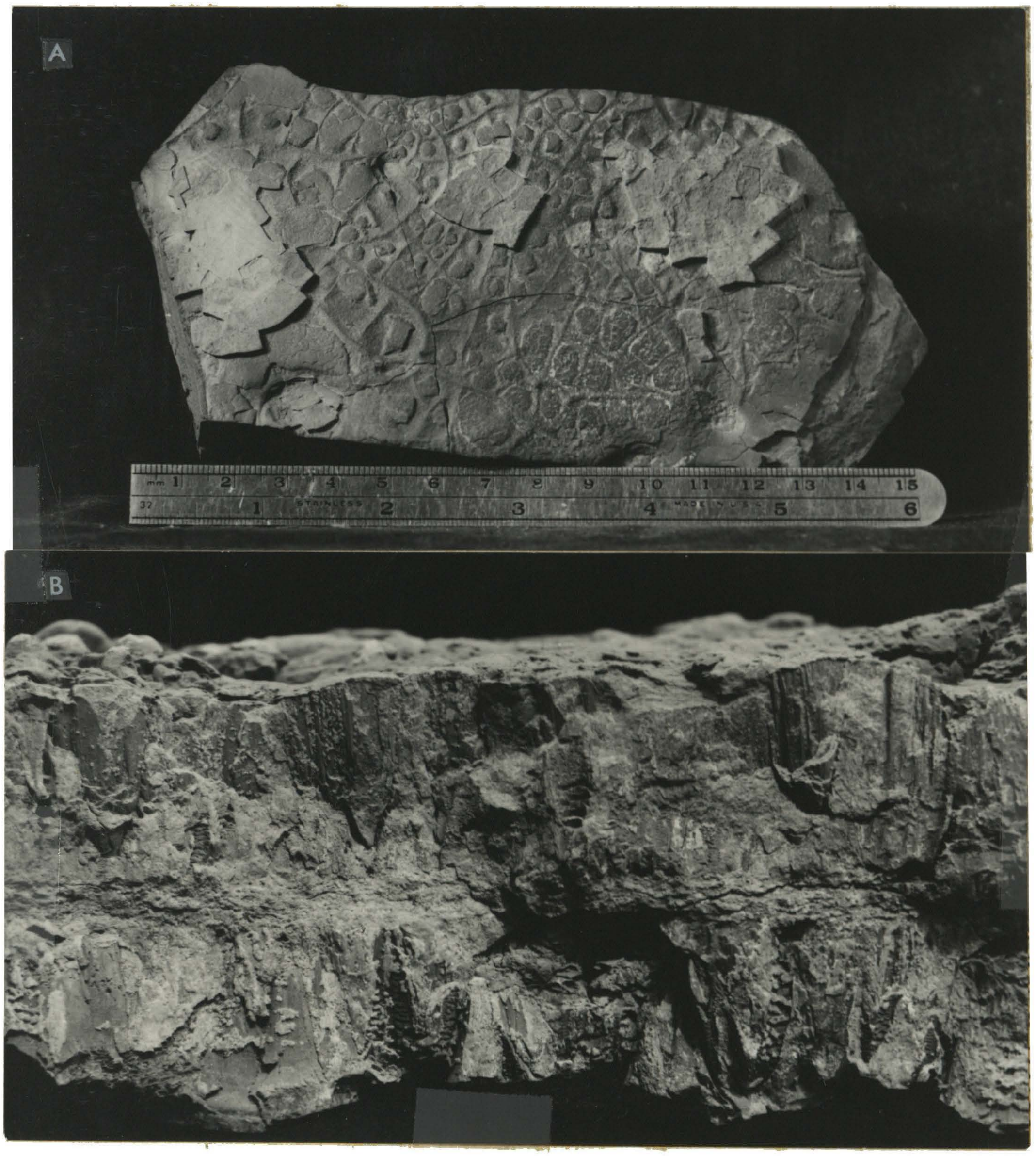


Fig. 12.--- Concretionary structures in Kiowa shale. A) Fragment of impure siderite (clay-ironstone) concretion from SE¼ SW¼ sec. 1, T. 16 S., R. 7 W., Ellsworth County, Kansas. Unusual surface markings and polygonal cracks probably are colloidal phenomena allied to synaeresis during lithification.

B) Sample of cone-in-cone structure from lenticular bed in SE¼ NE¼ sec. 19, T. 16 S., R. 6 W., Ellsworth County, Kansas. The upper layer of cone-in-cone has apices oriented down and is separated from lower layer by an irregular seam of microgranular calcite. Apices of cones in lower layer point up. Sample is about 10 cm thick.

concretions break along the cracks to form angular fragments composed largely of hydrated iron oxides. The fragments are a useful criterion for recognition of Kiowa shale in grass-covered areas.

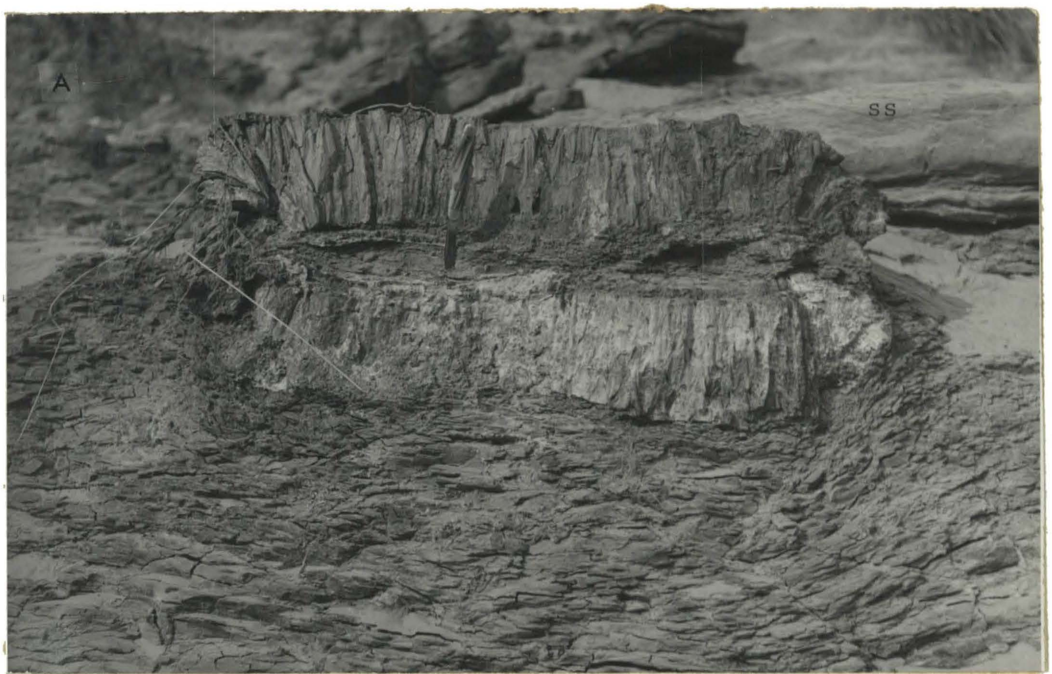
Concretions (cone-in-cone) in Kiowa shale.---

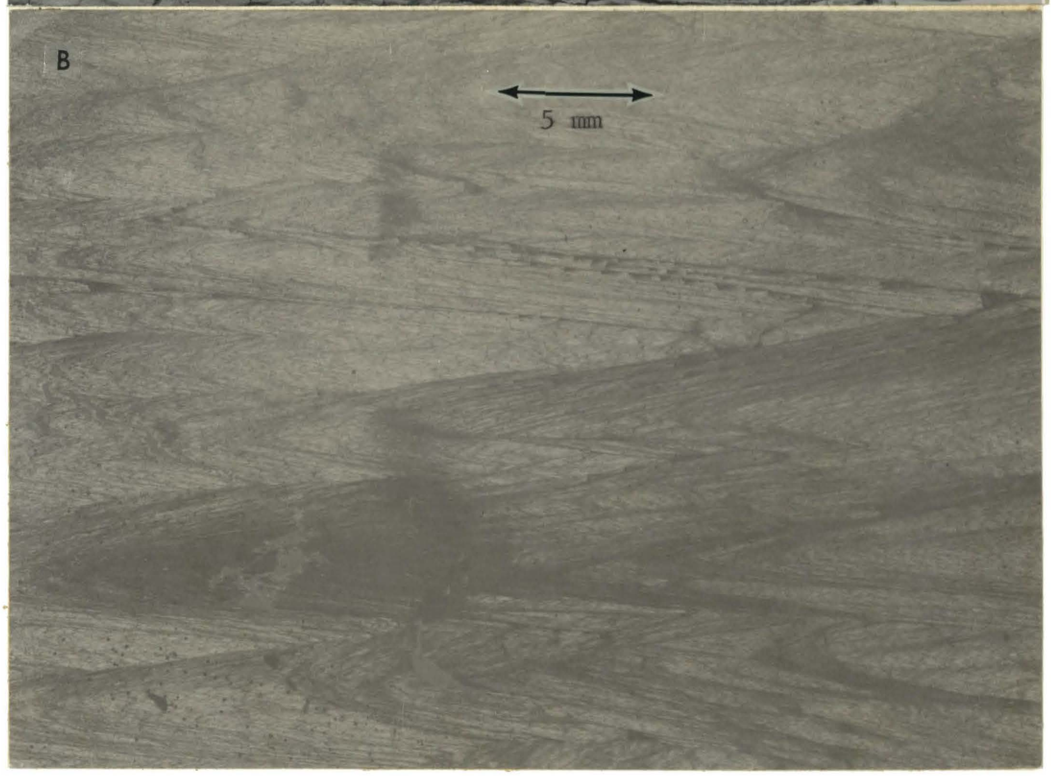
Calcareous cone-in-cone structure also is common in the Kiowa Formation and float from weathered cone-in-cone is an excellent guide for recognition of Kiowa shale in covered areas. The cone-in-cone structures provide insight into diagenetic processes and conditions below the sediment-water interface in the Kiowa sea. The cone-in-cone occurs both as thin lenticular beds and as discoidal to ellipsoidal concretions in shale, and in a few places as irregular layers as much as 0.2 foot (6 cm) thick in beds of sandstone enclosed in argillaceous rock.

Cone-in-cone structure is well exposed on the shores of Kanopolis Reservoir, Ellsworth County, and upstream in cutbanks of the Smoky Hill River (Plate 2). There the cone-in-cone occurs as lenticular beds (Fig. 12-B) and as discoidal to ellipsoidal concretions (Fig. 13-A) in one or more zones of thinly laminated illitic shale having scattered thin beds of very fine-grained sandstone or siltstone. The sandstone or siltstone beds are cemented by calcite and contain numerous disseminated crystals, blebs, and nodules of marcasite, as well as abundant disseminated carbonaceous debris. The lenses of cone-in-cone are as much as 0.5 foot (15 cm) thick and 30 feet (9 m) long, whereas the concretions of cone-in-cone are about 1 foot thick and generally are less than 6 feet long. Individual cones in the concretions and lenticular beds range from 2 to 12 cm in height. Apical angles range from 15 to 70 degrees, and the shorter cones show the larger apical angles. The structure of the cones is much like that described by Durrance (1965) and the shorter cones show well-developed "rings" or annular clay-filled depressions like those described by Tarr (1922, p. 201-202), but annular rings are less obvious or lacking in the longer cones. Shale enclosing concretions of cone-in-cone commonly is

Fig. 13.--- Calcareous cone-in-cone structure in Kiowa shale near cen. $S\frac{1}{2}$ sec. 33, T. 15 S., R. 7 W., Ellsworth County, Kansas. A) concretion showing cone-in-cone structure. Apices of cones point toward shale core that nearly bisects the concretion. Shaly laminae are contorted around the concretion. Sandstone bed (ss) is warped partly over the top of the concretion, which is about 0.8 foot (25 cm) thick.

B) photomicrograph of thin section of calcareous cone-in-cone structure. Apices of cones are to the left; original orientation was with apices down. Note cone-shaped plumose aggregates of fibrous calcite and traces of conical layering brought out by clay films and angulate patches of clay. Apical angles of the plumose aggregates are near 20^{o}, about the same angle as the cones that they form. The calcite fibers composing the plumose aggregates are less than 6 microns in diameter and as much as 3 cm long. Angulate aggregates of clay are less than 0.5 mm long and are the fillings of annular rings seen in cone cups of hand samples. Nicols partly crossed.


A
SS


B
5 mm

contorted about the concretions and a sandstone bed is warped partly over the top of the conretion shown in Figure 13-A.

The cone-in-cone structure commonly contains disseminated crystals and irregularly shaped blebs and masses of marcasite that are associated with and enclose finely divided carbonaceous matter. In thin section, the marcasite both in the cone-in-cone and in the associated beds of sandstone shows sutured margins against calcite, and encloses and embays remnants of calcite. The marcasite seems to have formed by replacement. Shale above and below zones of shale containing cone-in-cone has abundant dis-coidal concretions of impure siderite, but the thin beds of sandstone or siltstone associated with the siderite concretions are nearly devoid of calcareous cement; iron sulfides are scarce where siderite concretions abound. Apparently conditions favoring growth of calcareous cone-in-cone structure were not compatible with conditions favoring growth of con-cretions of siderite.

Woodland (1964) has examined specimens of cone-in-cone structure from many different stratigraphic units scattered widely throughout the United States. All samples examined petrographically by him were composed of fibrous carbonate, mainly calcite, and laminae of argillaceous material. Cone-in-cone structure in concretions in the Kiowa Formation has similar microscopic structure. Figure 13-B is a photomicrograph of a sample collected from a cone-in-cone concretion in Ellsworth County (unit 2, Measured Section 5, Appendix and Plate 4). The cone-in-cone structure consists of interfering cones composed of nested and interfering cone-shaped plumose aggregates of fibrous calcite. Individual cones are sepa-rated from their neighbors by argillaceous films as much as 0.02 mm thick. Thinner films separate the plumose aggregates. Locally clay has been concentrated in angulate patches that correspond to the fillings of the annular rings (Tarr, 1922, p. 201-202) seen in the cone cups of some hand samples. Trace amounts of carbonaceous matter are concentrated along the clay films, and aggregates of marcasite are localized by bits of carbonaceous matter.

Locally, as in NE 1/4 sec. 13, T. 17 S., R. 1 W., northeastern McPherson County, cone-in-cone structure is found as irregular layers in fine-grained argillaceous sandstone cemented with calcite and containing both marcasite and abundant carbonaceous debris. The cones in sandstone tend to be less distinct than those developed in the calcareous lenses and concretions in shale. The cones are oriented with their apices pointing up or down, even within the same sample.

Thin section examination of the sandstone containing layers of cone-in-cone shows that the sandstone is composed of subrounded to subangular quartz grains that are less than 0.4 mm in long diameter. The rock also contains appreciable disseminated clay, sparse carbonaceous matter, and patches of subhedral marcasite that are intimately associated with the carbonaceous debris. Calcite cement approximates 30 percent of the rock and is composed of grains and fibrous aggregates of calcite that measure less than 0.06 mm long. The calcite shows lobate margins against the detrital grains and has replaced the outer fringes of most of them.

The layers of cone-in-cone in the calcite-cemented sandstone are composed almost wholly of calcite and contain only a few percent disseminated detrital quartz (Fig. 14-A), but the layers grade abruptly into the enclosing sandstone. The conical layering or cupping of the cone-in-cone structure is composed of a series of nested and intersecting plumose aggregates of fibrous calcite that are aligned more or less parallel to

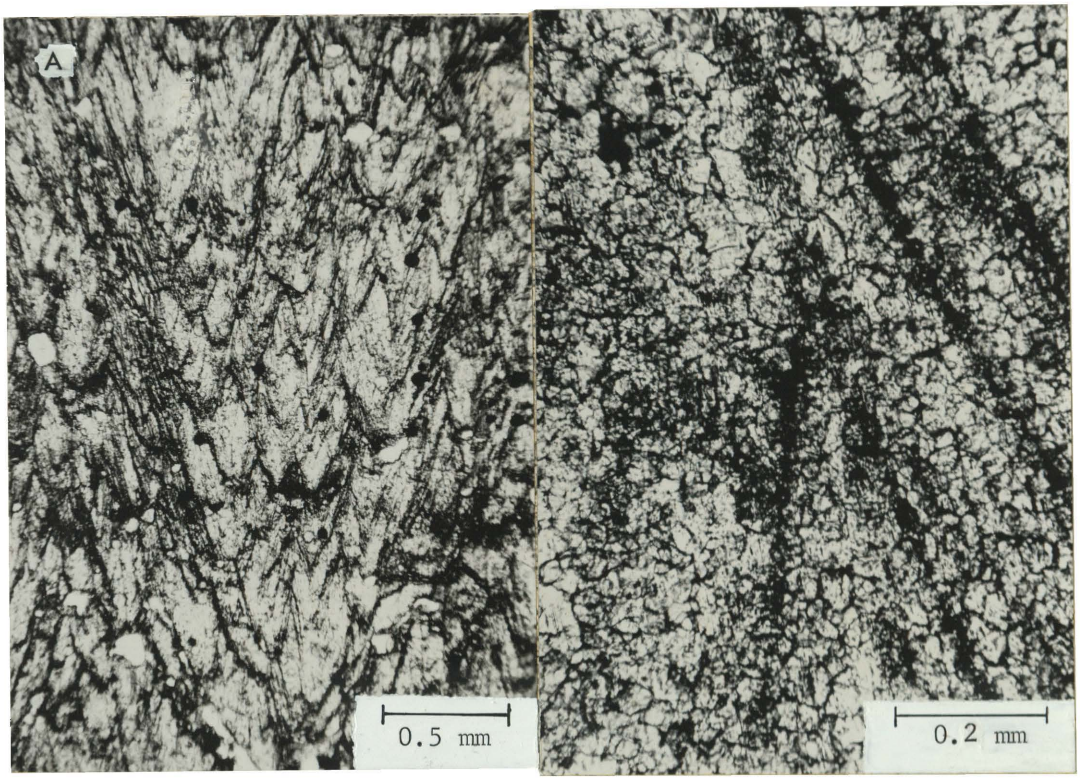


Fig. 14.--- Photomicrographs of calcareous cone-in-cone structure, north-central Kansas. Plane-polarized light.

A) Thin section of cone-in-cone structure in sandstone, NE¼ sec. 13, T. 17 S., R. 1 E., McPherson County. Note cone-shaped plumose aggregates of fibrous calcite, scattered detrital grains of quartz (very light gray to white), and traces of conical layering brought out by clay, marcasite, and fine-grained calcite (dark gray to black). Calcite fibers in the plumose aggregates are less than 2 microns in diameter and as much as 0.5 mm long. Small, round black spots are bubbles on underside of thin section. Original orientation of cone was with apex up.

B) Thin section of cone-in-cone structure cut from cone about 2 cm long in a lenticular bed of cone-in-cone at same locality as sample shown in Figure 12-B. Note microgranular habit of calcite, conical layering, and stringers of inclusions that impart a fibrous aspect to parts of the thin section. Calcite grains are as much as 0.08 mm in diameter. Original orientation of cone was with apex down.

the axes of the cones. Individual cones, which measure as much as 3 cm in height, have apical angles between 70 and 100 degrees whereas the plumose aggregates have apical angles between 25 and 40 degrees. The conical layers are defined by laminae less than 0.25 mm thick that contain flakes of clay, disseminated blebs of marcasite, and grains of calcite smaller than 2 microns in diameter. Contrary to statements by Pettijohn (1957, p. 210), there is little reason to think that pressure solution was operative or that the fibrous structure actually antedates the cone-in-cone developed in this sample of Kiowa sandstone or in the concretions of cone-in-cone (Fig. 13-A, -B). Because the layers of cone-in-cone in the calcite-cemented sandstone are so irregular in shape and contain only sparse, isolated detrital grains of quartz, the detrital framework of the sandstone is thought to have been expanded by the addition of calcite and the formation of cone-in-cone structure.

Cone structures that developed in thin lenticular beds of cone-in-cone are composed of microgranular calcite (Fig. 14-B). The conical layering appears in thin section as bands of granular calcite less than 0.4 mm thick. The bands are separated by zones that are composed of very fine-grained calcite and along which flakes of clay and minute particles of marcasite and carbonaceous matter are disseminated. What can be interpreted as relict fibrous structure is brought out in thin section by stringers of elongate inclusions, most of which seem to be clay. The inclusions measure less than 0.03 mm long and less than 5 microns wide. They commonly extend across grain boundaries and tend to be aligned at relatively gentle angles to the axes of the cones (20^{o} or less).

Both Woodland (1964) and Durrance (1965) concluded that cone-in-cone structure developed during early diagenesis through the force of crystallization of calcite. Both authors related the apical angles of the cones to the plasticity of the enclosing medium in which the cone structure grew, smaller apical angles indicating a more plastic medium. The apical angles of cones developed in shale and those developed in sandstone in the Kiowa Formation are in keeping with the concept. Woodland also related the development of cone structures to the stress fields set up by growing fibers of calcite and the effect of one fiber on the next. Contortion of shale and sandstone beds about concretions of calcareous cone-in-cone structure and the expanded volume and detrital framework of sandstone beds containing layers of calcareous cone-in-cone indicate that cone-in-cone in the Kiowa Formation developed before the enclosing sediments were lithified and while they still were quite plastic.

Along the shores of Kanopolis Reservoir in Ellsworth County, lenticular beds of cone-in-cone like that shown in Figure 12-B are underlain by fossiliferous shale that not only contains imprints of pelecypods, but locally contains shells of Turritella that have been replaced by marcasite. On the steep bluff in the NE 1/4 sec. 4, T. 17 S., R. 6 W., on the south shore of Kanopolis Reservoir, a lenticular bed of cone-in-cone is underlain by and in contact with a bed of fossil coquina (Fig. 15). The coquina has been recrystallized and contains crystals of secondary gypsum that presumably have been derived by oxidation of marcasite. Although conical layering is well preserved in the cone-in-cone, the calcite has been converted to a microgranular aggregate. It is likely that decaying organic matter below the lenticular beds of cone-in-cone structure may have lowered the pH in the sediments next above sufficiently to bring about reorganization of the calcite in the cone-in-cone. Upward migration of some acid agent, perhaps H_2S, is implicit in the suggestion.

Twenhofel and Tester (1926) noted the abundance of cone-in-cone structure in southeastern Ellsworth County and in nearby parts of Rice and McPherson counties. They suggested with some reservation that the cone-in-cone was part of an extensive "layer" that might have correlative value. That the cone-in-cone does not constitute a layer is seen from its

Fig. 15.--- Photomicrograph of thin section of calcareous cone-in-cone structure in contact with coquinoid limestone. Sample is from NE¼ sec. 4, T. 17 S., R. 6 W., Ellsworth County, Kansas. Conical layering in cone-in-cone is well developed although the cone-in-cone is composed of microgranular calcite. Individual grains of calcite are less than 0.02 mm in diameter. Underlying coquinoid limestone is composed largely of recrystallized pelecypod shell fragments but contains interstitial clay, silt-sized quartz, and iron-oxide cement as well as microgranular calcite. Large black fragment is phosphatic and shows organic structure under intense illumination. A few rounded pellets of glauconite (gray) are embedded in matrix binding shell fragments. Tabular crystals (lower right) are gypsum, which also fills the central parts of some shell fragments. Plane-polarized light. Sample collected by R. W. Scott.

concretionary and lenticular development. In some localities, more than one zone of cone-in-cone is present (units 2 and 3, Measured Section 5, Appendix and Plate 4). Moreover, cone-in-cone structure is found both high and low in the Kiowa Formation in north-central Kansas although most would seem to occur in the lower part of the formation where typical gray Kiowa shale is most abundant. Nonetheless, the usefulness of cone-in-cone structure for correlation is questionable.

Coquinoid limestone

Shell beds or coquinoid limestone constitute a volumetrically insignificant but genetically important part of the Kiowa Formation in north-central Kansas. They are found mainly within thick sequences of typical gray Kiowa shale where they commonly occur above or below zones of shale containing cone-in-cone structure, above beds of fine-grained sandstone or siltstone, or alone in sequences of shale. They occur as discontinuous beds up to 0.5 foot (15 cm) thick mostly in eastern Ellsworth County, northeastern Rice County, and western McPherson County (Plate 1). Most consist of reworked ostreid shell fragments and less numerous shell fragments of other pelecypods. Locally, shells of the high-spired gastropod Turritella are abundant. The shell debris (Fig. 15) seems to have been locally derived. Calcite and iron-oxide cement are common and accumulations of clay, detrital grains of quartz, and rounded pellets of glauconite are interstitial to the shell debris. Along the west line SW 1/4 sec. 22, T. 15 S., R. 2 W., Saline County, a fairly extensive shell bed is exposed. The bed is a calcite-cemented mass of ostreid shells nearly one foot (30 cm) thick. Most of the shells do not seem to have been transported, but rather they seem to have grown essentially in place. The bed rests on and grades laterally into siltstone. Beds of coquinoid limestone in Rice and McPherson counties commonly can be traced laterally into beds of fine-grained calcite-cemented sandstone containing ostreid and other fossils.

Carbonaceous sequences in Kiowa Formation

In addition to sequences composed largely of thinly laminated gray shale, the Kiowa Formation contains dominantly argillaceous sections of mudstone, claystone, and shale composed of illite, montmorillonite, and variable amounts of kaolinite. The rocks show variable plasticity and range from light gray or light brownish gray to grayish black or brownish black. These argillaceous rocks commonly contain appreciable carbonaceous matter, locally verge on being lignite, and tend to be somewhat more kaolinitic than typical Kiowa shale. Intercalated laminae and beds of siltstone and sandstone commonly contain abundant macerated plant debris and U-shaped burrows referred to the genus Arenicolites (Hantzschell, 1962; cf MacKenzie, 1963). The siltstone beds and laminae may contain abundant interstitial clay and commonly show transverse ripple marks, various current ripples, micro-cross-stratification, or evenly spaced thin laminae. The argillaceous rocks generally grade upward into siltstone and sandstone through an interlaminated zone in which so-called starved ripple marks are common. Measured Section 5 (Appendix and Plate 4) includes descriptions of some of these rock types, which commonly but not universally are found in the upper part of the Kiowa Formation in north-central Kansas, particularly where argillaceous rocks are intercalated with sandstone on the flanks of thick lenticular deposits of Kiowa sandstone. The sequence described in Measured Section 5 is replaced within one-half mile (1.3 km) southward by a section composed completely of sandstone.

Where sequences of gray, brownish-gray, or nearly black carbonaceous claystone, mudstone, and shale are found near the top of the Kiowa, they underlie and grade both upward and laterally into sandstone that about marks the top of the formation (Measured Sections 5, 8, and 11, Appendix and Plate 4). Best exposures of carbonaceous material in the upper part of the Kiowa Formation are along the banks of the Smoky Hill River and its tributaries in Ellsworth County, but carbonaceous sections also are found in western Saline County, parts of Ottawa County, and locally in Clay County. Carbonaceous rocks also occur in the lower part of the Kiowa Formation. The sample of calcite-cemented sandstone showing cone-in-cone structure and described in the preceding section is from a carbonaceous sequence near the base of the Kiowa in the NE 1/4 sec. 13, T. 17 S., R. 1 E., McPherson County. The sandstone contains carbonized logs as much as 8 inches (20 cm) in diameter. Carbonaceous sequences in the middle parts of the Kiowa Formation are well exposed in the bluffs and steep slopes on the south shore of Kanopolis Reservoir in secs. 3 and 8, T. 17 S., R. 6 W., Ellsworth County. The fossil amber (jelinite) found in NW 1/4 SW 1/4 sec. 18, T. 17 S., R. 6 W. (Buddhue, 1939a, 1939b) probably came from a similar sequence in the lower part of the formation. Unfortunately, the locality now is caved and flooded by the waters of Kanopolis Reservoir. Langenheim and others (1965) have discussed this occurrence of amber and have considered the possibilities of its being in either the Kiowa or the Dakota formations. The locality can be referred unequivocably to the Kiowa.

Sandstone

Although the Kiowa Formation contains little sandstone in its type area in Kiowa County, sandstone is an important component of the formation elsewhere in Kansas. Deposits of sandstone span nearly the full thickness of the Kiowa in parts of north-central Kansas; extensive lenses of sandstone compose the upper parts of the formation west of the type area in Clark County, Kansas.

Most sandstone in the Kiowa Formation of north-central Kansas is fine grained (Table 3), but it ranges from very fine grained to coarse grained and conglomeratic. Most medium- to coarse-grained sandstone, fine-grained sandstone containing coarse grains, and conglomeratic sandstone, however,

Table 3.--- Results of sieve analyses of 110 samples of cross-stratified Kiowa and Dakota sandstone. Parameters from Inman (1952) and Folk (1964).

		Median diameter (mm)	Phi median diameter	Phi graphic mean	Phi deviation measure (sorting)	Phi inclusive graphic standard deviation	Phi skewness measure	Phi inclusive graphic skewness	Phi graphic kurtosis	Normalized phi graphic kurtosis	Number of samples	Percentage samples with median diameter <2.00φ
Dakota Formation	Mean	0.206	2.28	2.32	0.37	0.41	0.16	0.22	1.33	0.56	87	23
	Standard Deviation	——	0.45	0.44	0.12	0.13	0.14	0.16	0.38	0.07		
	Range	0.504, 0.099	0.99, 3.34	1.18, 3.35	0.21, 0.94	0.24, 0.93	-0.13, 0.55	-0.56, 0.66	0.27, 2.77	0.21, 0.73		
Janssen Clay Member, Dakota Formation	Mean	0.183	2.45	2.48	0.35	0.37	0.13	0.18	1.24	0.54	41	12
	Standard Deviation	——	0.44	0.34	0.12	0.12	0.12	0.16	0.36	0.08		
	Range	0.266, 0.099	1.91 3.34	1.92, 3.35	0.21, 0.94	0.23, 0.93	-0.13, 0.40	-0.56, 0.38	0.27, 2.33	0.21, 0.70		
Terra Cotta Clay Member, Dakota Formation	Mean	0.230	2.12	2.17	0.38	0.44	0.19	0.26	1.40	0.58	46	43
	Standard Deviation	——	0.47	0.47	0.11	0.14	0.15	0.16	0.39	0.05		
	Range	0.504, 0.107	0.99, 3.22	1.18, 3.29	0.21, 0.65	0.24, 0.68	-0.10, 0.56	-0.04, 0.65	0.98, 2.77	0.49, 0.73		
Kiowa Formation	Mean	0.203	2.30	2.34	0.37	0.42	0.13	0.22	1.35	0.56	23	21
	Standard Deviation	——	0.53	0.53	0.13	0.17	0.13	0.14	0.46	0.06		
	Range	0.536, 0.100	0.90, 3.32	0.96, 3.29	0.22, 0.68	0.22, 0.78	-0.11 0.48	-0.05, 0.60	0.87, 2.90	0.48, 0.70		

occur along the eastern fringes of the outcrop belt. Kiowa sandstone tends to be well sorted (Folk, 1954, footnote 3, p. 349; Folk, 1964, p. 45) but ranges from moderately sorted to very well sorted (Table 3; Fig. 16-A, -B). Skewness of almost all samples analyzed is positive but slight (Table 3). Of 23 samples, only one showed negative skewness using Folk's (1964, p. 46) "inclusive graphic skewness," and three using Inman's (1952, p. 130) "phi skewness measure." Samples showing strong positive skewness mostly are very fine grained and contain more than 5 percent interstitial clay. Calculation of kurtosis values (Folk, 1964, p. 47) showed that the samples range from platykurtic to very leptokurtic, but most are leptokurtic (Table 3). The sorting in the tails of the distributions is not as

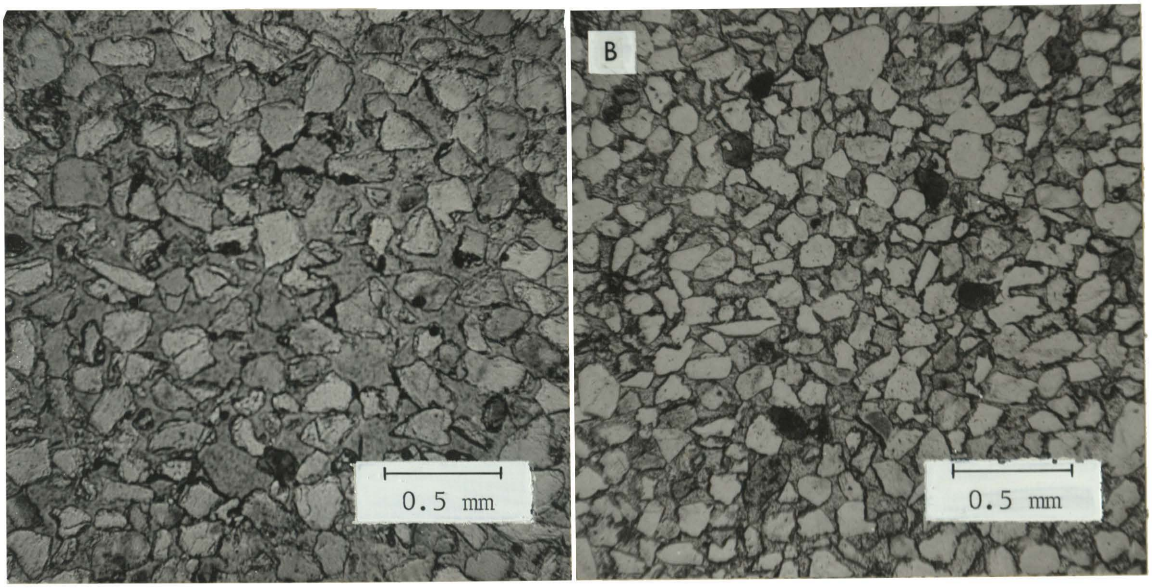


Fig. 16.--- Photomicrographs of thin sections of Kiowa sandstone, Ellsworth County, Kansas. Plane-polarized light. A) Fine-grained quartz-rich sandstone from thick lenticular deposit in SE¼ sec. 1, T. 16 S., R. 7 W.. Note generally subangular character of the quartz grains. The rock contains less than one percent interstitial clay and is from the same lenticular deposit as the calcite-cemented sandstone shown in Figure 18.

B) Fine-grained calcite-cemented sandstone near cen. N½ SW¼ sec. 1, T. 16 S., R. 7 W. (unit 4, Measured Section 6, Appendix and Plate 4). The thin sandstone bed is intercalated with Kiowa shale and is composed of angular to subrounded quartz grains (light gray) and calcite cement (medium gray) that forms optically continuous patches nearly 1 cm long. Rounded pellets of glauconite (dark gray) approximate one percent of the rock.

good as in the central parts and may reflect only weak bimodality.

Quartz approximates 95 percent or more of the detrital components in most Kiowa sandstone, and in light of the sorting characteristics, Kiowa sandstone is classified as mature (Folk, 1951). Polycrystalline quartz amounts to as much as 5 percent of the detrital components in some coarse-grained to conglomeratic samples, but in very fine grained sandstone it is present mainly in trace amounts. Grains of chert are almost universally present in Kiowa sandstone, but they generally do not exceed one percent of the detrital components. Feldspar amounts to as much as 3 percent of the detrital components in some fine- and very fine grained sandstone, but it was not detected in coarse-grained to conglomeratic samples. Microcline and untwinned potash feldspar are more abundant than plagioclase. Mica, mainly muscovite, generally is a trace component and occurs as comminuted and bent books, largely in fine-grained and very fine grained Kiowa sandstone. Chlorite was detected only in one or two thin sections of fine-grained Kiowa sandstone. Schistose and phyllitic rock fragments occur only in trace amounts. Interstitial clay and silt are most abundant in fine- to very fine grained sandstone, but they generally do not exceed 5 percent of the rock except in gradational intervals between shale and sandstone. In medium-grained and coarser rocks, interstitial clay commonly is present in amounts smaller than one percent. It may be relatively abundant in some conglomeratic Kiowa sandstone, but iron-oxide cement prevents reasonable estimation of proportions of clay. Thin section studies and sieve analyses show that trace amounts of abraded shell fragments and fish scales and teeth are detrital components of some sandstone samples.

Rounded pellets of glauconite are present chiefly in fine-grained and very fine grained Kiowa sandstone that is intercalated with thick sequences of shale. It is most common where calcite or other carbonate cement has protected it from oxidation and weathering (Fig. 16-B). Generally glauconite does not exceed one percent of the sandstone, but a fossiliferous fine-grained sandstone cemented by siderite near the NW cor. sec. 10, T. 15 S., R. 5 W., Saline County, contains about 10 percent glauconite as rounded pellets up to 0.3 mm in long diameter. The siderite cement approximates 40 percent of the rock and is present as minute anhedra measuring less than 0.01 mm long. The margins of the enclosed quartz grains, and to a lesser extent the glauconite pellets, are embayed and replaced by the siderite cement. Interstitial aggregates of glauconitic mica as well as rounded pellets of glauconite were noted in some samples of fine-grained calcite-cemented sandstone.

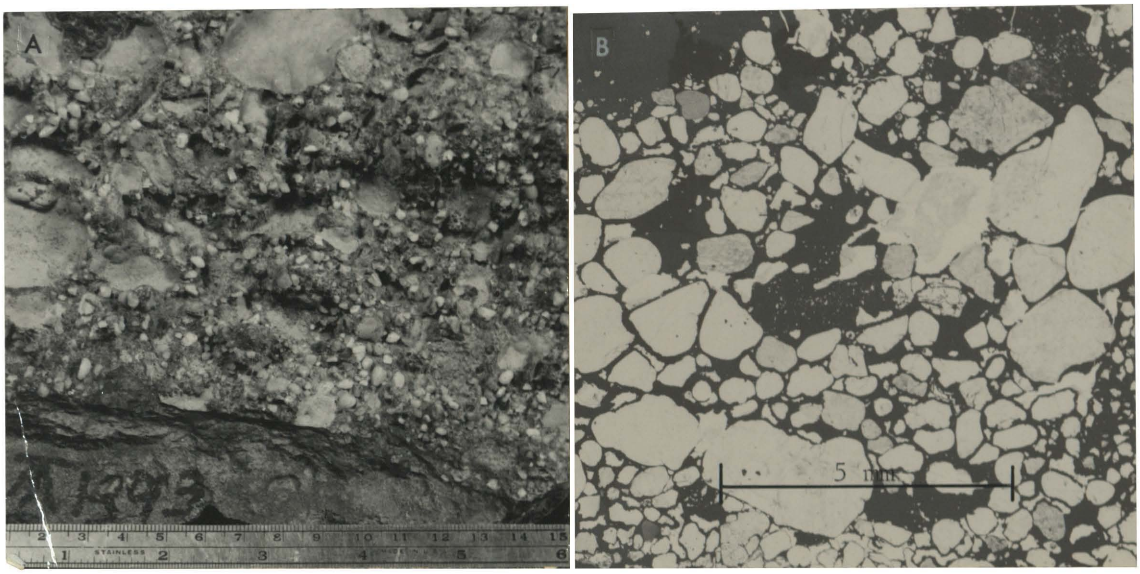


Fig. 17.--- Conglomeratic Kiowa sandstone, Ottawa County, Kansas. A) Close-up of bedding surface of dominantly fine-grained sandstone near cen. sec. 8, Tl 11 S., R. 2 W.. The irregular surface is paved with well-rounded coarse grains and granules of quartz, quartzite, and chert as well as with molds of rounded shale pebbles.

B) Photomicrograph of thin section of conglomeratic sandstone from SW¼ sec. 28, T. 12 S., R. 2 W.. The conglomerate occurs as a lens in a thick lenticular deposit of sandstone and is composed mainly of grains of quartz and quartzite (light gray), but contains shale pebbles stained by iron oxide (black) and iron-oxide cement. Some shale pebbles contain silt-sized particles of quartz. The thin section was cut from a sample containing an articulated specimen of the clam Flaventia. Nicols partly crossed.

Conglomeratic sandstone generally does not contain grains coarser than granules, other than penecontemporaneously reworked shale pebbles (Fig. 17). Exception is in sandstone near the base of the formation that contains pebbles of quartz, quartzite, and chert reworked from the pebble zone along the unconformity separating Permian and Cretaceous rocks. Granules in conglomeratic sandstone are composed mainly of quartz and quartzite. Many of the quartzite granules are pale yellowish orange to moderate reddish orange. The colors are similar to those of the Precambrian Sioux Quartzite of South Dakota and Minnesota. Grains having the same colors in fine-grained Kiowa sandstone probably are fine-grained particles of the same rock type.

The sand-sized detrital grains in Kiowa sandstone range from very angular to well rounded (Powers, 1953). The degree of roundness is a strong function of grain size (Fig. 16, 17). Very fine grained to fine-grained Kiowa sandstone generally is angular to subangular whereas medium- to coarse-grained sandstone mainly is subangular to subrounded. Very coarse grains and granules in Kiowa sandstone tend to be well rounded. Sphericity correlates directly with grain size and roundness so that greatest sphericity is shown by granules and pebbles. Quartz grains in well sorted samples commonly have quartz overgrowths, most of which do not surround the grains completely. Etched quartz grains also are present.

Most sandstone in the Kiowa Formation is friable and only lightly stained by iron oxide. Locally, extensive areas of sandstone are stained moderate red to reddish brown by hematite, as in Red Rock Canyon, sec. 5, T. 16 S., R. 6 W., Ellsworth County. Most iron-oxide cement, however, is found where sandstone caps hills and benches. Where abundant iron oxide has accumulated in sandstone, the rock is highly indurated and bedding is masked by Liesegang rings and pipe-like structures (Fig. 18-A). Locally, however, distribution of iron-oxide cement is controlled by stratification (Fig. 18-B). Swineford (1947, p. 72-76) has noted that much iron-oxide cement in Kiowa sandstone is a surface or "case-hardening" phenomenon. Topographic distribution of iron-oxide cement in Kiowa sandstone indicates that much of it stems from geologically young post-Cretaceous weathering.

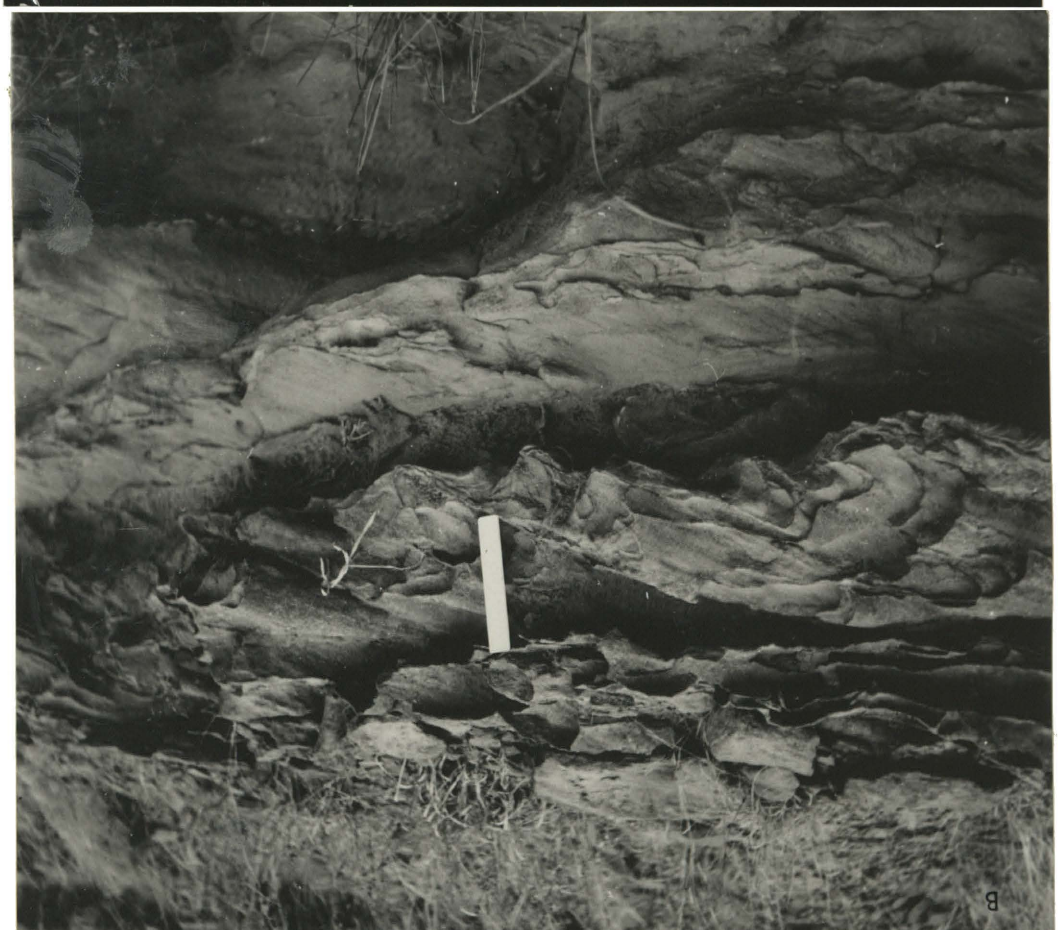
Calcite cement is a common feature in Kiowa sandstone and has been described throughly by Swineford (1947). It is found at various stratigraphic levels in the formation. In most places, calcite cement forms concretionary masses as much as 12 feet (3.6 m) in diameter and has resulted in bizarre spheroidal boulders showing excellent preservation of

Fig. 18.--- Iron-oxide cement in Kiowa sandstone, north-central Kansas.

A) Oblique view of diffusion structures in iron-oxide cemented sandstone from NW¼ NW¼ sec. 14, T. 17 S., R. 4 W., McPherson County. Ruler lies along the broken face of the sample. The sandstone from which the sample was taken caps a broad bench. Note complete obliteration of bedding.

B) Cross-stratified sandstone in SE¼ NE¼ NW¼ sec. 12, T. 11 S., R. 3 W., Ottawa County. Note concentration of iron-oxide cement in upper part of the exposure and partial control of diffusion structures by stratification. Scale is 7 inches (18 cm) long.


A

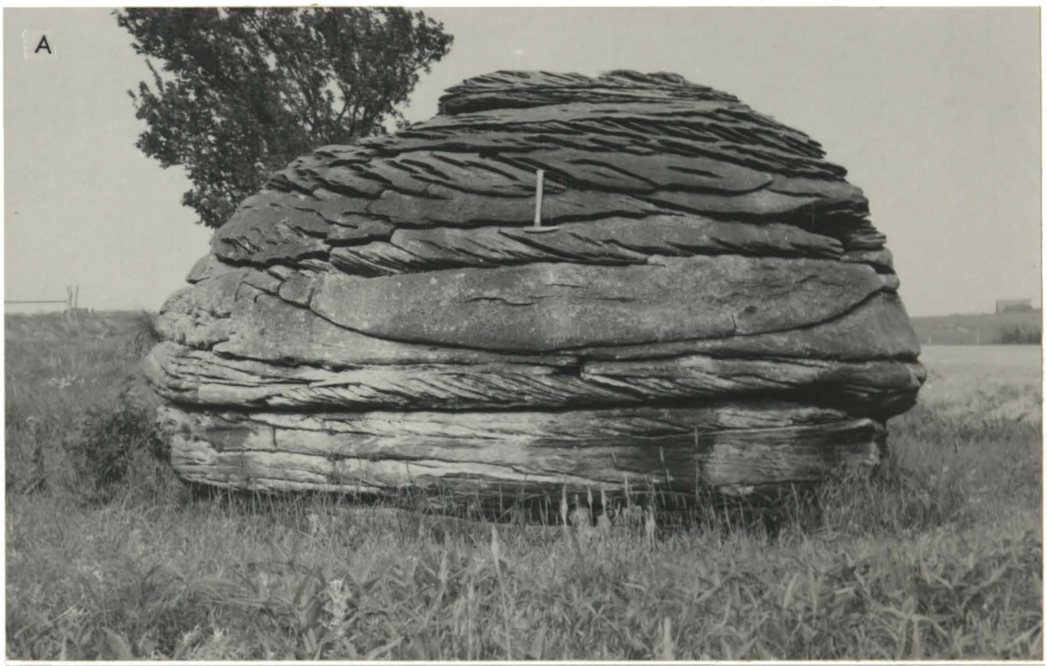


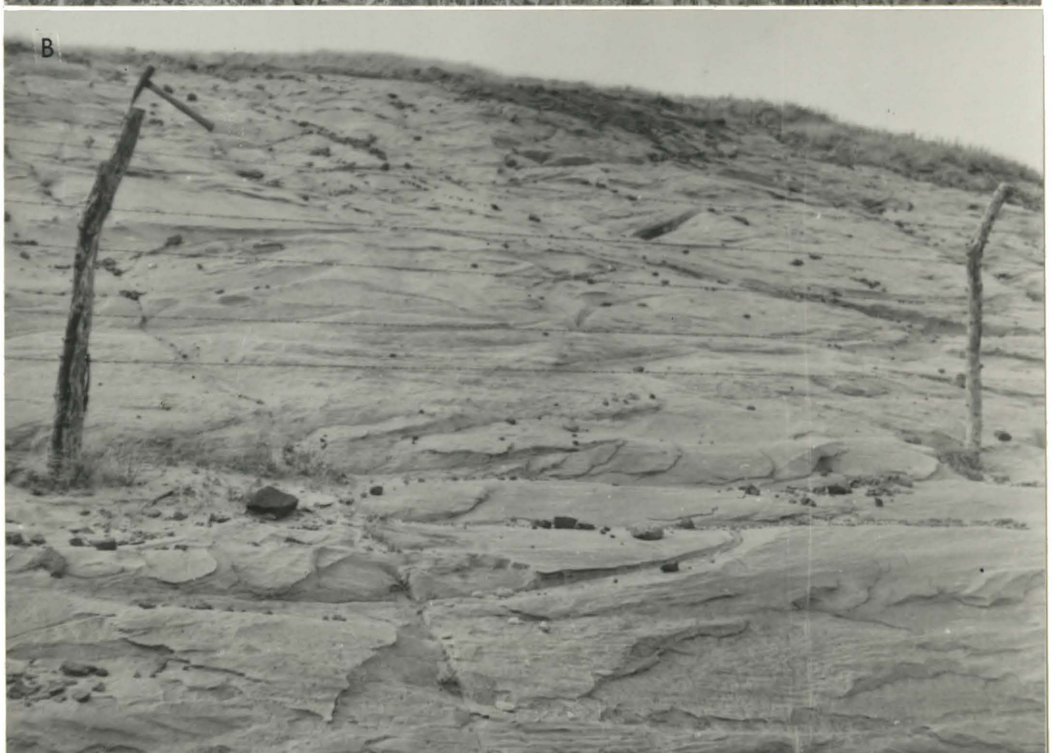
bedding structures (Fig. 19-A). Elsewhere, cementation by calcite has largely obliterated bedding and developed irregularly shaped nodular concretions similar in size to that in Figure 19-A. Although few concretions have formed, the bulk of a sandstone lens is cemented by calcite in parts of secs. 7 and 8, T. 17 S., R. 1 E., Marion County.

Marcasite and pyrite commonly are associated with calcite cement in Kiowa sandstone. Many of the concretionary masses of calcite contain nodules and disseminated blebs of iron sulfide, some of which seem to have acted as centers of accumulation for the carbonate cement. The iron sulfide commonly is localized on and has partly replaced bits of carbonaceous debris or other organic matter. The intimate association of calcite-cement, iron-sulfide, and organic matter suggests that the three may be genetically related. The expanded detrital framework in layers of cone-in-cone in some calcite-cemented Kiowa sandstone (Fig. 14-A) and evidence offered by Swineford (1947, p. 87) indicate that calcite cement was added prior to lithification of the enclosing rock during early diagenesis. Evidence also has accumulated that FeS_2 is precipitated during early stages of sedimentation or diagenesis (Love, 1957; Vallentype, 1963; Degens, 1965, p. 155-161). Brown (1954) suggested that the relationship between organic matter and calcareous concretions (specifically cone-in-cone structure) might be more than fortuitous and that organic matter may have supplied some of the CO_2 necessary for formation of calcite. Weeks (1957) suggested that decaying organic matter may have released ammonia that raised pH sufficiently for calcite to be precipitated as concretions about fish remains in Cretaceous shale in Colombia. Perhaps some combination of all these factors gave rise to environments favorable to localization of calcite cement in Kiowa sandstone. Universally present organic matter may have

Fig. 19.--- Cross-stratified sandstone in Kiowa Formation, north-central Kansas. A) concretionary calcite cement in sandstone at Mushroom Rocks State Park, SE¼ SW¼ sec. 19, T. 15 S., R. 6 W., Ellsworth County. Cross-stratification is medium and small scale tabular and wedge planar and dips mainly to the south and southeast. The locality is in the upper part of a thick lenticular deposit of sandstone near the top of the Kiowa Formation where ellipsoidal masses of calcite-cemented sandstone on pedesta of less-indurated sandstone give rise to the name of the park.

B) medium-scale trough cross-stratification in thick lenticular deposit of Kiowa sandstone near cen. E line SE¼ sec. 32, T. 11 S., R. 3 W., Ottawa County. The cross-strata dip mainly west away from the camera.


A


B

Thick lenticular deposits of sandstone.---

Sandstone in the Kiowa Formation can be divided into two genetically different types of deposits. The one forms relatively thick lenticular bodies of sandstone that locally are as much as 100 feet (30 m) thick; the other forms deposits mainly less than 10 feet (3 m) thick. One prominent bluff with petroglyphs carved near its base in sec. 31, T. 15 S., R. 6 W., Ellsworth County, is composed completely of sandstone and is nearly 60 feet (18 m) high. The bluff exposes part of a sandstone lens that extends more than one mile (1.6 km) northward at least as far as Mushroom Rocks State Park in sec. 19 and 30, T. 15 S., R. 6 W., Ellsworth County, (Fig. 17-D) and more than one mile (1.6 km) southward into sec. 1, T. 16 S., R. 7 W.. The lens is in the upper part of the Kiowa and locally can be seen in contact with mudstone and claystone in the basal parts of the overlying Dakota Formation. Similar thick deposits of sandstone in the upper part of the Kiowa Formation are found at "Rock City" (Fig. 17-C) in sec. 14, T. 11 S., R. 4 W., Ottawa County, and in nearby areas.

Although comparatively thick deposits of sandstone are common in the upper parts of the Kiowa Formation, the sandstone exposed near the intersection of Kansas highways 4 and 141 in T. 17 S., R. 6 W., Ellsworth County, extends almost from the top of the Permian to the base of the Dakota Formation. Its thickness is nearly 100 feet (30 m). Thick sandstone occurs close to the top of the Permian in the vicinity of Twin Mounds, sec. 1, T. 18 S., R. 2 W., McPherson County (Plate 1) where about 100 feet (30 m) of sandstone containing some lenticular shaly beds is exposed. The highland that extends about 20 miles (32 km) northward from T. 17 S., R. 2 W. in McPherson County almost to Salina in T. 14 S., R. 2 W., Saline County (Plate 1), is underlain almost completely by Kiowa sandstone, some of which is in direct contact with underlying Permian rocks. The Kiowa section exposed above the Longford Member in southwestern Dickinson County and northwestern Marion County (Plate 1) is estimated to be about 80 percent sandstone in much of the area. The prominent topographic high in T. 13 S., R. 2 W. in northern Saline County is underlain mainly by Kiowa sandstone. Much of the Kiowa in eastern Ottawa County is composed of thick lenticular deposits of sandstone and the same is true of western Clay County. The thick sandstone deposits in eastern Ottawa County and western Clay County mostly are separated from Permian rocks by the fine clastics of the Longford Member of the Kiowa Formation, but some deposits of sandstone extend downward nearly through the Longford Member, as in the outlier in sec. 16 and 21, T. 9 S., R. 2 E., Clay County. Areas underlain by the thick lenses of sandstone generally are deeply dissected, but in many places they are gentle upland surfaces that are interrupted only by low rounded hills or steep outliers of the overlying Dakota Formation.

The grain size of thick lenticular deposits of Kiowa sandstone differs appreciably from place to place and within individual lenticular bodies. Medium- to coarse-grained and conglomeratic sandstone essentially is restricted to the thick lenticular deposits. The conglomeratic sandstone generally consists of scattered coarse grains, granules, and shale pebbles on bedding surfaces of finer grained sandstone (Fig. 17-A). In a few places coarse-grained and conglomeratic sandstone (Fig. 17-B) forms lenticular beds, most of which are less than one foot (0.3 m) thick, within finer grained sandstone.

Most sandstone in thick lenticular deposits in Ellsworth and Rice counties as well as in many parts of north-central Kansas does not contain either granules or coarse grains, but it is coarser grained than sandstone in the thin deposits. Table 4 gives the results of sieve analyses of five representative samples collected from thick lenticular deposits and six samples from thin deposits (less than 10 feet thick) in Ellsworth County. The samples from thick lenticular deposits are fine grained whereas those from thin deposits of sandstone range from very fine grained to fine grained. Sorting tends to be good in the thick lenticular deposits and skewness values are small. The negative skewness computed for two samples of sandstone from thick lenticular deposits, however, may be significant inasmuch as Friedman (1961) found that skewness of beach sands generally is negative. Figure 16-A is a photomicrograph of a sample collected from a thick lenticular deposit of sandstone in Ellsworth County and illustrates the fine-grained, well-sorted, subangular character of most thick lenticular deposits of Kiowa sandstone.

Contacts between thick lenticular deposits of sandstone and underlying Kiowa shale are both gradational and disconformable, even in different parts of the same sandstone body. Where contacts are gradational, grain size of the sandstone decreases downward as laminae of shale become more abundant. The gradational sequences generally are less than 10 feet (3 m) thick. Where scour-fill contacts with Kiowa shale occur, fragments or pebbles of penecontemporaneously reworded shale are common in the basal parts of the sandstone.

Sandstone in thick lenticular deposits shows a wide variety of cross-stratification, but horizontal stratification is scarce. More common types of cross-stratification include high-angle cross-strata in small- and medium-scale tabular- and wedge-planar sets (Fig. 19-A) and medium-scale trough-shaped sets (Fig. 19-B). Dip of individual cross-strata generally is in the range 20 to 25 degrees. Dips as high as 30 degrees are seen only

Table 4.--- Size and sorting characteristics of thick lenticular deposits and thin deposits (less than 10 feet thick) of sandstone in the Kiowa Formation, Ellsworth County, Kansas. Data from sieve analyses of 11 representative samples. Parameters from Inman (1952).

	Median diameter (mm)	Phi median diameter	Phi mean diameter	Phi deviation measure (sorting)	Phi skewness measure
Thick lenticular sandstone	0.203	2.30	2.29	0.44	-0.02
	0.196	2.35	2.36	0.34	0.01
	0.186	2.43	2.47	0.25	0.16
	0.184	2.44	2.42	0.32	-0.06
	0.157	2.67	2.69	0.47	0.04
	0.155	2.69	2.74	0.28	0.18
Mean	0.180	2.48	2.50	0.35	0.08
Sandstone beds 10' thick	0.154	2.70	2.73	0.26	0.12
	0.121	3.05	3.13	0.55	0.14
	0.113	3.15	3.24	0.35	0.26
	0.107	3.22	3.30	0.37	0.22
	0.100	3.32	3.35	0.32	0.09
Mean	0.119	3.09	3.15	0.37	0.17
Grand mean	0.152	2.76	2.79	0.36	0.10

locally and dips as low as 15 degrees were noted in some trough-shaped sets. The boundaries of the wedge-planar sets of high-angle cross-strata commonly are nearly horizontal but locally are inclined in either the same direction as or the reverse direction from the direction of dip of the enclosed cross-strata.

In some places, gently inclined (15 degrees or less) thin-laminated to thin-bedded cross-strata are found in sets as much as 6 feet (1.8 m) thick in which individual cross-strata are as much as 30 (9 m) feet long (Fig. 20). The wedge-planar bounding surfaces of the sets, which generally dip in about the same direction as the cross-strata, locally show transverse ripple marks. Wedge-planar sets of large-scale relatively low-angle (20

Fig. 20.--- Kiowa sandstone in SE¼ sec. 1, T. 16 S., R. 7 W., Ellsworth County, Kansas, same general locality as sandstone shown in Figure The sandstone is part of a thick lenticular deposit that includes Mushroom Rocks State Park (Fig. 19) and trends about S10°E. Several varieties of cross-stratification are present in the exposure. A set of large-scale low-angle cross;strata at top of exposure dips gently to the southwest and rests in the left-hand part of photograph on a coset of intersecting medium-scale trough-shaped cross-strata that dip mainly to the south. Near base of exposure on the left, the pick hangs from the top of a tabular-planar set about 3 feet (1 m) thick of high-angle cross-strata that dip to the southwest. The tabular-planar set is overlain by nearly horizontal beds. In center and right-hand parts of exposure, concave tangential cross;strata form wedge-planar sets whose bounding surfaces are inclined both to the northeast and to the southwest whereas the cross-strata dip at high and low angles to the southwest. Pick handle is about 2.5 feet (0.8 m) long.

to 10 degrees) tangential cross-strata locally are associated with the low-angle cross strata and both types may be associated with trough, wedge-planar, and tabular-planar sets of high-angle cross-strata (Fig. 20). Only locally is simple cross-stratification seen (Fig. 21).

Fig. 21.--- Simple cross-stratification in thick lenticular deposit of Kiowa sandstone in W½ SW¼ sec. 31, T. 15 S., R. 6 W., Ellsworth County, Kansas. The set of simple cross-strata shows steep dip to the west-southwest and a reverse dip of a few degrees to the east-northeast. An inclined planar surface separates the set from wedge-planar set above. The set of simple cross-strata also is separated from a set of trough-shaped cross-strata below by a zone of seemingly structureless sandstone in the center part of the photograph, but to the right the simple cross-stratification occupies a scour cut into the set of trough-shaped strata. The sandstone is part of the same thick deposit pictured in Figures 19-A and 20.

Fossils are scarce in thick lenticular deposits of Kiowa sandstone. One conglomeratic bed (Fig. 17-B) in a thick lenticular deposit in SW 1/4 sec. 28, T. 12 S., R. 2 W., Ottawa County, contained a clam of the genus

Flaventia preserved as an iron-oxide cast. The valves were articulated but open. The open shell was filled almost completely by granules of quartz and quartzite, but it seems unlikely that the shell was transported very far for it to have remained so much intact. The dorsal plate of the crocodile *Dakotasuchus* reported by Vaughn (1956) was from an area of thick lenticular deposits of Kiowa sandstone in sec. 18, T. 16 S., R. 6 W., Ellsworth County.

Thin deposits of Kiowa sandstone.---

Thick lenticular deposits of Kiowa sandstone finger out laterally into typical gray Kiowa shale and into sequences of carbonaceous mudstone, claystone, and shale where thin layers of sandstone generally less than 10 feet (3 m) thick are found. Lateral gradation of thick deposits of sandstone into thin deposits intercalated with shale and with carbonaceous sequences is well exposed along the east shore of Kanopolis Reservoir in Ellsworth County and northwestward up the Smoky Hill River. Measured Section 5 (Appendix, Plate 4) in sec. 33, T. 15 S., R. 7 W., Ellsworth County, exemplifies this sort of lateral change. Similar intertonguing of argillaceous deposits and sandstone can be detected in most parts of north-central Kansas, but thin deposits of sandstone commonly occur as isolated beds and lenses within shaly sections. Moreover, thin deposits of sandstone commonly cemented by calcite grade laterally into coquinoid limestone in parts of Rice County.

The thin deposits are composed of very fine to fine-grained well-sorted sandstone (Table 4). The quartz grains have low sphericity and are mainly angular to subangular (Fig. 16-B). Except where the sandstone marks the top of the Kiowa Formation, the beds in dominantly argillaceous sequences commonly contain more than 5 percent interstitial clay and silt-sized material. Where calcite cement has protected them from extensive weathering, interstitial glauconitic mica and rounded pellets of glauconite are common components. Figure 16-B is a photomicrograph of a sample of calcite-cemented and glauconitic fine-grained sandstone that is more-or-less representative of much of the sandstone comprising thin deposits except that the sample is from a bed only 0.2 foot (6 cm) thick.

Upward gradation of shale or other argillaceous rocks into thin deposits of Kiowa sandstone is characteristic (Fig. 3). The gradational interval is composed of interlaminated shale, siltstone, and very fine-grained sandstone showing either horizontal thin lamination or ripple laminae. So-called starved ripple marks are common in the gradational sequences. Bedding within the thin deposits of sandstone is varied and encompasses various current structures and both symmetric and asymmetric transverse ripple marks (Evans, 1941). Current structures include small- to medium-scale wedge-planar and tabular-planar high-angle cross-stratification and micro-cross-stratification as well as linguloid or cuspate ripple marks. The symmetric and asymmetric transverse ripple marks have wavelengths of about 0.3 foot (9 cm). Locally interference ripple marks are preserved (Fig. 22). Even horizontal stratification composed of thin-laminated sets as much as 0.5 foot thick also is common (Fig. 3).

Micro-cross-stratification in thin deposits of Kiowa sandstone gives some insight into the environment of deposition even though micro-cross-stratification occurs in both marine and nonmarine deposits. Harms and others (1962, p. 576) inferred that micro-cross stratification "presumably may form beneath wide but relatively shallow currents." Allen (1963, p. 107) has found that it forms by the filling of scours on the downcurrent side of cuspate ripples provided that the sand supplied from suspension is "substantially less than the volume of the ripple."

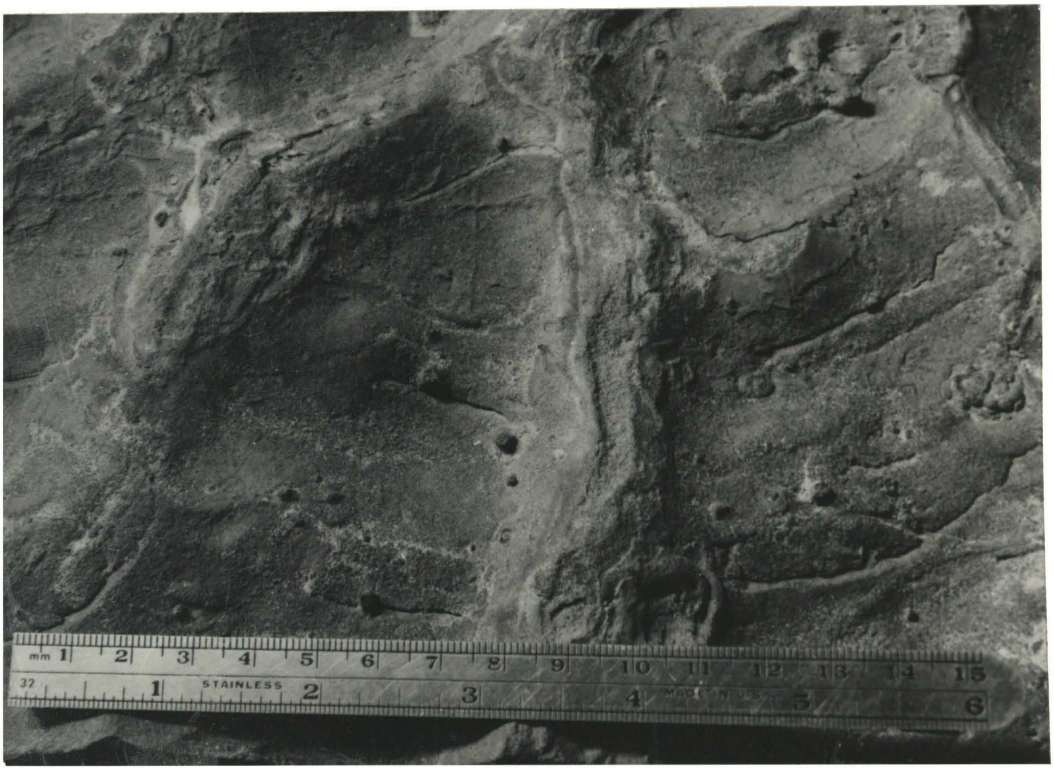


Fig. 22.--- Ripple-marked Kiowa sandstone, cen. W½ sec. 7, T. 16 S., R. 6 W., Ellsworth County, Kansas, east shore of Kanopolis Reservoir. Interference ripples are well developed, as are wartlike casts of sand-filled U-shaped burrows attributed to Arenicolites.

Tracks and trails of various crawling and burrowing animals are common on bedding surfaces of thin deposits of Kiowa sandstone. U-shaped burrows attributed to Arenicolites (Hantzchell, 1962) are diagnostic of the thin sandstone (Fig. 22) and are common in the underlying gradational sections. "Mentor" fossil assemblages are restricted essentially to thin deposits of Kiowa sandstone and range from near the base to the top of the formation. They are preserved mainly as molds and casts by iron-oxide, but the siderite cemented sandstone near the NW cor. sec. 10, T. 15 S., R. 5 W., Saline County, contains abundant well-preserved shell material. Locally, abundant fossil leaves occur in the thin deposits of sandstone.

Cross-stratification studies.---

Evaluation of information on types and orientation of cross-stratification in marine and near-shore deposits is handicapped by lack of data from comparable modern environments. Accordingly, interpretation by analogy with modern sediments commonly is not reliable. As was observed in the description of thick lenticular deposits of Kiowa sandstone, small- to medium-scale tabular-planar, wedge-planar, and trough varieties of high-angle cross-stratification are common. In addition, micro-cross-stratification and tabular- and wedge-planar cross-stratification have been observed in thin deposits of Kiowa sandstone. In Recent sediments, these same types of cross-stratification have been described mostly from point-bar and related deposits of streams and rivers (Frazier and Osanik, 1961; Harms and others, 1962; Lane, 1963b; McKee, 1938, 1939; among others) where the depositional mechanism is thought to be subaqueous sand waves or dunes (Stewart, 1961; Potter and Pettijohn, 1963, p. 99-103).

Jordan (1962), however, showed that the depositional mechanism for formation of cross-stratification, sand waves, is common in shallow-water environments. Moreover, the numerous studies of ancient marine deposits cited in Potter and Pettijohn (1963, Chapter 4) verify development of various type of cross-stratification in near-shore and marine sediments. Cross-stratification in Recent beach and lagoonal environments has received considerable attention (Thompson, 1937; McKee, 1957a, 1964) although low foreshores of beaches, shore-face terraces, and offshore bars generally have been ignored. Experimental work by McKee and Sterrett (1961), however, has provided insight into bar and beach sedimentation.

Paleogeographic and other considerations provide background for evaluation of cross-stratification. Reeside (1957) indicated that the Kiowa sea of Kansas lay on the eastern side of the Early Cretaceous seaway that extended northward into the Western Interior. The erratic increase in grain size of Kiowa sandstone in an easterly and northeasterly direction toward the margins of the Kiowa outcrop belt together with distribution of the Longford Member on the eastern fringes of the outcrop belt supports the concept. Moreover, it seems likely that the Longford Member (p. 104) represents deposits accumulated at or near the margins of the Kiowa sea.

Close-spaced sampling of dip bearings of cross-strata in the Kiowa Formation of Ottawa County revealed considerable local diversity in orientation of vector resultants and a degree of variation in the dispersion of individual cross-strata dip bearings about their respective vector resultants. Nearly antipodal vector resultants were calculated for two different localities a few miles apart in T. 10 S., R. 1 W., (Plate 2). One vector resultant trends northeast, the other southwest. Franks and others (1959, p. 235) related greatest diversity in orientation of vector resultants to areas showing greatest topographic relief in which vector resultants consequently were calculated for cross-strata dip bearings measured in different sandstone bodies at various stratigraphic levels. Locally, as in sec. 4, T. 11 S., R. 3 W. and in secs. 1 and 14, T. 11 S., R. 4 W. (Plate 2), measurements probably were made in the same sandstone deposits, as might be inferred from similarity in type of cross-stratification, orientation of vector resultants, dispersion of the cross-strata about them, and from proximity to the Kiowa-Dakota contact.

Vector resultants calculated for each of the several localities sampled in the Kiowa Formation of Ottawa County are plotted in Figure 23-D. The circular histogram shows considerable dispersion of the vector resultants and an average inferred transport direction of S55°W. However, in-

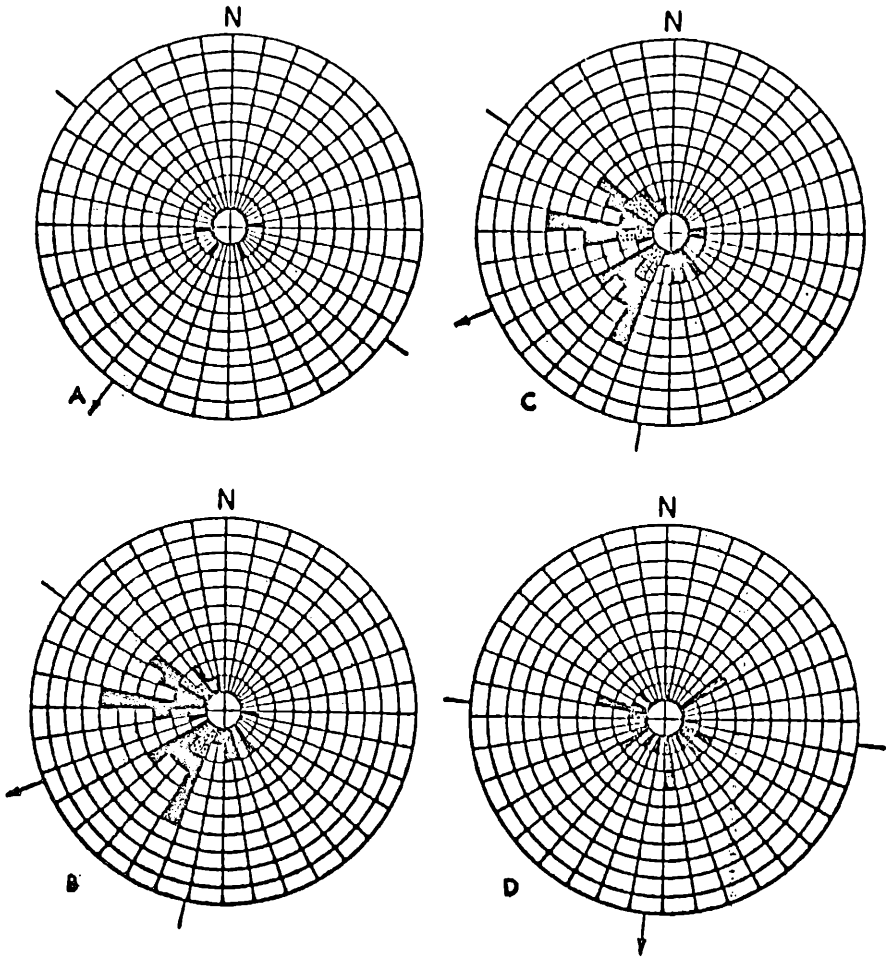


Fig. 23 .--- Circular histograms of vector resultants of cross-strata dip bearings calculated for localities in Ottawa County, Kansas. Vector resultants are plotted in 10-degree sectors; each segment represents one vector resultant. Stipples designate vector resultants used to simulate one-locality-per-township sampling grid. Arrows show grand vector resultants; arc between lines is one standard deviation plotted on each side of grand vector resultant.

A) Janssen Clay Member, Dakota Formation; 5 localities; grand vector resultant, S36°W; consistency ratio, 0.294; standard deviation, 91°.

B) Terra Cotta Clay Member, Dakota Formation; 49 localities; grand vector resultant, S67°W; consistency ratio, 0.610; standard deviation, 56°.

C) Dakota Formation, Terra Cotta Clay and Janssen Clay members; 54 localities; grand vector resultant, S66°W; consistency ratio, 0.576; standard deviation, 57°.

D) Kiowa Formation; 25 localities; grand vector resultant, S5°W; consistency ratio, 0.216; standard deviation, 89°.

dividual vector resultants can be resolved in terms of several modes, the most prominent of which trends about N55°E. Other prominent modes are centered near S5°E and N75°W. Less obvious modes can be detected near S55°W and S55°E. Replotting the vector resultants in 30-degree class intervals (Plate 2) imparts somewhat different modality to the data but strong northeast, southeast, southwest, and northwest modes are retained. Though the grand vector resultant calculated for the Kiowa of Ottawa County may signify an average transport direction, it is meaningless in terms of inferring either paleoslopes or general direction in which the source area of Kiowa sediments may have lain. The grand vector resultant is significantly different from that calculated for the Dakota Formation, but the northwesterly and southwesterly modes do correspond closely to the major modes apparent in Figure 23-C for the whole of the Dakota Formation as well as to the major modes for the Terra Cotta Clay Member of the Dakota Formation (Fig. 23-B). The same relationships can be detected in the histograms plotted on Plate 2.

Less extreme but similar dispersion of vector resultants in the Kiowa Formation is seen in Ellsworth County (Plate 3). The circular histogram (Fig. 24-D) shows a strong mode centered near S10°W and a scattering of vector resultants in the southwest quadrant. If the data are plotted in 30-degree sectors (Plate 3) a weak mode trending about the same direction as the major mode for cross-stratification in the Dakota Formation is obtained between S60°W and west. The strong mode near S10°E is enhanced.

The variations in type of cross-stratification and in their dip bearings together with the directions of elongation of some thick lenticular deposits of Kiowa sandstone indicate that some of the sandstone may have been deposited by the combined action of longshore currents and of waves. A strong southerly to southeasterly transport direction is seen on Plate 3

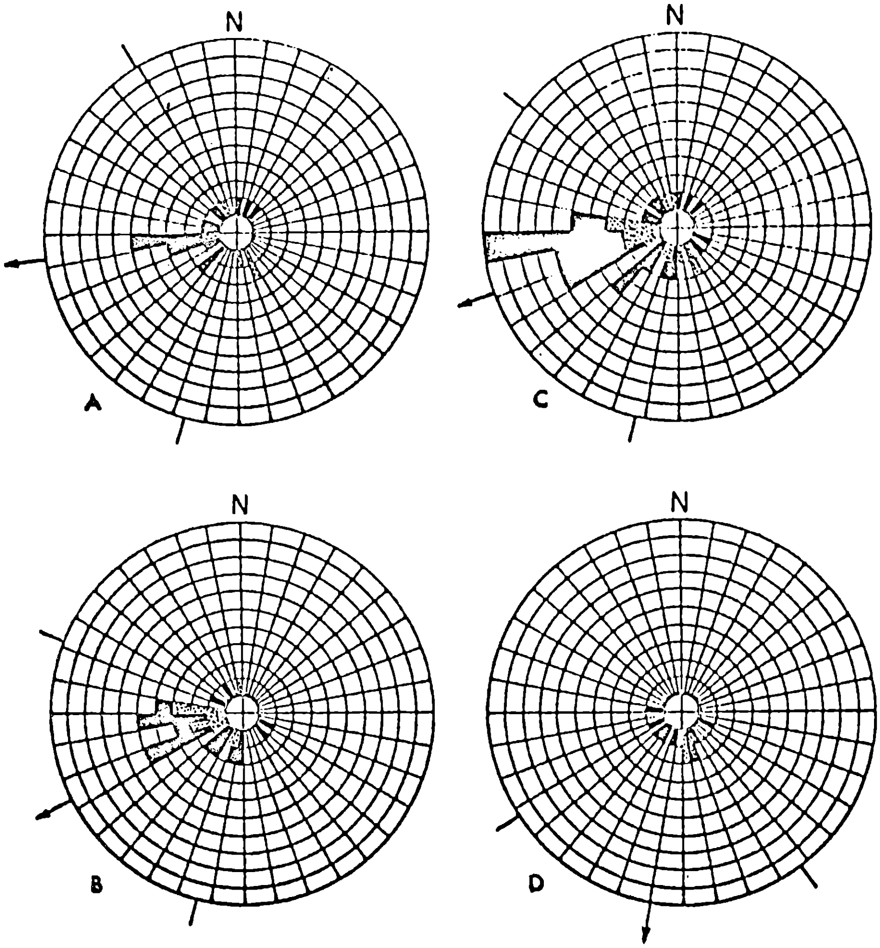


Fig. 24.--- Circular histograms of vector resultants of cross-strata dip bearings calculated for localities in Ellsworth County, Kansas. Vector resultants are plotted in 10-degree sectors; each segment represents one vector resultant. Stipples designate vector resultants used to simulate one-locality-per-township sampling grid. Arrows show grand vector resultants; arc between lines is one standard deviation plotted on each side of grand vector resultant.

A) Janssen Clay Member, Dakota Formation; 21 localities; grand vector resultant, S83°W; consistency ratio, 0.534; standard deviation, 67°.

B) Terra Cotta Clay Member, Dakota Formation; 31 localities; grand vector resultant, S64°W; consistency ratio, 0.718; standard deviation, 49°.

C) Dakota Formation, Terra Cotta Clay and Janssen Clay members; 52 localities; grand vector resultant, S71°W; consistency ratio, 0.636; standard deviation, 58°.

D) Kiowa Formation; 11 localities; grand vector resultant, S10°W; consistency ratio, 0.730; standard deviation, 47°.

in a belt encompassing the vector resultants plotted between sec. 9, T. 16 S., R. 6 W. and sec. 34, T. 17 S., R. 6 W. in southeastern Ellsworth

County. To this same general trend could be added the similar dip of cross-strata at Mushroom Rocks in sec. 19 and 30, T. 15 S., R. 6 W. (Fig. 19-A). The same trend also is seen in sec. 13, T. 16 S., R. 6 W. All of the vector resultants were calculated for thick lenticular deposits of Kiowa sandstone except for the sets of measurements made in so-called thin deposits of sandstone in sec. 28, T. 16 S., R. 6 W. and in sec. 3, T. 17 S., R. 6 W. A strong southerly to southeasterly trend of elongation is inferred for the thick lenticular deposits of Kiowa sandstone in southeastern Ellsworth County, not only from dip bearings of cross-strata, but also from distribution of sandstone in the field.

Directions of dip of cross-strata in the thick deposits of sandstone in southeastern Ellsworth County, however, are not so uniform and parallel to the trend of elongation of the sandstone lenses as might be inferred from the vector resultants plotted on Plate 3 and from the dispersion of the data about individual vector resultants. For example, all of the exposures illustrated in Figures 19-A, 20, and 21 are in the same sandstone lens, which can be traced from Mushroom Rocks in sec. 19, T. 15 S., R. 6 W. to sec. 12, T. 6 S., R. 7 W. and sec. 6 and 7, T. 16 S., R. 6 W. as well as southeastward into the thick sequences of sandstone on the east shore of Kanopolis Reservoir. The locality whose west-trending vector resultant is plotted in sec. 36, T. 15 S., R. 7 W. also is in the same sequence of sandstone, as is the simple cross-stratification that dips to the west-southwest and is shown in Figure 21. Trough cross-stratification is found at both locations and shows a prominent westerly dip whereas vector resultants showing southerly and southeasterly trends in southeastern Ellsworth County were calculated from measurements gathered mostly from tabular- and wedge-planar cross-stratification similar to that shown in Figure 19-A.

The complex assemblage of cross-stratification shown in Figure 20 suggests that a variety of agents and processes operated to form the bedding assemblage. It seems unlikely that a stream or river regimen would account for the variety of types of cross-stratification or the variety of directions in which the cross-strata dip: cross-strata in the tabular-planar set and the tangential cross-strata dip mainly to the southwest; the trough cross-stratification dips to the south and southeast; and the low-angle cross-strata dip west-southwest. The low-angle cross-stratification is of a type commonly reported from beach and foreshore deposits (Thompson, 1937; McKee, 1957). The simple cross-stratification (Fig. 21), which dips to the west-southwest, is of a type found on modern beaches by Hoyt (1962) and has been produced experimentally in simulated beach and bar environments by McKee and Sterrett (1961). Simple cross-stratification observed by Hoyt dipped in a shoreward direction as did many of the similar structures produced by McKee and Sterrett. However, the simple cross-stratification illustrated in Figure 21 shows remarkable resemblance to seaward-dipping high-angle simple cross-stratification developed in a tidal berm on the seaward side of Cat Island, Mississippi (Foxworth and others, 1962, p. 32, Fig. 13). High angle seaward-dipping cross-stratification in shoreface terraces was produced by McKee and Sterrett (1961) if sand was fed on the seaward side of the experimental beaches and bars in order to simulate supply of sand by longshore currents.

If the southerly and southeasterly cross-stratification dip bearings in thick lenticular deposits of Kiowa sandstone can be attributed to the action of longshore currents and sand waves generated by them, then the various types of cross-stratification and the various modal distributions of vector resultants can be interpreted in a fashion that is in accord with the paleogeography, with changes in grain size in Kiowa sandstone to the east and northeast, and with geographic distribution of the Longford Member (Fig. 1). For example, the west-dipping trough cross-stratification associated with the simple cross-stratification in sec. 31, T. 15 S., R. 6 W. and in sec. 36, T. 15 S., R. 7 W. (Plate 3 and Fig. 21) may be similar to trough cross-stratification ascribed by Lane (1963a) to deposition on a cusped foreshore. The abundant northeasterly trends determined for tabular-planar, wedge-planar, and trough cross-stratification in Ottawa County may stem from storm-generated sedimentation on the landward sides of bars or from growth of tidal inlet deltas into lagoonal environments, or from sedimentation on shoreface terraces. The southwesterly vector resultants of Kiowa sandstone are in accord with the gross transport directions shown by the Dakota Formation and in accord with the regional depositional slope. They may represent foreshore deposits or sand deposited by stream currents as finger bars or in estuarine sites. They may also reflect deposition of sand in linear sand bars generated by tidal currents similar to the features described by Off (1963) for many coastal areas.

Southeasterly cross-strata dip bearings were measured in thick lenses of sandstone containing the conglomeratic sandstone (Fig. 17-B) in which the specimen of Flaventia described earlier was found with both valves intact in the SW 1/4 sec. 28, T. 12 S., R. 2 W., Ottawa County (Plate 2). The association of the pelecypod with conglomeratic sandstone in a lens showing southeasterly cross-strata dip bearings indicates not only the marine genesis of the cross-stratification but also that strong currents or sorting by wave action were factors in development of the sandstone deposit. Similar inferences apply to shale-pebble conglomerate, which is found at the base of some sandstone lenses having southeasterly dip of cross-stratification.

The overall pattern of vector resultants of cross-strata dip bearings in the Kiowa Formation shown on Plate 1 does not differ significantly from the pattern shown in the detailed maps of Ottawa and Ellsworth counties although there is somewhat less dispersion of individual vector resultants about the grand vector resultant (Fig. 25; Table 5). Strong southerly or southeasterly modes and a strong southwesterly mode still are obvious in the results of the wide-spaced sampling program and the grand vector resultant calculated still seems to lack significance for determination of paleoslopes. The same factors that controlled deposition of Kiowa sandstone in Ottawa and Ellsworth counties seem to have been generally operative throughout the map area. Table 6 summarizes data on the dispersion of individual cross-strata dip bearings about their respective vector resultants. The standard deviation of cross-strata dip bearings about their respective vector resultants averages 34^{o} for the Kiowa Formation. Seemingly the current systems that deposited most Kiowa sandstone behaved in a relatively constant fashion. Such constancy is in accord with the thickness of sandstone deposits relative to the thickness of the formation. Sites of sand sedimentation evidently persisted in the same general areas throughout much of Kiowa time.

Heavy minerals.---

The basic heavy mineral suite in Kiowa sandstone does not differ appreciably from that described by Swineford and Williams (1945). Heavy minerals amount to less than 0.5 percent by weight of most Kiowa sandstone. Opaque heavy minerals are about as abundant as nonopaque heavy minerals and include leucoxene, ilmenite, hematite, and magnetite(?).

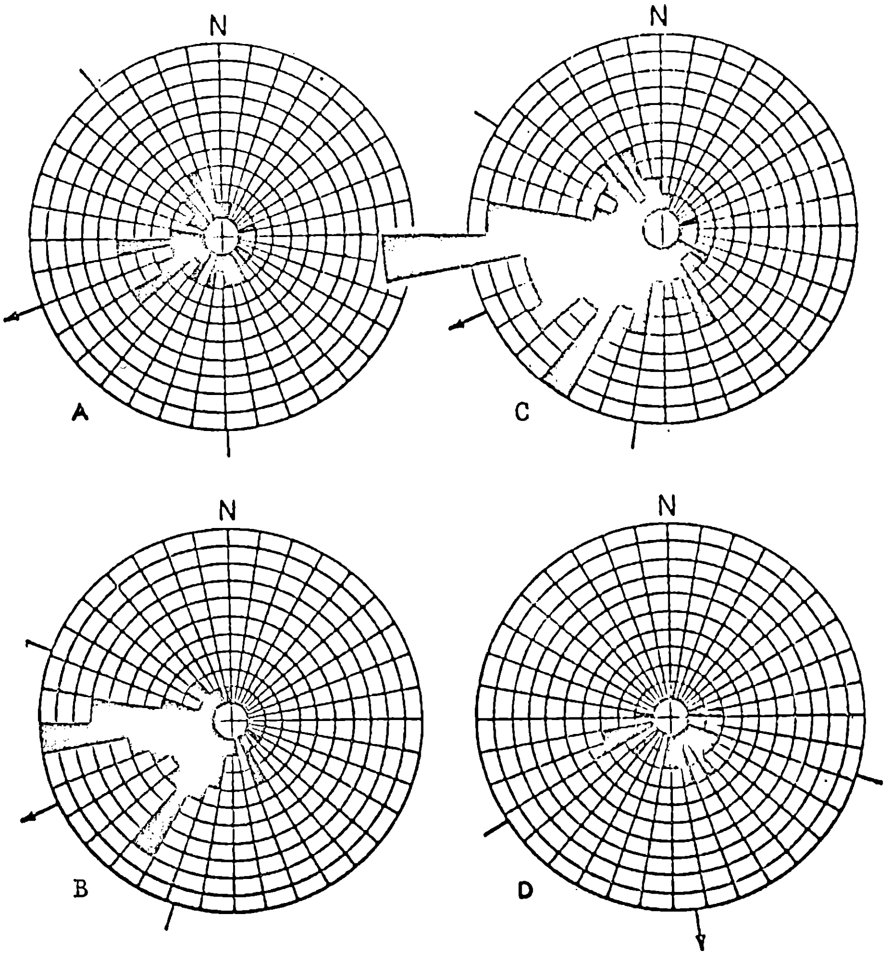


Fig. 25.--- Circular histograms of vector resultants of cross-strata dip bearings calculated for localities in north-central Kansas. Vector resultants are plotted in 10-degree sectors; each segment represents one vector resultant. Sample density is one locality per township. Arrows show grand vector resultants; arc between lines is one standard deviation plotted on each side of grand vector resultant.

A) Janssen Clay Member, Dakota Formation; 44 localities; grand vector resultant, S70°W; consistency ratio, 0.456; standard deviation, 70°.

B) Terra Cotta Clay Member, Dakota Formation; 66 localities; grand vector resultant, S65°W; consistency ratio, 0.722; standard deviation, 47°.

C) Dakota Formation, Terra Cotta Clay and Janssen Clay members; 110 localities; grand vector resultant, S66°W; consistency ration, 0.615; standard deviation, 57°.

D) Kiowa Formation; 31 localities; grand vector resultant, S7°E; consistency ratio, 0.520; standard deviation, 65°.

Leucoxene is most abundant. Translucent to nearly opaque brown iron oxides also are common in heavy mineral separations not treated with hydrochloric acid. Grain counts of the nonopaque heavy minerals (Table 7)

Table 5.--- Grand vector resultants and dispersion (consistency ratio and standard deviation) of individual vector resultants of cross-strata dip bearings of sandstone in Kiowa and Dakota formations in north-central Kansas and in Ellsworth and Ottawa counties. Results from close-spaced sampling (sample grid approximating one locality every 2 miles) and wide-spaced sampling (one locality per township) included for comparison.

Stratigraphic Unit	Area	Sample Density	Number of Localities	Grand Vector Resultant	Consistency Ratio	Standard Deviation
Dakota Formation	North-central Kansas	1 loc/Twp	110	S66W	0.615	57°
	Ellsworth and Ottawa counties	1 loc/2 miles	106	S68W	0.605	59°
		1 loc/Twp	26	S71W	0.643	53°
	Ellsworth County	1 loc/2 miles	52	S71W	0.636	58°
		1 loc/Twp	15	S66W	0.590	59°
	Ottawa County	1 loc/2 miles	54	S66W	0.576	57°
		1 loc/Twp	11	S77W	0.722	46°
Janssen Clay Member, Dakota Formation	North-central Kansas	1 loc/Twp	44	S70W	0.456	70°
	Ellsworth and Ottawa counties	1 loc/2 miles	26	S79W	0.470	74°
		1 loc/Twp	6	S43W	0.292	83°
	Ellsworth County	1 loc/2 miles	21	S83W	0.534	67°
		1 loc/Twp	5	S14W	0.410	84°
	Ottawa County	1 loc/2 miles	5	S36W	0.294	91°
		1 loc/Twp	1	N42W	-----	---
Terra Cotta Clay Member, Dakota Formation	North-central Kansas	1 loc/Twp	66	S65W	0.722	47°
	Ellsworth and Ottawa counties	1 loc/2 miles	80	S66W	0.652	53°
		1 loc/Twp	20	S74W	0.760	43°
	Ellsworth County	1 loc/2 miles	31	S64W	0.718	49°
		1 loc/Twp	10	S78W	0.777	44°
	Ottawa County	1 loc/2 miles	49	S67W	0.610	56°
		1 loc/Twp	10	S70W	0.746	45°
Kiowa Formation	North-central Kansas	1 loc/Twp	31	S 7E	0.520	65°
	Ellsworth and Ottawa counties	1 loc/2 miles	36	S 9W	0.373	77°
		1 loc/Twp	9	S 8E	0.478	79°
	Ellsworth County	1 loc/2 miles	11	S10W	0.730	47°
		1 loc/Twp	2	S15E	1.000	0°
	Ottawa County	1 loc/2 miles	25	S 5W	0.216	89°
		1 loc/Twp	7	S 2E	0.333	92°

revealed a relatively uniform suite of stable heavy minerals including zircon, tourmaline, staurolite, rutile, and anatase as major components in the size fraction between 0.044 and 0.125 mm. Proportions of zircon are much reduced whereas the proportions of tourmaline are markedly in-

Table 6.--- Mean and standard deviation of values for dispersion (consistency ratio and standard deviation) of individual cross-strata dip bearings about their respective vector resultants in Kiowa and Dakota formations, Ottawa and Ellsworth counties, Kansas. Data based on 106 localities for Dakota Formation; 26 localities for Janssen Clay Member; 80 localities for Terra Cotta Clay Member; and 36 localities for Kiowa Formation.

Stratigraphic Unit	Mean Consistency Ratio	Standard Deviation of Consistency Ratio	Mean Standard Deviation	Standard Deviation of Standard Deviation
Dakota Formation	0.801	0.167	38°	19°
Janssen Clay Mem., Dakota Fm.	0.664	0.208	53°	22°
Terra Cotta Clay Mem., Dakota Fm.	0.846	0.124	33°	14°
Kiowa Formation	0.835	0.109	34°	13°

creased in the size fraction between 0.125 and 0.250 mm. Other differences are minor by comparison. Small amounts of kyanite, garnet, and chloritoid were detected in nearly all samples examined. Other components noted included apatite, collophane, sillimanite, epidote, green spinel, fibrous amphibole, microcrystalline sphere, and chlorite. The internal structures of many grains show that much of the apatite and collophane is of organic origin. Round aggregates of glauconite also were seen in some samples from fine-grained sandstone, but were not counted. Angular fragments of barite generally clouded with carbonaceous inclusions were seen in some samples but were not counted inasmuch as barite is a common cement in Kiowa sandstone.

Grains of zircon, which are the dominant heavy mineral in the fine fraction, mostly are rounded. Little significance can be attached to

Table 7.--- Percentages of nonopaque heavy minerals in sandstone samples from the Kiowa and Dakota Formations in Ellsworth, Marion, McPherson, Rice, and Russell counties, Kansas. TR (trace) is less than 1 percent. Miscellaneous heavy minerals include collophane, apatite (some of which is of obvious organic origin), sphene, sillimanite, rounded grains of barite, topaz, corundum, spinel, chlorite, epidote, and fibrous amphibole (?).

Size Fraction	Stratigraphic Unit		Percentages	Zircon				Tourmaline				Staurolite	Kyanite	Garnet	Chloritoid	Rutile and Anatase	Miscellaneous	No. of Samples
				Total	Round	Angular	Crystal	Total	Round	Angular	Crystal							
0.044 - 0.125 mm	Dakota Fm.	Janssen Clay Member	Mean	44	37	5	2	32	22	8	2	9	1	2	2	8	2	18
			Range	21-74	16-59	1-20	0- 5	11-49	8-33	1-21	0- 6	5-15	0- 4	0-11	0-12	5-11	-	
		Terra Cotta Clay Member	Mean	35	29	5	1	37	24	11	2	13	1	2	1	8	3	15
			Range	13-72	12-64	1- 9	0- 4	13-66	11-45	1-20	0- 7	3-25	0- 2	0- 6	0- 4	5-13	-	
	Kiowa Formation		Mean	31	25	4	2	34	24	8	2	21	3	2	1	6	2	11
			Range	12-54	10-39	TR-12	TR-4	14-55	7-45	3-18	TR- 8	4-35	0- 7	TR- 4	0- 2	2- 9	-	
0.125 - 0.250 mm	Dakota Fm.	Janssen Clay Member	Mean	6	5	TR	TR	73	56	15	2	11	1	2	2	3	2	12
			Range	0-21	0-21	0- 2	0- 1	31-87	27-82	2-39	0- 6	2-21	0- 5	0-15	0- 7	0-10	-	
		Terra Cotta Clay Member	Mean	6	4	1	TR	64	47	15	2	21	2	1	TR	4	2	10
			Range	0-28	0-20	0- 6	0- 2	48-81	35-60	7-25	0-10	4-49	0- 6	0- 6	0- 2	0-14	-	
	Kiowa Formation		Mean	2	1	TR	TR	72	52	17	3	17	1	2	TR	2	4	9
			Range	0- 7	0- 5	0- 4	0- 1	60-84	38-75	5-29	0- 3	11-25	0- 3	0- 6	0- 1	0- 8	-	

roundness estimates for zircon, however, inasmuch as nearly 25 percent of the grains counted show a shelled or zonal structure that Poldervaart and Eckelman (1955) consider indicative of zircon from granitized areas. Such zirçon tends to be rounded even in the parent rock. Most of the angular grains noted were broken prisms. Most of the zircon is clear, but some pink and brown grains were seen in nearly every sample. Partly altered grains are common.

Most tourmaline grains in Kiowa sandstone also are rounded. A few grains were observed that showed rounded overgrowths of clear or nearly clear tourmaline on brown cores. Even grains showing prism outlines have rounded corners. Most of the angular grains were broken grains that previously had been rounded. Some rounded grains are broken grains that had been transported and rounded again. A wide variety of colors were noted but shades of brown and olive to olive brown were most common. Practically every slide contained one or two grains of blue or blue and green tourmaline. Pink, yellowish, and reddish-brown tourmaline also were seen.

Pleochroic pale-yellow or brownish-yellow staurolite is a common component of both the fine and coarse fractions examined. Nearly all grains are delicately dentate and only half a dozen or so rounded grains were noted in all Kiowa samples studied. The delicate nature of the hackly or dentate margins of the grains indicates that their form was acquired after deposition and presumably can be attributed to intrastratal solution.

Rutile and anatase were counted together because of the difficulty of distinguishing between yellow rutile and anatase when interference figures cannot be obtained. Rutile, however, seems much more abundant than anatase. Most grains of rutile are rounded although some have retained their prismatic habit and a few show characteristic geniculate twinning.

Subrounded grains of kyanite were present in most samples examined from the size fraction between 0.044 and 0.125 mm, but the mineral is a minor component. It was found less commonly in the coarser fraction examined. One slide containing 7 percent kyanite was prepared from calcite-cemented sandstone in which kyanite would have been protected from either weathering or prolonged intrastratal solution. Its abundance in the mineral separations may depend more on protection from destructive processes than on initial abundance in the sediment.

Pink, pale yellow, and clear garnet was universally present in the fine fraction studied, but was not encountered in many slides of the coarse fraction of heavy minerals. Grains of clear garnet, some of which are composite grains, are most common. Chloritoid, which is easily recognized by its intense green pleochroism, high relief, abnormal interference colors, and cleavage was seen in practically every slide examined.

If Krynine's (1946) suggestions concerning source rocks of tourmaline in heavy mineral suites are valid, the ultimate source area for the Kiowa Formation was an exceptionally heterogeneous terrain. Rounding of broken grains that had been rounded during some earlier depositional cycle, rounding of overgrowths on tourmaline, and the abundance of rounded zircon all indicate that the Kiowa Formation derived much of its sand from previously deposited sediment. The maturity of the sandstone and the stable nature of the heavy mineral suite point to the same conclusion.

Longford Member, Kiowa Formation

The distinctive siltstone that marks the top of the Longford Member (Fig. 5-C,-D) is composed largely of subangular to rounded silt-sized quartz grains that approximate 95 percent of the rock. This siltstone, as well as other siltstone in the member, characteristically contains as much as one percent disseminated rounded to subangular grains of quartz that show nearly straight extinction and measure as much as 0.2 mm in diameter. The rounded sand-sized quartz grains impart a striking bimodal grain size distribution to the rock (Fig. 26-A). One percent or less heavy minerals are present and interstitial clay makes up the bulk of the remainder of the siltstone except for trace amounts of detrital muscovite. The heavy minerals are mainly zircon and tourmaline. Locally, discoidal and spheroidal concretions of calcite cement the rock and have replaced the clay matrix. In places, pyrite nodules enclose fragments of sparse scattered carbonaceous debris. Locally, the siltstone contains abundant carbonized plant debris or imprints or vegetal trash on bedding surfaces. The siltstone is thinly laminated but generally weathers to thin and very thin beds each of which is composed of thin laminae. The laminae are uniform and horizontal, wavy, or ripple marked. The ripple marks include symmetric transverse forms having wavelengths between 0.1 and 0.3 feet (3 and 6 cm).

The bimodal distribution of rounded sand-sized grains of quartz set in a matrix of silt-sized quartz is similar to the texture of much siltstone from the Upper and Middle Permian of southern Kansas described by Swineford (1955, esp. Plate 19-D, p. 128). The quartz grains in both the Longford Member and in the Permian rocks are rounded and show nearly straight extinction. The siltstone marking the top of the Longford Member probably formed by reworking of previously deposited Longford sediments and perhaps indirectly by reworking of Permian rocks. Absence of feldspar, which generally is present in Permian siltstone, probably can be attributed

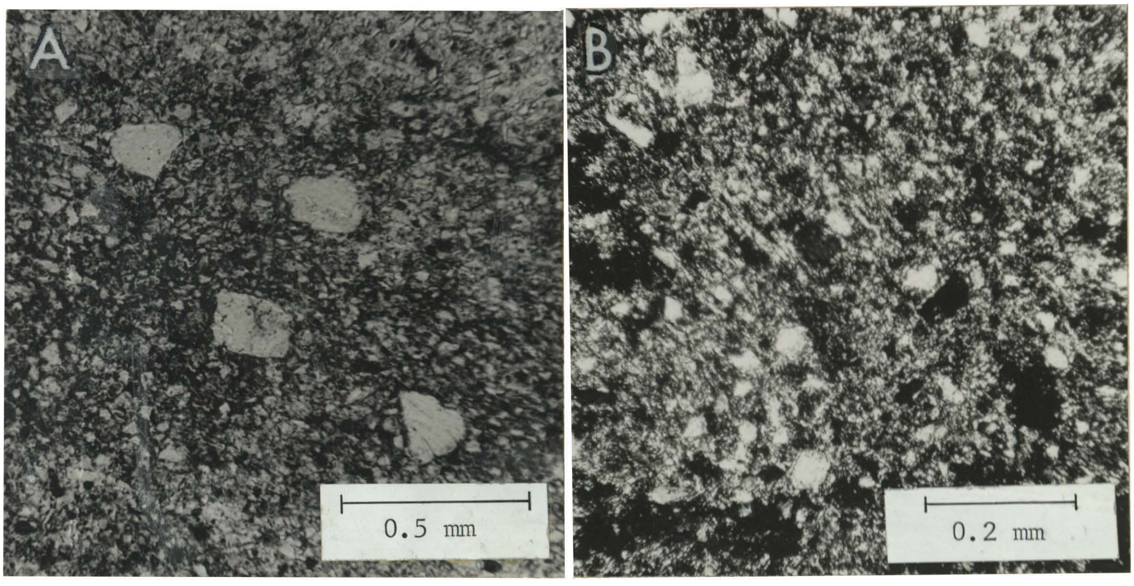


Fig. 26.--- Photomicrographs of thin sections of siltstone and mudstone, Longford Member, Kiowa Formation, north-central Kansas.

A) Siltstone in upper part of Longford Member, cen. W line SW¼ sec. 9, T. 10 S., R. 1 E., Clay County (unit 13, Measured Section 12, Appendix and Plate 5). Carbonaceous lamina (dark gray area) contains subrounded quartz grains as much as 0.2 mm in long diameter. The rock also contains appreciable interstitial clay. Plane-polarized light.

B) Red-mottled mudstone in SW¼ NW¼ sec. 4, T. 12 S., R. 1 W., Ottawa County. X-ray diffraction shows that the clay fraction is composed largely of kaolinite but contains appreciable illite, sparse montmorillonite, and detectable chlorite or vermiculite. Most black areas in the photograph are hematitic stain. Angular to rounded silt-sized quartz (mainly white) abounds. Aggregates of clay flakes and comminuted mica show local preferred orientation of their long dimensions trending from lower right to upper left and less obvious preferred orientation at right angles to that trend. Crossed nicols.

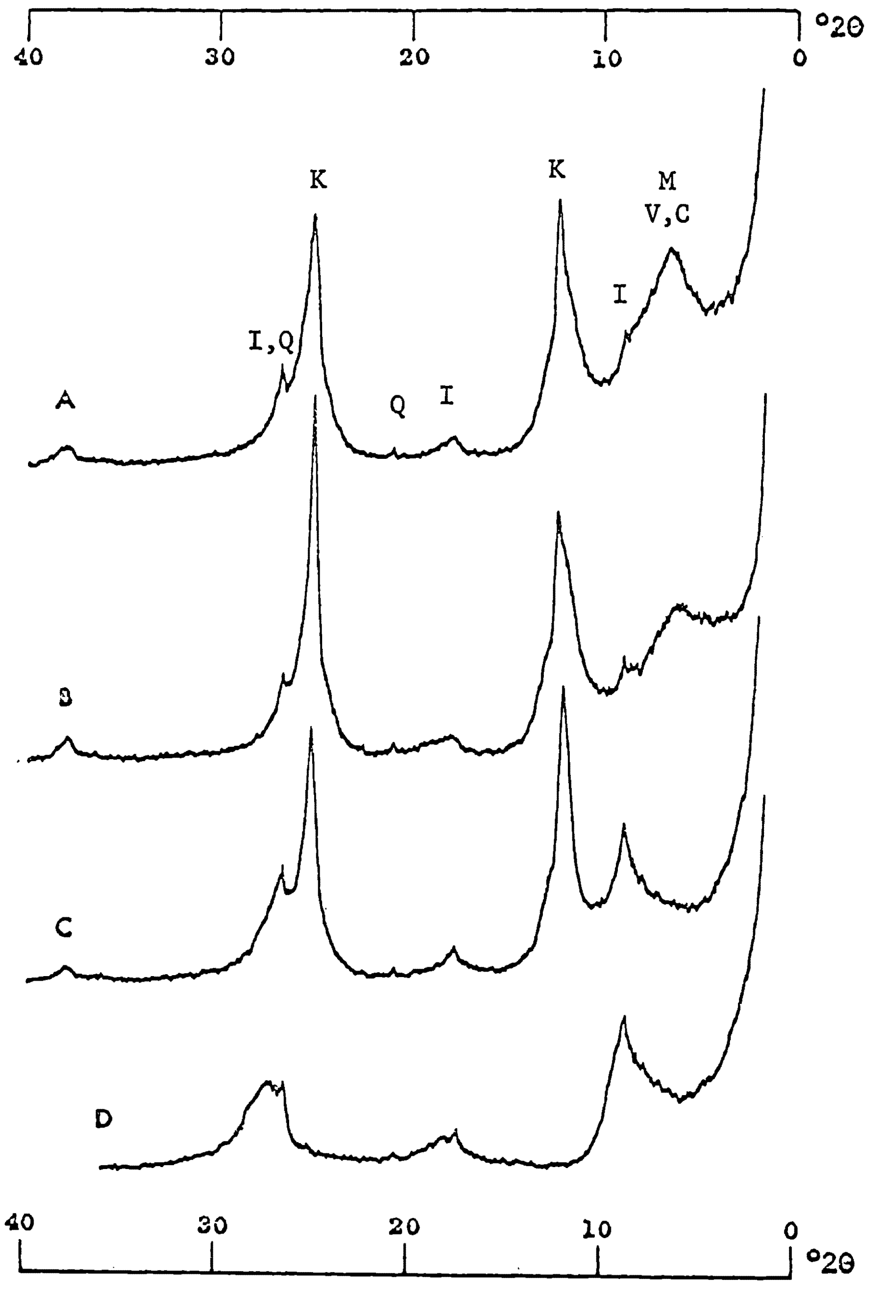
to weathering of Permian source rocks prior to reworking.

Argillaceous rocks in the Longford Member range from dark-gray and brownish-black plastic claystone and thin-laminated brownish-gray carbonaceous shale to red-mottled mudstone (Fig. 5; Measured Sections 10 and 12, Appendix and Plate 5). Characteristically they contain appreciable montmorillonite and kaolinite. In much of Clay County, the upper parts of the argillaceous sequence beneath the capping siltstone are dominantly kaolinitic whereas the lower parts are dominantly montmorillonitic. Mudstone and claystone in the Longford Member, however, generally contain detectable if not appreciable amounts of chlorite or vermiculite. Where typical gray Kiowa shale rests directly on Permian rocks, the clay fraction of the shale is devoid of chloritic or vermiculitic components. The chlorite and vermiculite are present mainly in mixed-layer structures with montmorillonite and illite and are most abundant near the base of the member.

Figure 27 shows a series of diffractograms of the fraction finer than 2 microns of a sample of brownish-gray silty mudstone containing scattered pebbles of chert and quartzite at the base of the Longford Member near the locality described in Measured Section 12 (Appendix and Plate 5). The elevation of the base of the mudstone (or the top of the Permian) corresponds to the middle of unit 5, Measured Section 12, about 18 feet (5.5 m) above the top of the Permian. The upper part of the Wellington Formation underlying the mudstone is intensely weathered and contains appreciable kaolinite and montmorillonite. The mudstone also contains abundant kaolinite and sparse illite and quartz. The presence of a chloritic or vermiculitic component interstratified with montmorillonite is apparent from failure of the prominent reflection near $6.4^{o}2\theta$ (13.8A) to undergo complete expansion to 18 A after treatment with glycerol and from incomplete collapse of the reflection to 10A ($8.8^{o}2\theta$) on heating to 450^{o} and 575^{o} C.

Locally the argillaceous rocks of the Longford Member contain complex kaolinitic mixed-layer clays that probably are the products of reworking of weathered Permian rocks. The clay fraction of a sample collected at the base of the Longford Member of the Kiowa Formation near the cen. SE 1/4 sec. 23, T. 16 S., R. 1 E., Dickinson County (Fig. 5-C; unit 3, Measured Section 10 and Plate 5) is composed largely of a mixed-

Fig. 27.--- Diffractometer patterns of fraction finer than 2 microns from silty brownish-gray to dark-gray mudstone at base of Longford Member, Kiowa Formation, SE¼ SW¼ SW¼ sec. 9, T. 10 S., R. 1 E., Clay County, Kansas. The patterns illustrate the tendency for clay in the Longford Member to contain appreciable kaolinite and illite, as well as chlorite or vermiculite as mixed-layer components. A) air-dried, B) glycerated, C) heated to 450°C, D) heated at 575°C for one-half hour. Pattern A shows the presence of abundant kaolinite (K), lesser amounts of illite (I), and small amounts of quartz (Q). The montmorillonite or mixed-layer peak near 6.4°2θ (13.8A) (M,C,V) shows sign of a possible "superlattice" diffraction near 2.8°2θ (31 or 32A). In Pattern B, the montmorillonite or mixed-layer reflection shows only partial expansion toward 18A and is centered near 6.2°2θ (14.7A). Pattern C shows incomplete collapse of the 13.8-Angstrom peak toward 10A and consequent skewing of the illite 001 maximum past 6.5°2θ. Pattern D shows little change in the skewed 10-Angstrom reflection and the presence of appreciable vermiculite or chlorite interstratified with montmorillonite can be inferred.

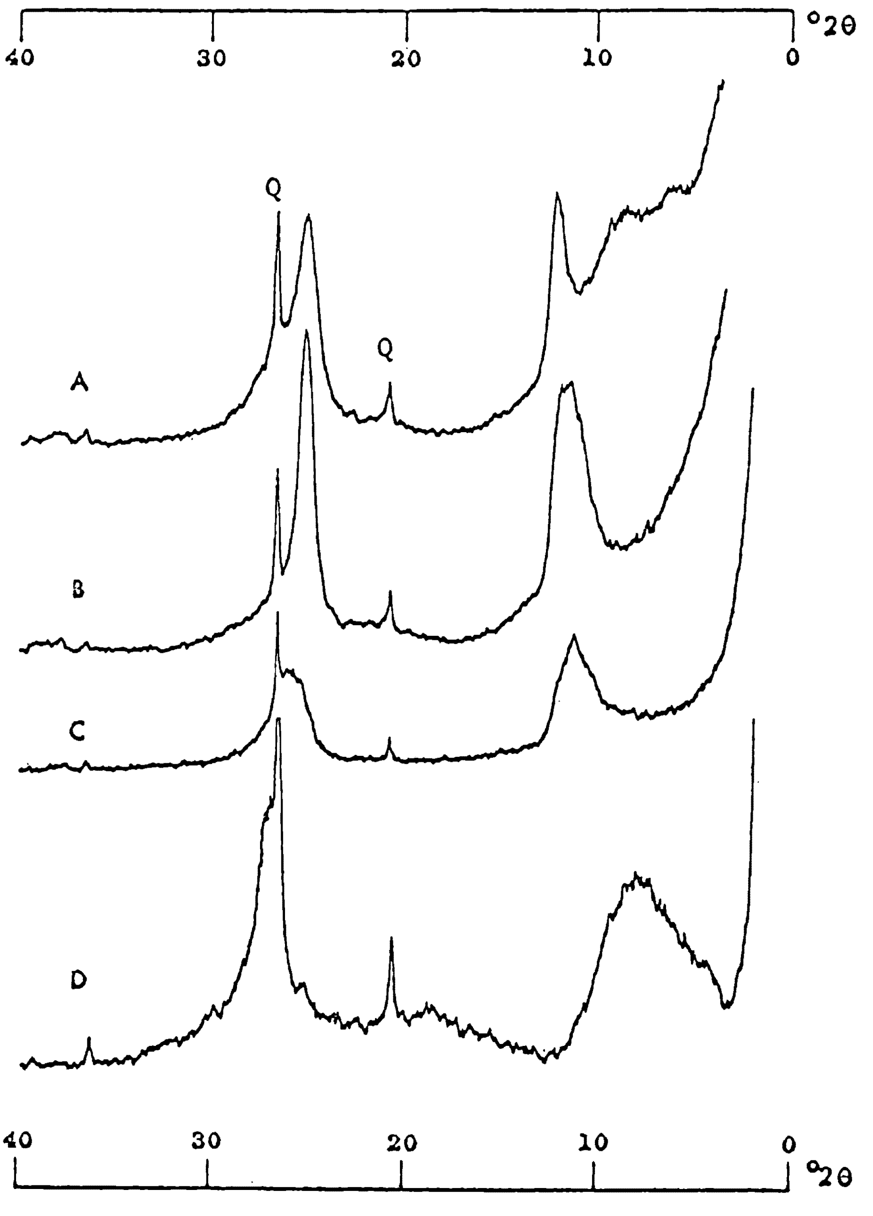


°2θ
40
30
20
10
0
K
K
M
V,C
I
I,Q
A
Q
I
B
C
D
40
30
20
10
0
°2θ

layer clay that contains kaolinite and illite together with montmorillonite and chlorite or vermiculite (Fig. 28). Prominent reflections at 12.2° and 25.1°2θ in the trace from the air-dried preparation together with loss of intensity or heating indicate the presence of appreciable kaolinite in the structure. Shift of low-angle superlattice reflections (not pictured) on glyceration demonstrates the presence of an expandable component, probably montmorillonite, but perhaps also vermiculite. Diffractions in patterns from the heated preparations indicate interlayering of a 10-Angstrom illitic component with a 14-Angstrom mineral, either chlorite or vermiculite. The weathering profiles studied by Altschuler and others (1963) not only entailed generation of kaolinite from montmorillonite but formation of mixed-layer structures containing both montmorillonite and kaolinite. Although no mixed-layer montmorillonite-kaolinite structures were detected in the weathered sequence at the top of the Permian at the locality where the mixed-layer clay was collected from the Longford Member, the claystone probably was formed by reworking of weathered Permian argillaceous rock. The presence of contorted pods and fragments of variegated Permian mudstone and claystone at the base of the mottled Longford claystone (unit 3, Measured Section 10, Appendix and Plate 5) supports the hypothesis.

Much mudstone and claystone in the Longford Member resembles mudstone and claystone in the Dakota Formation. Unlike mudstone and claystone in the Dakota Formation, however, argillaceous rocks in the Longford Member commonly are highly plastic owing to the abundance of montmorillonite. Accordingly they show numerous shrinkage cracks and a characteristic puffy surface texture on weathered slopes (Fig. 5-A). In thin section, the nonfissile argillaceous rocks reveal plexoidal and domain fabrics

Fig. 28 .--- Diffractometer patterns of fraction finer than 2 microns of a kaolinitic mixed-layer clay from the base of the Longford Member, Kiowa Formation, in SE¼ sec. 23, T. 16 S., R. 1 E., Dickinson County, Kansas (unit 3, Measured Section 10, Appendix, Plate 5, and Fig.). A) air-dried, B) glycerated, C) heated to 450°C, and D) heated at 575°C for one-half hour. Pattern A shows prominent quartz peaks at 20.8° and 26.6°2θ and prominent, broad reflections at 12.2° and 25.1°2θ (7.25 and 3.54A). The reflection at 12.2°2θ is sharply skewed to 11.3°2θ (7.8A) and mixed-layer maxima are centered near 6°2θ (14.7A) and at 8.5°2θ (10.4A). The latter reflection also shows a sharp shoulder at 9.3°2θ (9.5A). Patterns run using ¼° slits (not figured) reveal a "superlattice" reflection centered near 3.6°2θ (24 to 25A). Pattern B does not show the low-angle mixed-layer diffractions except perhaps for an inflection point near 5.2° 2θ. The peak at 25.1°2θ is sharpened and intensified. The peak at 12.2° 2θ is broadened, shows a distinct shoulder at 12.0°2θ, has a maximum at 11.2°2θ (7.4 to 7.9A), and is sharply skewed to 9.6°2θ. Patterns run using ¼° slits show broad "superlattice" maxima centered near 1.7° to 1.8°2θ (about 50A) and near 2.5°2θ (25A). The patterns also verified the presence of an inflection point near 5.2°2θ (17A). The strength of the peaks at 12.2° and 25.1°2θ in Pattern A and the loss of intensity and low-angle shift of the major reflections in Patterns C and D indicate that kaolinite is a major component of the mixed-layer clay. Kaolinite may also be present as a distinct mineral species. The low-angle shift of the "superlattice" reflections on glyceration indicates the presence of an expansible component, probably montmorillonite, as does appearance of a weak inflection point at 17A. The diffraction maximum centered near 8.5° 2θ in Pattern A suggests the presence of a 10-Angstrom component, although the maximum may be due to interference effects. Shifting of the peaks on heating can be explained both by the destruction of a kaolinite component and by collapse of the expansible material to 10A. The breadth of the low-angle diffraction in Pattern D is most easily explained by interlayering of a 10-Angstrom and a partly collapsed 14-Angstrom component, i.e., illite or collapsed montmorillonite with chlorite or perhaps with vermiculite.


°2θ
40
30
20
10
0
Q
Q
A
B
C
D

(Fig. 26-B) that indicate deposition in a flocculated state (Meade, 1964). Spherulitic siderite, which is common in mudstone and claystone of the Dakota Formation, was not seen in rocks of the Longford Member. The highly varied clay mineralogy of the Longford Member contrasts with the generally monotonous clay mineral assemblages found in the bulk of the Kiowa Formation (Plate 5).

Red-mottled siltstone in the Longford Member (Fig. 5-B) is restricted mainly to the northern parts of Clay County. Red-mottled mudstone is most abundant in western and southern Clay County and in eastern Ottawa County. Southward into Saline County, gray mudstone and claystone as well as carbonaceous beds become more abundant. In southwestern Dickinson County and northwestern Marion County beds of lignite are found and the argillaceous rocks are mainly gray, dark gray, brownish black, and brownish gray. Red mottles are less abundant. The distribution of rock types beneath the capping siltstone of the Longford Member indicates that the depositional strike of the member lay in a northwest-southeast direction, perhaps nearly normal to the southwesterly mode of vector resultants of cross-strata dip bearings in Kiowa sandstone.

Thickness

Thicknesses of the Kiowa Formation generally are difficult to determine in most of north-central Kansas owing to the width of the outcrop belt, to poor exposure of upper and lower contacts, and to irregularities induced by the unconformable contact with underlying Permian rocks. In the southern part of the area, thicknesses approximate 100 to 150 feet (30 to 45 m). Plummer and Romary (1942, p. 323) reported that a water well drilled in the northeast corner of sec. 15, T. 17 S., R. 7 W., Ellsworth County, penetrated a thickness of 113 feet (34 m) of Kiowa.

The well was collared in the Dakota Formation and bottomed in Permian rocks. A thickness of 108 feet (32 m) was measured in sec. 5, T. 18 S., R. 5 W. and sec. 32, T. 17 S., R. 5 W., McPherson County (Measured Section 8, Appendix and Plate 5). Thickness inferred at Coronado Heights in sec. 36, T. 16 S., R. 4 W. and sec. 31, T. 16 S., R. 3 W., Saline County is only about 65 feet (20 m) (Measured Section 9, Appendix and Plate 4). Estimates based on differences in elevation of the upper and lower contacts in Ellsworth County are as great as 150 feet (45 m). In southwestern Dickinson County where the full thickness of the formation is not present owing to post-Cretaceous erosion, thicknesses locally may exceed 150 feet (45 m).

The Kiowa Formation thins irregularly to the northeast. In northern Saline County it seems to be on the order of 100 feet (30 m) thick, but in the vicinity of Longford in southwestern Clay County, the Longford Member alone is as much as 100 feet (30 m) thick. In the general area west of Clay Center in western Clay County, the bulk of the Kiowa Formation is the Longford Member. There thicknesses of the formation range from as little as 50 feet (15 m) to as much as 100 feet (30 m). To the northeast near the Washington County line, maximum thickness approximates 50 feet (15 m), but there are numerous areas where the Dakota Formation rests directly on Permian rocks. In the main, only the Longford Member is exposed near the wedge-edge of the Kiowa Formation, but in the NE cor. sec. 1, T. 6 S., R. 1 E., Clay County as much as 30 feet (9 m) of Kiowa shale, siltstone, and sandstone overlie the Longford Member. In southwestern Dickinson County, the Longford Member ranges from 0 to 40 feet (0 to 12 m) thick.

Many of the variations in thickness of the Kiowa Formation in Clay County can be attributed to variations in the elevation of the top of the Permian System, but locally, scour and fill at the base of the Dakota Formation can be detected. In the southern part of the area, particularly in Ellsworth, McPherson, and Dickinson counties, the thickness of the Kiowa Formation is related to the presence of thick lenticular deposits of sandstone. Where sandstone is abundant, the Kiowa tends to be thickest, probably because of differential compaction of the enclosing shale sequences, but differences in thickness may also reflect differences in rates of sedimentation.

Paleontology of the Kiowa Formation

Twenhofel (1924) reported on the abundant pelecypods and gastropods found in the Kiowa Formation and noted some variations in burrows and other trace fossils. The most common genera in north-central Kansas include Ostrea, Gryphea, Cardium, Cucullaea, Trigonia, and Turritella. Locally, linguloid brachiopods occur in fine-grained sandstone and in shale. Loeblich and Tappan (1950) described an assemblage of brackish-water foraminifers in shale at the type area in Kiowa County. Fish scales, teeth, and bone fragments are relatively common both in sandstone and in shale. Aquatic turtles, plesiosaurs, crocodiles, and a wide variety of fish (including sharks) have been reported from the Kiowa of southern Kansas (Lane, 1944, 1946). A dorsal scute of a fossil crocodile, Dakotasuchus, was found in the Kiowa in Ellsworth County (Vaughn, 1956). Earlier finds of crocodiles (Cope, 1872; Mehl, 1941) have been referred to the Dakota Formation, but Cope's discovery in a dug well at Brookville in western Saline County can be referred without hesitation to the Kiowa. The specimen of Dakotasuchus described by Mehl (1941) reportedly came from the hills west of Salina and could have come from either the Kiowa or the Dakota. O.S. Fent reported (oral communication, 1965) that correspondence with one of the men who helped excavate the specimen indicates that the find may have been on the upland of Kiowa sandstone in southeastern Saline County.

Among the most common fossils in thin deposits of Kiowa sandstone are U-shaped burrows ascribed to the genus Arenicolites (Hantzschell, 1962; cf. MacKenzie, 1963, p. 137 - 139, Fig. 4, Plate 2). The burrows appear on exposed bedding surfaces as paired wartlike dots standing in relief owing to differential cementation of the burrows and the enclosing sandstone (Fig. 22). The paired casts are about 1 cm apart and individual casts measure about 2 mm or less in diameter. Arenicolites is a useful guide in recognition of Kiowa sandstone where the sandstone is overlain by the Dakota Formation.

Fossil dicotyledonous leaves have been reported from several localities in the Kiowa of north-central Kansas (Prosser, 1897; Twenhofel, 1920, 1924) but little or no systematic work has been done on them. As indicated by Berry (1920, 1922) many of the fossil leaves ascribed to the "Dakota flora" were collected with little regard to geographic or stratigraphic position. It is likely that at least some of the species assigned by Lesquereux (1874, 1883, 1892) to the Dakota were found in thin deposits of sandstone in the Kiowa of north-central Kansas. Berry (1922, p. 202) stated that the flora of the Cheyenne Sandstone and probably that of the Kiowa Formation does differ from what he referred to as a "true Dakota" flora (1920, p. 389), although the generic assemblages probably are grossly similar. If the gross similarity is true, land bordering the Kiowa sea probably supported growth of oak, willow, walnut magnolia, laurel, sassafras, and other deciduous plants as well as cycads and figs. The writer has seen imprints resembling oak, willow, and walnut leaves in thin deposits of Kiowa sandstone. Need for systematic study of the fossil plants of both the Kiowa and the Dakota formations is obvious.

The vertebrate and invertebrate animals reported from the Kiowa Formation in southern and north-central Kansas seem indicative of shallow-water marine, brackish-water, and near-shore environments of deposition (cf. Bergquist and Cobban, 1957; Loeblich and Tappan, 1950; Parker, 1960; Robertson, 1964). Reeside (1957, p. 512) found that the marine faunas of the Cretaceous of the Western Interior indicate that a mild, perhaps subtropical climate prevailed during the whole of the Cretaceous. If the fossil floras of the Kiowa and Dakota formations are grossly similar, the climate during deposition of the Kiowa Formation was mild and locally verged on subtropical (Lesquereux, 1892, p. 256).

Sedimentation, Diagenesis, and Source Areas of Kiowa Formation

Sedimentation and Diagenesis

The Kiowa Formation was deposited in, and near the margins of, an Early Cretaceous sea that transgressed into the Western Interior from the Texas Coastal Plain and had connections with an Early Cretaceous sea that extended into the Western Interior from the north (Reeside, 1957; Haun, 1963). Northeasterly increase in grain size of sandstone in the Kiowa, the distribution of the Longford Member (Fig. 1), and the distribution of rock types within the member indicate that the depositional slope was inclined to the west-southwest nearly parallel to the mode of vector resultants of cross-strata dip bearings centered between S50°W and

S70°W (Fig. 23, 24, 25). The inferred orientation of the depositional surface indicates that the sea transgressed across Kansas from southwest to northeast. The marked difference in lithology of the Longford Member and the bulk of the Kiowa Formation as well as the absence of marine or brackish-water fossils in the member suggests the possibility that deposition of the Kiowa in north-central Kansas took place close to the ultimate strand of the Kiowa sea.

The numerous fossils described by Twenhofel (1924) and his predecessors testify to the generally marine character of Kiowa sedimentation. The arenaceous foraminifers examined by Loeblich and Tappan (1950), however, indicate that the sea was at least partly brackish in the type area in southwestern Kansas. The abundance of pelecypods of the genera Ostrea and Cardium and allied forms indicate that the sea was brackish (Robertson, 1964) in north-central Kansas as well. Low salinity also is indicated by the occurrence of linguloid brachiopods in some fine-grained sandstone (as near the cen. sec. 26, T. 20 S., R. 10 W., Rice County). Parker (1960, p. 304 - 310, 312) noted the abundant oyster reefs in low salinity realms in the bays and lagoons of the modern Gulf Coast of Texas. Similar estuarine or lagoonal environments of low salinity may have been sites of accumulation for many of the oyster-rich coquinoid "shell beds" found in the Kiowa Formation in Kansas.

The abundance of interference ripples and symmetric and asymmetric transverse ripple marks of small amplitude and wavelength in thin deposits of Kiowa sandstone, in thin-laminated sequences of sandstone, siltstone, and shale, and locally in thick lenticular deposits of sandstone indicate that much Kiowa sedimentation may have taken place in shallow water above wave base. Numerous photographs published by Laughton (1963), however, show ripples at depths as great as 1700 m in the oceans and indicate that ripple marks must be used with caution as indicators of depth of water. The asymmetric ripple marks could be considered as indicators of sedimentation on shelving foreshores (Kuenen, 1950, p. 289) or on tidal flats (McKee, 1957a, p. 1742; van Straaten, 1959, p. 198), but because of their intimate association with typical gray Kiowa shale, the thin deposits of sandstone may have formed in water somewhat deeper than that in the littoral zone. If conditions on the modern Gulf Coast apply in interpretation of Kiowa sedimentation, local abundance in sandstone of the "Mentor" clam Cardium and other thick-shelled species also may indicate sedimentation in an agitated shallow neritic environment.

Micro-cross-stratification, linguloid ripple marks, and small- to medium-scale tabular- and wedge-planar high-angle cross-stratification in thin deposits of Kiowa sandstone are evidence of current movement. The intimate association of these features with "Mentor" fossils locally and with wave-formed sedimentary structures indicates that these beds were deposited in part by currents in the neritic zone. Intercalation of thin deposits of sandstone with typical illitic Kiowa shale and the local abundance of glauconite (Burst, 1958) supports the hypothesis.

Contortion of shale and locally of sandstone beds about cone-in-cone concretions indicates early diagenetic growth of cone-in-cone structure in Kiowa shale. Development of irregular layers of cone-in-cone in some sandstone and the consequent expansion of the detrital framework of the rock is evidence of the early diagenetic deposition of calcite cement in Kiowa sandstone and supports the evidence of cementation by calcite prior to lithification cited by Swineford (1947, p. 87).

Occurrence of siderite cement in a thin deposit of glauconitic sandstone containing "Mentor" fossils in Saline County was noted earlier in the report. Most "Mentor" fossil assemblages are in sandstone much indurated by iron oxides. It may be that the abundant iron oxide in many fossil finds in Kiowa sandstone stems from decomposition of siderite cement as well as glauconite. If so, a unique geochemical relationship between the occurrence of pelecypods of the "Mentor" type and development of siderite cement is indicated. Huber (1958) has shown that siderite generally is deposited under mildly reducing conditions in a mildly acid environment and it is likely that the necessary conditions of Eh and pH were controlled by decaying organic matter during early diagenesis.

Discoidal concretions of impure siderite, disseminated nodules of marcasite, localized preservation of Turritella shells by marcasite, and scattered pellets of glauconite in Kiowa shale indicate, as was suggested by Plummer and Romary (1942, p. 322), that "...reducing, rather than oxidizing conditions prevailed subsequent to the deposition of muds that formed the Kiowa shale." Replacement textures of marcasite against calcite in cone-in-cone structure in shale suggest formation of the iron sulfide under reducing conditions that ensued somewhat after the calcareous structures largely were developed. The occurrence of recrystallized lenticular beds of calcareous cone-in-cone above zones of fossil shells replaced by marcasite and above recrystallized coquinoid limestone also may indicate somewhat delayed onset of reducing conditions if upward migration of some acid agent, presumably H_2S, was responsible for recrystallization of the cone-in-cone. Localization of calcite cement about nodules of iron sulfide in some sandstone beds suggests precipitation of iron sulfide prior to cementation by calcite; replacement of glauconite by siderite indicates relatively late formation of siderite cement in "Mentor" sandstone. The various iron-bearing minerals and their relationships with enclosing rocks point not only to reducing conditions of differing intensities from place to place, but also in time.

Localized occurrence of red-mottled olive-gray Kiowa shale and claystone that is intercalated with more typical shale containing discoidal concretions of impure siderite in Ottawa and Saline counties may be evidence that the sediment supplied to the Kiowa sea was in large part red. The average ferric oxide content of the colloid fraction of 162 soils in the United States cited by Carroll (1958, p. 4) is 10.3 percent. According to James (1966, p. W40), "Presumably, an appreciable fraction of this is as separated particles, rather than clay-bound, which would separate from the clay host during erosion and transportation; nevertheless ... there seems little doubt but that much iron is transported as oxide films on clays." Red mottles in otherwise typically gray to olive-gray clays and shales normally associated with a reducing environment probably stem from incomplete reduction within the sediment. Although Kiowa shale is not particularly rich in iron oxide (Table 2, p. 55), the supplying of red sediment to the Kiowa sea by streams and rivers would be in accord with the mild temperate or subtropical climate inferred from the marine and leaf fossils.

Experimental work by Carroll (1958) has shown that bacterial action is effective in reduction of colloidal ferric oxide on the surfaces of clay particles not only in fresh and brackish-water environments, but in saline environments as well. The speed and extent of reduction is dependent on the degree of bacterial activity. Even under aerobic starting conditions in sea water, appreciable bleaching of clay particles and removal of iron oxide was accomplished in 21 days, but the rates of removal also depended upon the type of clay mineral used in the experiments

(Carroll, 1958, p. 12). In experiments simulating lagoonal environments, Carroll (p. 14 - 15) found, "Immediately on addition of the prepared water the clays started to bleach and the nontronite turned greenish .... On the first day the supernatants were brown after the clays had flocculated, but on the next day they became black and similar in appearance to the original muck." Depending upon the Eh and pH of the system, the reduced iron oxide may or may not go into solution. According to James (1966, p. W40), mobilization of iron from clays can take place both on the sea floor and beneath the sediment-water interface. Remobilized ferrous iron may "...redeposit as glauconite, chamosite, siderite, or sulfide."

Alternatively, iron oxide originally on clay micelles might enter into organic complexes in which iron is not susceptible to easy oxidation. Tannic acid solutions, among others, are capable of reducing ferric iron and forming complexes with ferrous iron that are relatively stable even under oxidizing conditions (Hem, 1960; Oborn, 1960a). The dioctahedral and aluminous character of the illitic and montmorillonitic clays in the Kiowa was noted earlier in the report. Formation of clay-organic complexes of these clays with such organic compounds may account for the redness of fired Kiowa shale. Dissolution and remobilization of part of the colloidal iron oxide on clay micelles may account for the local abundance of marcasite and siderite in sequences of Kiowa shale as well as locally abundant siderite cement in sandstone. Inasmuch as many land and aquatic plants make use of iron in their metabolism and extract it from their respective environments (Oborn, 1960a, 1960b), some of the iron in the Kiowa also may have been tied up in plant debris and released during its decay under anaerobic conditions to form marcasite in the more carbonaceous parts of the formation as well as the iron sulfide associated with carbonaceous trash in calcite-cemented sandstone.

Twenhofel (1924, p. 38) considered the "dark pyritiferous shale with crystals of gypsum" to have been deposited in quiet bays and sounds where foul bottom conditions were inhospitable to life. Typical gray to dark-gray Kiowa shale grades upward into sandstone through interlaminated sequences of sandstone, siltstone, and shale (Fig. 3) that commonly show starved ripple marks and various wave and current structures. The upward gradation and the sedimentary structures indicate that the environments in which the shale accumulated, although quieter perhaps, may not have been much deeper than the environments in which thin deposits of sandstone accumulated. Moreover, the presence of starved ripple marks in the gradational sequences suggests that deposition of shale prevailed in those areas where sand was in short supply but does not disallow the possibility that currents and waves affected the bottom. The thin-laminated nature of Kiowa shale reflects a preferentially oriented fabric of the clay particles induced by particle-by-particle settling. But thin lamination likewise does not preclude agitation of the bottom by currents and waves from time to time inasmuch as Hjulström (1939) has shown that muds, once deposited, are more difficult to erode than more arenaceous sediments because of the greater cohesiveness of the clay flakes. The environment at the sediment-water interface where shale was deposited may not have been as foul and unfavorable for life as thought by Twenhofel. The local abundance of imprints of pelecypods and other forms in thin-laminated Kiowa shale indicates that bottom conditions were not completely inhospitable, and the sorted accumulations of fish teeth, scales, and bone fragments associated with round pellets of glauconite indicate that currents and waves did from time to time affect the bottom.

The relative scarceness of evidence of burrowing in thin-laminated shale in contrast to evidence of burrowing in interlaminated sequences of sandstone, siltstone, and shale might be evidence that the bottom was inhospitable to life (Moore and Scruton, 1957). It might indicate, however, that the oxidation-reduction interface within the clay sediments was very close to the sediment-water interface or that the consistency of the clay made burrowing difficult. Gypsum on outcrops of Kiowa shale is not evidence of sedimentation under conditions of high salinity, but instead stems from oxidation of marcasite during recent weathering.

Thick lenticular deposits of Kiowa sandstone probably are of diverse origins. The good sorting of the sandstone indicates deposition by shallow neritic or littoral sedimentary processes (Friedman, 1961, 1962). Thick lenticular deposits of sandstone that are elongate in southerly to southeasterly directions and have high-angle cross-strata that dip in the same general direction, which is nearly parallel to the apparent northeast-southwest strike of the depositional slope, are attributed to longshore currents. Simple and low-angle wedge-planar cross-stratification dipping nearly at right angles to the trend of these deposits (Fig. 20 and 21) implies shoreline hydraulic processes and likely emergence as barrier bars. Local conditions of emergence perhaps also can be inferred from occurrence of the crocodile Dakotasuchus in the Kiowa Formation inasmuch as Mehl (1941, p. 64) has indicated that the structure of Dakotasuchus is such that it may have been "more at home on the land than in the water." Other thick lenticular deposits of sandstone may represent finger bars projecting into the Kiowa sea or linear sand bodies formed by tidal currents (Off, 1963).

Thick sequences of carbonaceous claystone, mudstone, and shale that commonly are adjacent to thick lenticular deposits of Kiowa sandstone and that locally contain beds of lignite are thought to have been deposited in lagoonal environments behind and perhaps between offshore bars and barrier beaches represented by some of the thick accumulations of sandstone. Although carbonaceous deposits are most common near the top of the Kiowa, similar accumulations, such as that in which amber has been found in Ellsworth County, are known from the lower parts of the formation. Intercalation of thin deposits of sandstone with carbonaceous sequences in the Kiowa Formation (Measured Section 5, Appendix and Plate 4), as well as local abundance of fossil deciduous leaves in thin deposits of sandstone, may also reflect deposition of the sandstone in lagoonal or bay environments.

The lignitic and carbonaceous deposits of the southern and western exposures of the Longford Member are thought to have been deposited in paludal areas fringing the transgressing Kiowa sea, perhaps in estuarine or tidal marshes whose distribution was controlled partly by topography developed on top of Permian rocks prior to deposition of the basal Cretaceous sediments. The red-mottled mudstone and claystone of the Longford Member probably are the result of estuarine or terrestrial flocculation of clayey sediment as the Kiowa sea transgressed. Intercalation of the red-mottled rocks with dark-colored and lignitic rocks in the Longford Member suggests that the environment of deposition may have been dominantly reducing and that the red mottles may be the product of incomplete reduction of red sediment. The hypothesis is supported by the localized occurrence of flecks of carbonaceous matter and iron disulfide in the interareas between the mottles and by the presence of red mottles in brownish-gray mudstone (Fig. 5-C). The chloritic and vermiculitic clay and variable proportions of kaolinite, montmorillonite, and illite indicate that much of the argillaceous material in the Longford Member was derived by reworking of weathered Permian source rocks. The siltstone marking the top of the Longford Member is interpreted as the result of the first marine reworking of Longford sediments, as well as the reworking of land-derived sediment supplied to the Kiowa sea.

Upward increase in abundance of sandstone and carbonaceous deposits in the Kiowa Formation perhaps marks the onset of regressive phases of sedimentation heralding retreat of the Kiowa sea and deposition of the overlying Dakota Formation. Upward increase in abundance of kaolinite in the argillaceous rocks of the Kiowa also is in accord with the onset of regressive sedimentation and increased supply of kaolinite to the shallow sea (See, for example, units 6, 7, 8, 13, Measured Section 5, and unit 5, Measured Section 6, Plate 4, vs. the lower parts of Measured Section 6, units 6 and 9, Measured Section 8, Plate 4, and the whole of the Kiowa in Measured Section 7, Plate 5.).

Source Areas and Mineral Distributions

The clay mineralogy of the Longford Member of the Kiowa Formation is compatible with relatively local derivation of the clays from weathered Permian rocks. Permian rocks along the unconformity below the Cretaceous System have been altered from illite-chlorite assemblages containing only minor amounts of kaolinite to suites of montmorillonite, kaolinite, and mixed-layer clays containing chlorite and vermiculite. The clay mineral assemblages in the lower part of the Longford Member correspond ideally with the weathered suites of clay minerals at the top of the Permian.

The northwest-southeast strike of the depositional slope of the Kiowa Formation inferred from the distribution of rock types in the Longford Member, easterly and northeasterly increase in grain size of Kiowa sandstone, and west-southwest dip of some cross-strata indicate that the bulk of Kiowa sediment probably came from the northeast and east. The generally stable heavy mineral suite of the Kiowa Formation, the degree of rounding of the heavy minerals, the presence of broken and then rerounded grains of tourmaline, rounded overgrowths on sparse grains of tourmaline, and the wide variety of tourmaline all indicate derivation of sand from older sedimentary rock. Likewise, the general maturity of Kiowa sandstone indicated by the abundance of quartz, scarcity of mica and feldspar, and small percentages of phyllitic and schistose rock fragments, suggests that the sandstone was a multicycle sediment. Seemingly the Paleozoic terrain of the stable interior provided the bulk of the Kiowa sediment. Occurrence of rounded grains of quartzite similar to Precambrian Sioux Quartzite may or may not indicate direct contribution of materials from Precambrian terrain to the north. The small percentages of chloritoid in the heavy mineral separates (Table 7), however, may indicate minor contribution from a northerly Precambrian terrain inasmuch as James (1955, p. 1464-1465) has reported minor amounts of the mineral in the Precambrian of Northern Michigan. Moreover, the abundance of chloritoid increases to the north and west in Lower and basal Upper Cretaceous rocks of the Western Interior (Chisholm, 1963; Mapel and others, 1964; MacKenzie and Poole, 1962).

If sandstone in the Kiowa Formation stems from reworking of older deposits in the continental interior, a source for the staurolite in the heavy mineral suite seems to be wanting. Potter and Prior (1961) reported that the mineral generally is absent from the Paleozoic section of the continental interior. James (1955) reported only sparse staurolite in the metamorphosed Precambrian rocks of Northern Michigan. Wayne Martin (written communication, 1966) reported that staurolite "occurs only rarely, if at all, in the heavy mineral suites of the subgraywackes of the Dunkard Group." However, Swineford (1955) and Swineford and Williams (1945) found appreciable staurolite in Middle and Upper Permian sandstone in Kansas, and the assemblages described do not differ significantly from those in Kiowa sandstone. Potter and Pryor (1961) did find that the suite of nonopaque heavy minerals in Upper Cretaceous sandstone in the Mississippi Embayment is composed almost completely of staurolite, kyanite, and sillimanite. They inferred that the source area for the assemblage was the Piedmont Province of the ancestral southern Appalachian Mountains.

The Piedmont region of the southern Appalachian Mountains is an unlikely source for the staurolite in the Kiowa Formation. Continuous sedimentation along the northeastern Gulf Coast during Early Cretaceous time probably served as a sink for any sediment that might have been supplied to the Western Interior from the southern Appalachians. Moreover, the Ozark area probably acted as a barrier to transport from southeast to northwest. Groshkopf (1955) recorded an erosion surface overlain by Late Cretaceous rocks and cut on Paleozoic rocks in the subsurface of the northern Mississippi Embayment that Bretz (1965, p. 74) has interpreted as a downwarped peneplain that once extended into the area of the Ozark Mountains. The extent to which the Ozark Mountains served as a source of sediment is a matter of conjecture.

Groot (1955) studied the heavy mineral suites of Cretaceous sandstone of the Delaware coastal plain in remarkable detail. The bulk mineralogy of the assemblages studied by him grossly resembles the heavy mineral suites of the Kiowa Formation as well as the heavy mineral suites described by Swineford and Williams (1945) and by Swineford (1955). The assemblages described by Groot include not only staurolite, but chloritoid and anatase as well. The source areas of the heavy minerals examined by Groot included not only the Piedmont Province, but also the Blue Ridge and folded Appalachians.

Evidence of more than one cycle of erosion and deposition in the heavy mineral suites of the Kiowa Formation and gross similarity to suites in Middle and Upper Permian sandstone in Kansas (Swineford, 1955, p. 99 - 100; Swineford and Williams, 1945, Table 3) may mean that Middle and Upper Permian (or younger) rocks now gone from the continental interior were temporary resting places for part of the Kiowa heavy minerals. Thus, the original source areas of some of the heavy minerals in the Kiowa Formation may have been the central Appalachian Mountains. Blending of minerals derived originally from the Piedmont and Blue Ridge provinces with heavy minerals from Paleozoic rocks in the continental interior probably produced the assemblage now seen in the Kiowa Formation in north-central Kansas. Chisholm (1965) proposed a similar answer for various assemblages in Jurassic and Cretaceous strata of the Western Interior.

The distribution of clay minerals, particularly chlorite and vermiculite, in the argillaceous rocks of the Kiowa also poses problems of interpretation. The Longford Member and the subsurface equivalents of the Kiowa in northwestern Kansas (Franks and Plummer, _in_ Merriam and others, 1959) contain appreciable chloritic and vermiculitic material in their respective clay fractions. But the bulk of the Kiowa Formation exposed at the surface in north-central Kansas does not. Whitehouse and others (1960) have indicated ways in which differential transport and sedimentation of various clay minerals could be accomplished. Differences in particle size, concentration of clays in suspension, and variations in pH, concentrations of salts, and concentrations of organic compounds in the transporting and depositional media may result in one clay mineral being preferentially sedimented and another bypassed. Grim and Johns (1954) observed an increase in the content of both illite and chlorite in sediment away from the mouth of Guadalupe River near Rockport, Texas. The increase in the content of illite and chlorite corresponded with a decrease in the content of montmorillonite and an increase in chlorinity of the water. They attributed the distribution to diagenesis of montmorillonitic clay to illite and chlorite. Weaver (1959) reviewed their paper (among others) and suggested that the clay mineral distribution observed by Grim and Johns could be accounted for by differential transport and sedimentation. More recently, Griffin (1962) examined the distribution of clay minerals in northeastern Gulf of Mexico and concluded that the distribution was a function of differential transport and sedimentation, mixing of clays from different source areas, and transport by longshore currents. He also found that montmorillonitic clays occur offshore whereas kaolinite was flocculated close to shore. Chloritic clays were more common far from shore.

If the clay minerals supplied to the Kiowa sea came from the east and northeast, as is inferred, the source areas included a vast expanse of Permian and Pennsylvanian rocks, which are known to contain chlorite or vermiculite as well as abundant illite and variable amounts of kaolinite. Depending on the degree of weathering of the source rocks, illite, montmorillonite, kaolinite, and chlorite or vermiculite probably stained red by colloidal iron oxide were supplied to the general area of Kiowa sedimentation. Kaolinite and montmorillonite derived from distant sources as well as from weathered Permian rocks in north-central Kansas were flocculated in the terrestrial and marginal environments of the Longford Member. Some illite and chloritic or vermiculitic clay also was flocculated and deposited, but the bulk of the illite and much of the chloritic and vermiculitic clay as well as a certain amount of montmorillonite and kaolinite were bypassed. Although illite, kaolinite, and perhaps also some montmorillonite settled out in the brackish Kiowa sea of north-central Kansas, chloritic and vermiculitic materials seemingly remained in suspension until they arrived in what probably was a more saline realm in the western parts of Kansas.

Summary

The Kiowa Formation in north-central Kansas is thought to have been deposited in and along the margins of a shallow brackish neritic sea that advanced across Kansas from the southwest or west over the eroded and weathered surface of underlying Permian rocks. A period of erosion either preceded or partly coincided with deposition of the basal Cretaceous sediments in Kansas so that only compressed local remnants of soil profiles are preserved on topographic highs on the erosion surface. A mantle of gravel that presumably covered the Permian surface largely was disrupted and reincorporated into the basal Cretaceous sediments.

As the sea advanced, red clayey sediment was supplied from a low-lying landmass to the east and northeast and the argillaceous rocks of the Longford Member were deposited largely by flocculation of clay rich in montmorillonite and kaolinite but containing some vermiculite and chlorite. Much of the clay deposited in the Longford Member probably was reworked locally from the weathered top of the underlying Permian rocks. The carbonaceous and lignitic mudstone and claystone of the Longford probably were deposited in swamps fringing the Kiowa sea. Landward, red-mottled mudstone and siltstone accumulated. Mottling probably was induced during diagenesis by partial reduction of initially red sediment. As the sea continued to advance, reworking of detritus derived from Paleozoic rocks and the upper parts of the Longford Member gave rise to the siltstone that marks the top of the member.

Seaward, illitic shale was deposited in relatively quiet water where the bottom was occasionally disturbed by currents and waves and where conditions were not completely inhospitable to maintenance of benthonic life. Neritic currents and wave action locally built up deposits of interlaminated shale and sand or silt that grade upward into sandstone containing interstitial clay and commonly showing sign of abundant bottom life. Oyster and other shell beds formed locally in estaurine bays or other places where currents or waves and low salinity provided favorable environments. Where currents and waves acted with more force, the shell beds were destroyed and reworked to form coquinoid limestone.

The dominantly illitic sediment supplied to the Kiowa sea is thought to have been stained red by colloidal iron oxide. Reduction of the iron oxide during diagenesis probably released some of it for redeposition as marcasite and siderite. Calcareous cone-in-cone structure formed during early diagenesis not only as concretions and lenticular beds enclosed in shale, but locally as seams in calcite-cemented sandstone. Introduction of calcite and other cement into sandstone also is thought to have taken place during diagenesis before the sandstone was lithified.

Where the supply of sand derived from the low-lying landmass to the east and northeast was sufficiently great, currents and waves built bars and barrier beaches behind and between which carbonaceous muds were deposited and locally lignitic materials accumulated. In places, leaves washed into lagoonal areas from the nearby land and were trapped and preserved in deposits of thin-bedded and ripple-marked sandstone. Crocodilian carnivores roamed barrier bars and sharks and fish patrolled the shallow sea, the bottom life of which was only part of a fairly varied diet for some of the swimming predators. The climate on the nearby land was mild enough to support humid temperate to subtropical dominantly deciduous forests.

The upward increase in the abundance of sandstone and associated carbonaceous deposits as well as the upward increase in kaolinite in the argillaceous rocks are taken as evidence of regressive sedimentation that heralded deposition of the overlying, largely nonmarine Dakota Formation.

KIOWA-DAKOTA CONTACT IN NORTH-CENTRAL KANSAS

The Kiowa and Dakota formations in Kansas generally have been thought to be conformable as well as vertically and laterally gradational. Twenhofel (1920, 1924) and Tester (1931) visualized wholesale, large-scale, and intimate intertonguing of the two units. Latta (1946, p. 249) stated:

> In the upper part of the Medicine Lodge Valley in the Belvidere area [Kiowa County, Kansas] , the Kiowa shale grades with apparent conformity into beds of sandstone, shale, and clay which contain fossil plants and are lithologically similar to certain beds in the Dakota formation of central Kansas.

Swineford (1947, p. 58) held that "The Dakota formation...is conformable on and interfingering with the Kiowa shale, although in the northernmost part of the area it overlaps directly on Permian rocks." In his study of Rice County, Kansas, Fent (1950, p. 57) described his placement of the Kiowa-Dakota contact as follows: "...the contact between the predominantly marine beds of the Kiowa shale and the nonmarine beds of the Dakota formation is arbitrarily placed at the top of the uppermost zone known to contain abundant marine fossils." Mack (1962, p. 17), on the other hand, indicated that the Dakota Formation rests unconformably on the Kiowa in Ottawa County, Kansas.

Plummer and Romary (1942, p. 332) tended to place the Kiowa-Dakota contact at the base of one or more beds of siltstone or fine-grained sandstone containing ellipsoidal masses of calcite cement. They locally included light-colored argillaceous rocks beneath the sandstone beds in the Dakota Formation.

When mapping of the Kiowa-Dakota contact was started in Rice County, note was taken of the generally monotonous thick sequence of gray and dark gray shale in the type area of the Kiowa Formation. This and the presence of thick channel sandstone deposits in the Dakota Formation led to the decision that mapping might be done most conveniently if the contact were placed at the top of typical gray to dark-gray, plastic, illitic Kiowa shale characterized by cone-in-cone structure and clay-ironstone concretions. This premise entailed that thick deposits of sandstone be classed as part of the Dakota Formation, but that any fossiliferous sandstone of the "Mentor type" or thin deposits of glauconitic sandstone be classed as Kiowa. There was awareness that the following sorts of contacts might be encountered:

Dakota sandstone on Kiowa shale

Dakota sandstone on Kiowa sandstone

Dakota mudstone or claystone on Kiowa shale

Dakota mudstone or claystone on Kiowa sandstone.

It was also thought that sandstone cemented by concretionary masses of calcite was a good guide to the approximate position of the contact. As work progressed, breakdown in the various parameters outlined above led to their abandonment as means of separating the two formation. The lithologic heterogeneity of the Kiowa Formation was not realized during the early stages of fieldwork.

The lithology most characteristic of the Dakota Formation in north-central Kansas is light-gray to light greenish-gray mudstone or claystone showing red to reddish-brown mottles and commonly containing numerous spherules of siderite or their limonitic or hematitic alteration products (Fig. 29). Red-mottled Dakota mudstone or claystone was found in many areas to rest directly on or a few feet above sandstone like that near the top of the Kiowa Formation in sec. 33, T. 15 S., R. 7 W., Ellsworth County (Measured Section 5, Appendix and Plate 4). A zone enriched in iron oxides commonly occurs at the top of similar sandstone, which in many places contains discoidal concretionary masses of calcite cement, or at the top of a thin shaly interval that grades laterally into such sandstone (Measured Section 6, Appendix and Plate 4). Experience began to show that mapping of the Kiowa-Dakota contact in much of north-central Kansas was most easily done by placing the contact approximately at the base of red-mottled Dakota mudstone and claystone.

Adoption of a contact at the base of red-mottled Terra Cotta mudstone or claystone entailed drastic reconsideration of older concepts. For example, the carbonaceous sequences at the top of the Kiowa Formation

Fig. 29.--- Red-mottled mudstone characteristic of the Terra Cotta Clay Member, Dakota Formation. Exposure near cen. S½ sec. 26, T. 5 S., R. 3 E., Washington County, Kansas. Claystone and mudstone showing red mottles in the Terra Cotta generally range from greenish gray to very light gray. Relatively recent weathering leads to redistribution of iron oxide and enhancement of red coloration as in the upper part of the photograph. Pocket knife is about 6 inches (15 cm) long.

(Measured Section 5, Appendix and Plate 4) are similar in some respects to parts of the Janssen Clay Member of the Dakota Formation and interfinger laterally with thick sections of sandstone, features that might be classed as characteristic of the Dakota Formation. However, placing the base of the Dakota Formation essentially at the base of red-mottled mudstone and claystone has allowed selection of a relatively uniform contact over a wide area with only minor differences in detail. Locally, however, red-mottled mudstone is not present at the base of the Dakota Formation, as in parts of sec. 5, T. 18 S., R. 5 W., McPherson County (Measured Section 8, Appendix and Plate 4; Fig. 30-A), but gray or brownish-gray argillaceous rocks can be traced laterally into red-mottled mudstone. In practice the top of the sandstone capping the Kiowa was the more convenient datum for mapping inasmuch as the sandstone tends to be exposed and to stand out better than the overlying basal Dakota mudstone or claystone (Fig. 30-A).

Because sandstone at the top of the Kiowa Formation commonly does not differ appreciably from other sandstone beds within the formation, the important characteristics of the sandstone generally used as a mapping reference need to be emphasized. The sandstone at the top of the Kiowa is mainly fine-grained and commonly occurs in beds less than 10 feet (3 m) thick. In many exposures it shows medium- to small-scale wedge- and tabular-planar high-angle cross-stratification; locally, medium-scale trough cross-stratification is present. Bedding surfaces commonly are rippled. The ripple marks include symmetric and asymmetric transverse types having wavelengths near 0.3 foot (9 cm). Linguloid current ripples, micro-cross-stratification, and horizontal stratification (Fig. 30-B) also are present. Close-spaced vertical jointing locally is prominent. Burrows of Arenicolites are common. Locally molds and casts of pelecypods are seen on horizontal stratification planes. Elsewhere, imprints of deciduous leaf fossils are found. In many places the sandstone is overlain directly by red-mottled mudstone and claystone typical of the Dakota Formation. It commonly, but not universally, grades downward through interlaminated sequences of shale, siltstone, and sandstone as much as 10 feet (3 m) thick into sequences of carbonaceous shale, claystone, and mudstone containing lignitic beds (Measured Section 5,

Fig. 30.---Exposures of Kiowa-Dakota contact, north-central Kansas. A) Kiowa-Dakota contact in N½ NE¼ sec. 5, T. 18 S., R. 5 W., McPherson County. The sandstone capping the Kiowa Formation is about 9 feet (2.8 m) thick and forms a prominent ledge overlain by brownish-gray and gray Dakota claystone, mudstone, and siltstone. The argillaceous rocks above the sandstone are positively identified as Dakota by lateral gradation into characteristic red-mottled mudstone. The Kiowa cap sandstone in this area locally contains numerous molds and casts of pelecypods and gastropods as well as abundant iron-oxide cement. Area is that of Twenhofel's (1924) "Natural Corral section" on which his concepts of intertonguing of the Kiowa and Dakota formations largely were based because of the occurrence of leaf fossils in Kiowa sandstone in the lower parts of the sequence just below prominent slump developed in Kiowa shale underlying the cap sandstone. See Measured Section 8, Appendix and Plate 4.

B) Kiowa-Dakota contact exposed on U. S. Highway 81 near cen. W line SW¼ sec. 25, T. 12 S., R. 3 W., Ottawa County. Red-mottled Dakota mudstone and claystone rest on fine-grained Kiowa sandstone showing abundant iron-oxide cement in top 0.3 foot (10 cm). Head of pick marks contact; handle is about 2.5 feet (0.8 m) long.


A


B
Kd
Kk

Appendix and Plate 4). The carbonaceous sequences, which locally are as thick as 20 feet (6 m), in turn give way downward to more sandstone, commonly similar to the cap sandstone, or to typical Kiowa shale. Locally the cap sandstone grades downward by alternation of lithology into typical Kiowa shale containing discoidal concretions of impure siderite, or beds or concretions of calcareous cone-in-cone structure. Laterally, the cap sandstone may merge with thick lenticular deposits of Kiowa sandstone, the lower parts of which commonly interfinger with Kiowa shale. In some areas, these thick lenticular deposits of sandstone in the upper parts of the Kiowa Formation support a topographic bench that approximately marks the top of the Kiowa Formation.

Re-examination of the Kiowa-Dakota contact in the type area of the Kiowa Formation showed it to be similar to the type of contact just described for north-central Kansas (Measured Sections 1 and 2, Appendix and Plate 6; Fig. 31-A). The concept of lateral and vertical gradation of the Kiowa and Dakota formations in the type area of the Kiowa goes back to Gould (1898) and has been perpetuated (Latta, 1946, 1948) because of the miscorrelation of a lenticular deposit of Kiowa sandstone ("Greenleaf sandstone"), which locally contains sharks' teeth, with sandstone in the lower parts of the Dakota Formation in the W$\frac{1}{2}$ sec. 3 and SE$\frac{1}{4}$ sec. 4, T. 18 S., R. 30 W.. It was not realized that the "Greenleaf sandstone" thinned and graded into the thin-laminated sequence shown in Figure 31-A in one direction, and because of the gentle southwesterly dip in the area, disappeared underneath typical Dakota mudstone and claystone in another direction. The friable so-called "Greenleaf sandstone" exposed along Spring Creek Draw in the SE$\frac{1}{4}$ sec. 4 and SW$\frac{1}{4}$ sec. 3,

Fig. 31.---Kiowa-Dakota contact in Kiowa and Ellsworth counties, Kansas. A) Contact in the vicinity of type Kiowa, SE¼ NW¼ sec. 3, T. 18 S., R. 30 W., Kiowa County. Handle of pick, which is about 2.5 feet (0.8 m) long, rests on siltstone marking the top of the Kiowa Formation. The head of the pick rests against Dakota mudstone that is cemented by abundant iron oxide released on decomposition of spherulitic siderite. The Kiowa siltstone and the overlying Dakota mudstone have both been classed as "Spring Creek Clays" (Fig. 2) and assigned to the Kiowa Formation. The siltstone grades laterally into so-called "Greenleaf Sandstone" that marks the top of the Kiowa Formation in nearby exposures. Sandstone higher in the Dakota section has been miscorrelated with the "Greenleaf Sandstone".

B) Scour in topmost Kiowa sandstone (Kk) filled with gray Dakota mudstone (Kd) having red mottles in grader ditch at Mushroom Rocks State Park near cen. S line SE¼ sec. 19, T. 15 S., R. 6 W., Ellsworth County, Kansas. "Tongue" of Kiowa sandstone projecting into basal Dakota mudstone may stem partly from undercutting and partly from penecontemporaneous slumping. Bench in left middle-ground and dark soil by shovel are relicts from an old, partly excavated grader ditch. Handle of pick is about 2.5 feet (0.8 m) long.


A


B
Kd
Kk

T. 18 S., R. 30 W. is part of a distinctly different lens of sandstone that is within the Dakota Formation.

Thick lenticular sandstone near the top of the Kiowa Formation in north-central Kansas generally is overlain almost directly by red-mottled Dakota mudstone or claystone. At one locality (Fig. 31-B), basal Dakota mudstone fills a scour in the upper surface of a thick lenticular Kiowa sandstone. It is not difficult to conclude that the Dakota Formation actually rests disconformably on the Kiowa and that the zone of concentration of iron oxide commonly seen at the top of the Kiowa Formation in many places is part of an ancient weathering profile developed prior to deposition of the overlying Dakota (See Measured Sections 5, 6, 8, 11, Appendix and Plate 4).

In many areas, the basal part of the Dakota Formation includes scour-fill deposits of medium- to coarse-grained conglomeratic sandstone generally cemented by much iron oxide and commonly containing numerous clay pebbles (Fig. 32) or deformed cobbles of mudstone. The sample in Figure 32-A is from an area in the western part of T. 10 S., R. 1 W., Ottawa County (Plate 2), where two Kiowa sandstone lenses dipping a few feet per mile to the south successively are truncated by basal Dakota sandstone and conglomerate that, in addition to clay pebbles, contains granules of quartz and quartzite. On Coronado Heights in Saline County (Measured Section 9, Appendix and Plate 4) the Kiowa Formation is exceptionally thin and conglomeratic Dakota sandstone occupies a scour where the cap sandstone of the Kiowa Formation and most of the underlying carbonaceous sequence were removed. Similar relationships are seen on Iron Mound (sec. 26, T. 14 S., R. 2 W., Saline County), and in several places in eastern Ottawa County, in western and northern Clay County, and in northeastern Ellsworth County.

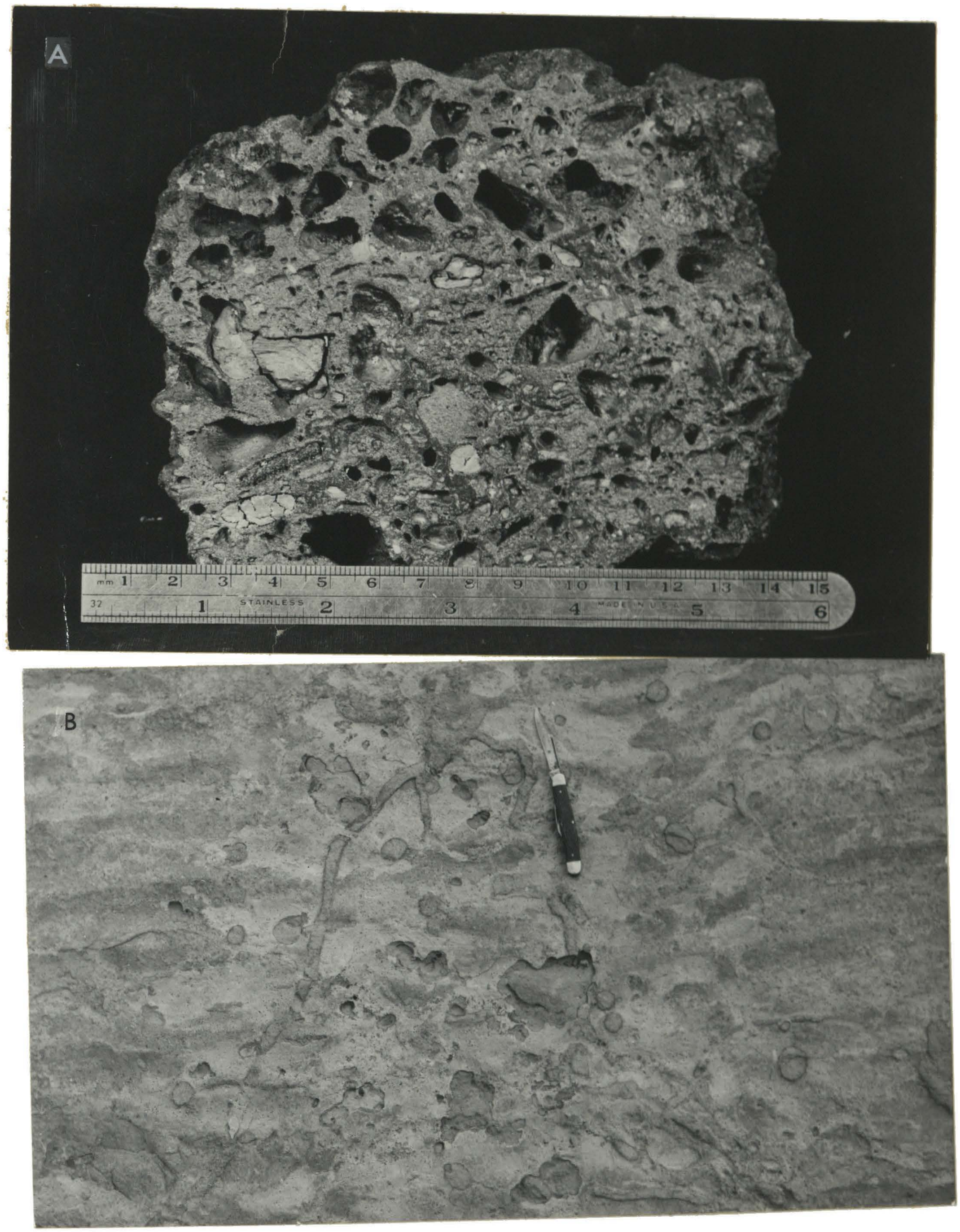


Fig. 32.--- Photographs of Dakota sandstone. A) Sawed face of sample of clay-pebble conglomerate near cen. N½ SW¼ sec. 17, T. 17 S., R. 1 W., Ottawa County, Kansas. Some clay pebbles were washed out of the central part of the specimen during sawing. Voids near the margins were produced by weathering.

B) Thin-bedded ripple-marked sandstone near cen. W½ SE¼ sec. 32, T. 16 S., R. 7 W., Ellsworth County, Kansas. The symmetric transverse ripple marks are similar to those in the Kiowa Formation, but the burrows and trails have a form and large size not noted in Kiowa sandstone. Pocket knife is about 6 inches (15 cm) long.

Evidence of a disconformable contact between the Kiowa and Dakota formations also is present south and east of the fault striking northeast in T. 17 and 18 S., R. 6 W., in southeastern Ellsworth and northeastern Rice counties (Plate 1). The basal Dakota rocks south and east of the fault include abundant coarse-grained to conglomeratic sandstone much indurated by iron oxide and containing numerous pebbles and granules of clay. Scour-fill contacts with underlying Kiowa rocks are exposed locally. The coarse-grained to conglomeratic Dakota sandstone may also indicate movement along the fault during deposition of the basal Dakota rocks. The downthrown beds at the base of the Dakota Formation on the southeast side of the fault dip towards the fault and locally are folded in small monoclines that strike parallel to the fault but dip at angles as great as 24 degrees toward the fault. The fault seems to show reverse drag similar to that described by Hamblin (1965), and the actual area of uplift seems to have been in the highlands southeast of the fault in northeastern Rice County.

Other faults near the Kiowa-Dakota contact in north-central Kansas show deformation of a type that Williams and others (1965) found useful for recognition of disconformities. The fault mapped in the north half of T. 7 S., R. 1 E., Clay County (Plate 1); for example, shows penecontemporaneous steep dips and slump structures that effect the topmost Kiowa sandstone but seem to be truncated by basal Dakota beds. The structures within the fault zone are suggestive of rotational slumping induced by differential loading along stream valleys marking a disconformity between the Kiowa and Dakota formation.

The general sharpness of the Kiowa-Dakota contact at or near the top of a Kiowa cap sandstone, concentration of iron oxide along the contact in many places, rotational slumping, and obvious evidence of pre-Dakota erosion in other areas indicate a disconformable contact between the two formations. But in many places the evidence is much less convincing. Where thick lenticular deposits of Kiowa sandstone are at the top of the Kiowa Formation, the elevation of the contact commonly is higher than in surrounding areas. Differences in elevation of the contact in part may reflect greater compaction of surrounding argillaceous rocks in the Kiowa Formation, but locally both the nature and position of the Kiowa-Dakota contact are problematic. Near the southeast cor. sec. 6, T. 17 S., R. 6 W., Ellsworth County, abundant fine-grained thin- to medium-bedded Dakota sandstone containing many shaly or silty interbeds and laminae seems to grade imperceptibly downward into similar sandstone in the upper part of a thick lenticular deposit of Kiowa sandstone. Similar relations are encountered elsewhere in Ellsworth County, parts of Ottawa County, and locally in Clay County. The contact was approximated with reasonable accuracy in these areas by tracing it in from nearby exposures where more easily deciphered contact relationships are found and where the basal parts of the Dakota Formation contain abundant red-mottled mudstone or claystone. In the SE¼ sec. 32, T. 16 S., R. 7 W., Ellsworth County, the Dakota Formation also rests on thick deposits of fine-grained sandstone assigned to the Kiowa Formation and contains abundant fine-grained thin-bedded sandstone in its basal parts. The sandstone shows transverse ripple marks as well as burrows and trails similar to trace fossils found in the Kiowa Formation (Fig. 32-B). Placement of the contact in this area was difficult except that the sandstone beds in the basal part of the Dakota Formation are intercalated with red-mottled mudstone and the burrows and trails are of a size and form not seen in the Kiowa Formation in north-central Kansas. The extent to which the fine-grained sandstone in the basal parts of the Dakota Formation is part of a gradational sequence or represents local reworking of Kiowa sand is a subject that warrants additional study.

In summary, evidence from numerous scattered exposures in north-central Kansas and in the type area of the Kiowa Formation shows that a sharp contact separating contrasting lithologies of the Kiowa and Dakota formations can be recognized and mapped. The sharpness of the contact, concentration of iron oxide along it in many areas, slumping of beds along the contact locally, and clear-cut evidence of scour and fill in many places indicate that the contact is in large part disconformable. Thinning of the Kiowa Formation northward together with local erosion of its topmost parts, as well as truncation of the siltstone marking the top of the Longford Member, are additional evidence of unconformable relations between the two formations. Apparent local gradation of thick lenticular deposits of Kiowa sandstone into similar beds in the basal parts of the Dakota Formation poses problems of interpretation, but not unresolvable problems in mapping. The gradational sequences may represent local intertonguing of the two formations, continuity of sand sedimentation, or reworking of topmost Kiowa sand. Intertonguing of the Kiowa and Dakota formations on the grand scale visualized by Twenhofel (1920, 1924) and Tester (1931), however, is negated by the field evidence.

Rapid withdrawal of the Early Cretaceous sea appears to have taken place over broad areas in the continental interior, resulting, at least locally, in subaerial exposure and erosion of the Early Cretaceous marine sediments prior to or contemporaneously with deposition of the Dakota

Formation and its stratigraphic equivalents on the eastern side of the Cretaceous seaway. Gries (1962) reported evidence of rapid withdrawal of the early Cretaceous sea at the start of Dakota sedimentation for parts of South Dakota and nearby areas. Although Baker (1962) assembled evidence of a disconformable contact between the Newcastle Formation (tongue of Gries' Dakota Formation) and the underlying Skull Creek Shale in southeastern Wyoming, he also inferred (p. 161) that retreat of the Skull Creek sea was "abrupt." The generally marine character of subsurface equivalents of the Kiowa and Dakota formations in northwestern Kansas (Merriam and others, 1959) suggests the possibility that deposition west of the outcrop belt in north-central Kansas may have been nearly continuous from Kiowa into Dakota time. Thus, although the contact between the Kiowa and Dakota formations is disconformable in many parts of north-central Kansas, the evidence of a disconformable contact cited above is compatible with relatively rapid withdrawal of the Kiowa sea.

DAKOTA FORMATION

The Dakota Formation in north-central Kansas comprises a thick heterogeneous sequence of claystone, mudstone, siltstone, and sandstone. Shaly and lignitic beds and lenses are present near its top and in many places near its base. The rock type most characteristic of the bulk of the Dakota, however, is light-gray to light greenish-gray kaolinitic mudstone or claystone that shows abundant red to reddish-brown mottles (Fig. 29).

The argillaceous character of the Dakota Formation in Kansas, Nebraska, and Iowa has been emphasized repeatedly in the literature (Logan, 1897; Barbour, 1903; Tester, 1931; Plummer and Romary, 1942, 1947; Plummer and others, 1954; Plummer, Bauleke, and Hladik, 1960; Plummer, Edmonds, and Bauleke, 1963; among others). The dominantly kaolinitic argillaceous rocks of the Dakota account for the important ceramic industry in central and north-central Kansas, in Nebraska, and near Sioux City, Iowa. Yet the concept that the Dakota Formation chiefly is sandstone persists, largely because of poor exposures of the mudstone and claystone.

Claystone, mudstone, and siltstone are estimated to amount to as much as 70 percent or more of the thickness of the Dakota Formation in many areas. Only locally does the aggregate thickness of sandstone account for more than about 40 percent of the thickness of the formation. The sandstone, however, is resistant to erosion and stands out in relief as capping layers on hills and benches, partly because of case hardening by iron oxide (Rubey and Bass, 1925, p. 57; Swineford, 1947, p. 71). The indurated sandstone largely controls development of the relatively rugged and scenic topography that is characteristic of the Dakota Formation, but the kaolinitic mudstone and claystone, which are much less plastic than shale in the Kiowa Formation, does stand locally as isolated buttes without capping sandstone.

The heterogeneity and lateral variability of the several rock types of the Dakota Formation are emphasized purposely to offset tendencies to define such things as "first, second, and third Dakota sands" and more-or-less illusory attempts to correlate sandstone beds from one hillside to the next. The Dakota Formation, however, is not without large-scale order, as is indicated by separation into the Terra Cotta Clay and Janssen Clay members (Plummer and Romary, 1942). Beds of gray and dark-gray mudstone and claystone as well as beds of lignite are confined mainly to the upper one-third of the formation (Janssen Clay Member) whereas red-mottled mudstone and claystone are found mostly in the lower two thirds (Terra Cotta Clay Member). The basal parts of the Terra Cotta, however, also contain gray, dark-gray, and lignitic beds. Laminae and beds of porcelaneous kaolinite also are found near the base and near the top of the formation.

Plummer and Romary (1942) devised a generalized stratigraphic section for the Dakota Formation that is reproduced here in the modified form presented by Bayne, Franks, and Ives (in preparation), who made the modifications in consultation with Norman Plummer. The generalized section is not everywhere applicable, but parts of it can be recognized in various places in the broad belt of outcrops of the Dakota. Sandstone, except for that near the top of the formation that locally contains molds and casts of marine and brackish-water invertebrates, generally has been omitted from the schematic generalized section. The section, which follows, sets the stage for much of the later discussions.

Schematic section illustrating nature of Dakota Formation in north-central Kansas. Sandstone lenses and beds, the aggregate thickness of which totals as much as 50 percent but mainly about 30 percent of the sequence, may be inserted any place in the section.

	Range in observed thickness (feet)
Janssen Clay Member:	
17. Siltstone or shale, pale yellowish-brown to brownish-gray. Generally laminated to thin-laminated; commonly contains concretionary "limonite," hematite, or siderite, and laminae of fine-grained sandstone. May be a transition zone between typical Dakota and typical Graneros. Locally gives way laterally to fine-grained sandstone containing molds and casts of brackish-water or marine pelecypods near top	0.1-5.0
16. Siltstone, gray to light-gray. Generally resistant and containing carbonized plant debris as well as nearly vertical tubes that resemble molds of reeds, roots, or worm borings. Commonly supports a bench and is good datum for mapping purposes. Locally gives way laterally to sandstone like that noted above	0.5-4.0

	Range in observed thickness (feet)
15. Claystone or mudstone, dark-gray to black; weathers gray to light brownish gray. Carbonaceous and generally containing one or more lignite seams. Laminated to indistinctly laminated; commonly contains intercalated siltstone laminae. Locally gives way laterally to sandstone like that noted under unit 17....................	0.0-8.0
14. Claystone or mudstone, medium-gray, plastic. Commonly contains lenticular beds of siltstone; carbonaceous debris and leaf fossils common. May be laminated or massive. Locally contains a white seam of porcelaneous kaolin as much as 0.6 foot thick near top of unit..	15.0-30.0
13. Claystone or mudstone, dark-gray with red mottles. Plastic; may contain irregular siltstone lenses or laminae..........	0.0-10.0
12. Claystone or mudstone, gray with abundant yellowish-orange stain, especially on or near fracture surfaces. Generally plastic; massive; conchoidal fracture. Commonly contains one or more zones of siderite spherules..	15.0-30.0
Typical thickness Janssen Clay Member, Dakota Formation..	50-100
Terra Cotta Clay Member:	
11. Mudstone or siltstone, medium- to light-gray. Contains abundant spherulitic siderite and generally weathers to form resistant ledge encrusted with iron oxides.........	0.0-4.0
10. Claystone or mudstone, gray with or without red mottles and yellow stain. Massive.................................	0.0-10.0
9. Siltstone, gray to yellowish-gray. Laminated to thin-bedded. Contains carbonaceous debris. Locally has ellipsoidal concretionary masses of calcite cement.........	0.0-10.0
8. Claystone, gray, massive; commonly contains fossil leaves and carbonaceous debris.............................	1.0-5.0
7. Claystone, dark-gray, carbonaceous, massive. Contains fossil leaves..	0.1-3.0
6. Claystone or mudstone, light-gray to very pale greenish-gray with abundant red mottles. Massive, conchoidal fracture. Parts along irregularly disposed slickensided fractures and contains several relatively persistent zones of spherulitic siderite at least partly altered to "limonite" or hematite. Generally contains thin beds of sandstone or siltstone locally cemented by	

	Range in observed thickness (feet)
concretionary masses of calcite cement. Contains local irregularly shaped lenses of gray claystone without red mottling	100.0-150.0
5. Siltstone or mudstone, light-gray with red mottles and yellow stain. Commonly calcareous and argillaceous and containing abundant siderite spherules. Weathers to form resistant ledge encrusted with iron oxide	0.5-3.0
4. Claystone or mudstone, light-gray with red mottles. Commonly contains spherulitic siderite	1.0-5.0
3. Porcelaneous kaolin bed or seam. Nonplastic, hard. Commonly appears as band of white fragments on weathered slopes	0.0-1.0
2. Claystone or mudstone, medium- to dark-gray. Plastic to nonplastic; commonly laminated to thin-laminated. Contains abundant carbonaceous debris and locally seams of lignite; generally contains nodular aggregates of pyrite and may contain seams of kaolin like unit 3 above as much as 0.1 foot thick. May also enclose lenses of light-gray claystone or mudstone with abundant red mottles	5.0-30.0
1. Claystone or mudstone, light-gray with red mottles. Plastic, conchoidal fracture, no obvious bedding. May enclose lenses of gray mudstone or claystone as in unit 2 above, or grade laterally into similar mudstone or claystone	0.0-5.0
Typical thickness Terra Cotta Clay Member, Dakota Formation	150-250
Typical thickness Dakota Formation	200-300

The usefulness of the recognition of the Terra Cotta Clay and Janssen Clay members lies mainly in the emphasis it places on their lithologic differences and in the exploitation of the contained clays. The zones of concretionary iron oxide, which Plummer and Romary (1942) suggested might be useful as reference beds for selection of a contact between the two members, occur at various stratigraphic positions from place to place and do not allow ready separation of the two members. Generally, however, the two members can be recognized by their gross differences in lithology, although each member contains beds like those characteristic of the other.

Lithology

Mudstone and claystone

The argillaceous rocks of the Dakota Formation range from massive red-mottled kaolinitic mudstone and claystone to highly carbonaceous gray to dark-gray massive or shaly mudstone and claystone. They also include thin seams of white to very light gray thin-laminated nearly pure porcelaneous kaolinite. The mudstone and claystone generally show little or no sign of lamination and commonly have conchoidal or blocky fracture. Much of the claystone parts along irregularly disposed slickensided surfaces. Even thin-laminated claystone and mudstone commonly show little or no sign of fissility, but fissile material is found near the top and bottom of the formation, particularly where the argillaceous rocks contain abundant carbonaceous matter. In contrast to the dominantly illitic shale of the Kiowa Formation, most mudstone and claystone in the Dakota probably contains less than 15 percent illite, but much clay near the base and near the top of the Dakota contains appreciable illite.

Beds of mudstone, claystone, and siltstone in the Dakota Formation are mainly lenticular. They pinch and swell, grade laterally into beds of somewhat different color or lithology, and enclose lenses of other lithology. In some roadcuts and clay pits, however, individual beds can be traced for distances up to 50 yards (46 m) without appreciable change in thickness or character. In general beds within the Janssen Clay Member are more persistent than beds in the Terra Cotta, but there are many exceptions. Plummer, Edmonds, and Bauleke (1963) described an area in Ellsworth County (sec. 25, T. 15 S., R. 6 W.) where claystone, mudstone, and particularly thin beds of white kaolinite near the base of the Terra Cotta showed amazing lateral persistence. In contrast, they also described (p. 10) an area in which the Janssen is made up of "...irregularly-shaped bodies of clay, sand, and silt of uncertain magnitude, showing great variation in thickness and lateral extent."

Pellets of spherulitic siderite as much as 2 mm in diameter are a common component of Dakota mudstone and claystone. In most surface samples the siderite is partly or completely weathered to goethite or hematite. Characteristically it is found in the light-gray to greenish-gray parts of red-mottled mudstone and claystone; locally it is found in gray and dark-gray mudstone and claystone. Pyrite and marcasite are common in carbonaceous and lignitic gray mudstone and claystone, and trace amounts have been detected in the gray or greenish-gray parts of red-mottled mudstone and claystone. Veinlets and aggregates of gypsum also are present in weathered samples of mudstone and claystone. Fish-tail twins and untwinned crystals of selenite occur on outcrops of carbonaceous and pyritic claystone.

The kaolinitic nature of the argillaceous rocks of the Dakota Formation is illustrated by the x-ray diffraction traces in Figure 10. Patterns B through E, Figure 10, were obtained from mudstone and claystone in both members of the formation. Except for pattern E, all the diffraction traces show evidence of a high degree of b-axis disorder: the 060 reflections near $62.4^{\circ}2\theta$ are poorly defined and resolution of distinct hkl reflections is poor. Nearly all the patterns indicate the presence of illite or montmorillonite in amounts not much greater than the limits of detection.

Numerous layers of nearly white porcelaneous kaolinite that probably are alteration products of volcanic ash occur near the base and the top of the Dakota Formation. Pattern E, Figure 10, is from the fraction finer than 2 microns of a seam of porcelaneous kaolinite about 1 cm thick in the lower part of the Terra Cotta Clay Member in the NE 1/4 sec. 25, T. 15 S., R. 7 W., Ellsworth County. The lamina can be traced for several yards (meters) along the outcrop and is similar to hard kaolinitic layers found elsewhere in the Terra Cotta Clay and Janssen Clay members that locally are as much as 1 foot (30 cm) thick. The diffraction trace shows that the kaolinite is well crystallized in contrast to most kaolinite in the Dakota Formation. Some quartz also is present in the sample.

Figure 33-A is a photomicrograph of a thin section of the porcelaneous lamina. The thin section shows that the poorly developed thin lamination seen in hand samples is produced by pods of microcrystalline kaolinite enclosed in a matrix of microcrystalline kaolinite and leucoxene. Many of the pods contain curved books of kaolinite measuring more than 0.01 mm long. The largest book seen composed a single pod. Only a few scattered detrital grains of silt-sized quartz were noted in the thin section. Probably most of the quartz detected in the diffraction pattern (Fig. 10-E) is cryptocrystalline silica masked in the kaolinite-leucoxene matrix.

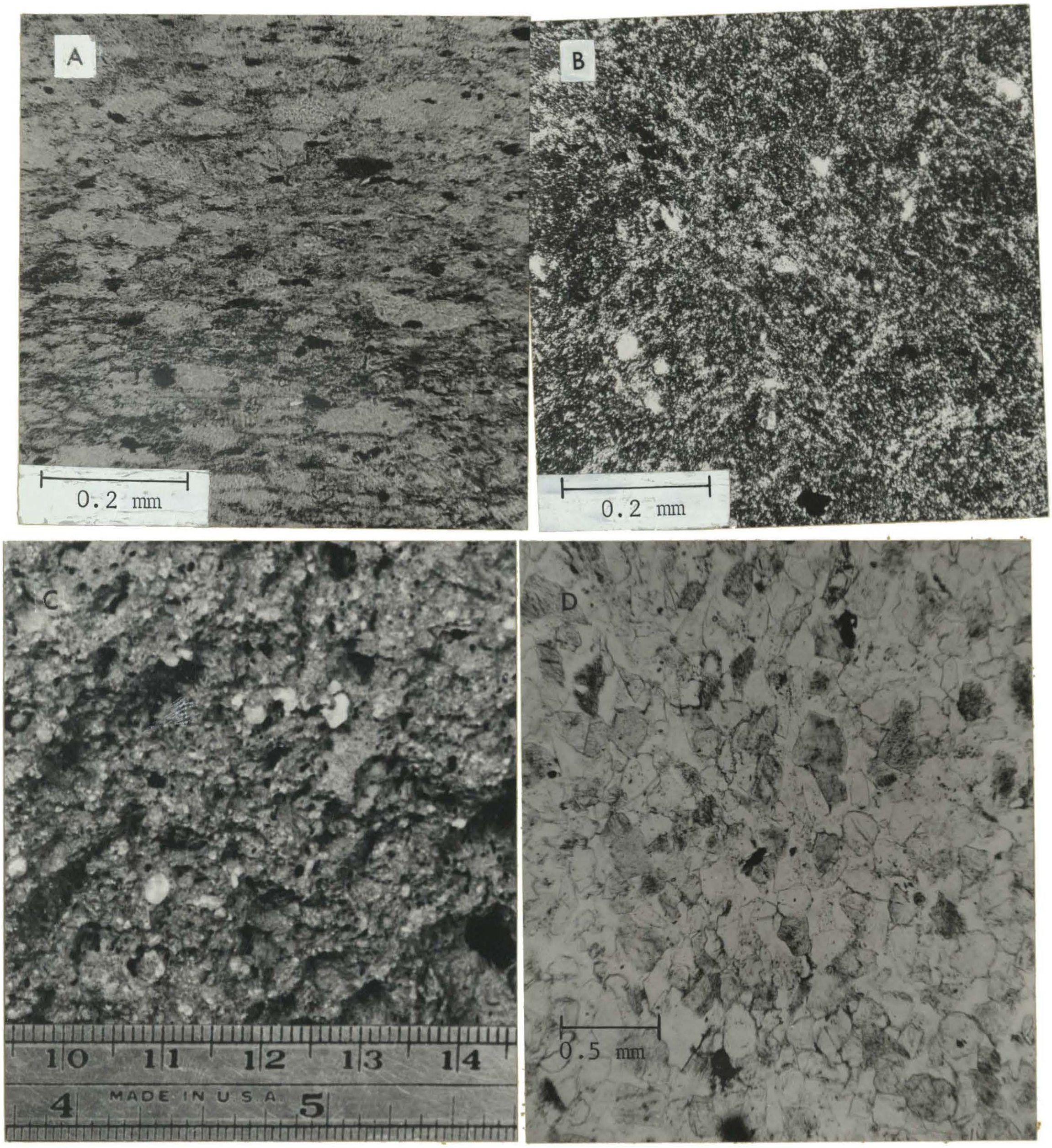
The porcelaneous kaolinite is thought to be the product of alteration of volcanic ash partly because of the difference in crystallinity of the kaolinite compared to surrounding Dakota mudstone and claystone, and partly because of the nearly complete absence of detrital quartz and the likely presence of cryptocrystalline silica. The peculiar fabric of the rock seemingly cannot be identified with a shard texture but may stem from reworking of the original ash either prior to or during the process of alteration. As pointed out by Schultz (1963) and by Weaver (1963),

Fig. 33.--- Photomicrographs and close-up of Dakota claystone, mudstone, and sandstone. A) Photomicrograph of thin section of porcelaneous kaolinite lamina in NE¼ sec. 25, T. 15 S., R. 7 W., Ellsworth County. The seam, which is about 20 feet (6 m) above the base of the Dakota Formation, is composed largely of well crystallized kaolinite (Fig. 10-E). The rock is thinly laminated. Pods of microcrystalline kaolinite (light gray) are as long as 0.2 mm. Individual kaolinite particles are less than 5 microns long, but the pods also contain curved books of kaolinite longer than 0.01 mm. Interareas between pods contain an admixture of finely crystalline kaolinite and leucoxene (dark gray to black in photograph). The rock is nearly free of detrital quartz. Plane-polarized light.

B) Photomicrograph of thin section of mudstone from Terra Cotta Clay Member in S½ SW¼ sec. 28, T. 15 S., R. 7 W., Ellsworth County (unit 18, Measured Section 5, Appendix and Plate 4). The rock is composed largely of kaolinite but contains appreciable illitic clay as well as silt-sized detrital quartz (white and black areas). Clay flakes and some comminuted flakes of detrital mica show preferred orientation at angles approximating 70 degrees. Deviation of each direction about the horizontal is about 35 degrees. The fabric indicates sedimentation by by flocculation. Same sample as Figure 34. Crossed nicols.

C) Close-up of Terra Cotta sandstone cemented with iron oxide. Same locality as Figure 32-A. The fine- to medium-grained sandstone contains numerous coarse to very coarse grains of quartz, quartzite, and chert and the matrix is rich in clay. Voids stem from weathering of granules and smaller fragments of penecontemporaneously reworked argillaceous rock.

D) Photomicrograph of thin section of fine- to medium-grained Terra Cotta sandstone in SW¼ NW¼ NW¼ sec. 1, T. 9 S., R. 1 W., Ottawa County. The sandstone sample was collected near the base of the Dakota Formation and is composed of about 95 percent quartz and less than 1 percent interstitial clay. Quartz grains that appear gray in the photograph are dusted with abundant inclusions. Note the well-sorted subangular to subrounded character of the quartz grains. Compare with Figure 16. Plane-polarized light.


A
0.2 mm
B
0.2 mm
C
10 11 12 13 14
4 MADE IN U S A 5
D
0.5 mm

however, identification of a bed or seam as the product of in situ alteration of volcanic ejecta is difficult.

Although montmorillonite has been considered to be the common alteration product of volcanic ash, Weaver (1963, p. 347) attributed the genesis of three kaolinite beds ("bentonites") in Colorado to "acid leaching" of volcanic ash. Sudo (1954) found that considerable Pleistocene volcanic ejecta in Japan weathers to allophane and hydrated halloysite as well as to montmorillonite. Which mineral forms is partly a function of depth in the soil profile. He also found that allophane and halloysite are generated under acidic or neutral condition attending strong leaching whereas montmorillonite is generated under conditions of less intense leaching and alkaline pH. According to Keller (1964, p. 25) alteration of volcanic ash to montmorillonite requires high concentrations of divalent cations. Assuming the correct pH for genesis of kaolinite, removal of monovalent and divalent cations from the parent ash, and redistribution or removal of silica, kaolinite can be the alteration product. Leaching of cations and silica can be accomplished either through percolation and good drainage or by dialysis in waterlogged environments.

Although most samples of Dakota mudstone and claystone are composed largely of kaolinite, many samples collected from the Terra Cotta Clay Member near the Kiowa-Dakota contact contain appreciable illite and mixed-layer illite-montmorillonite; chlorite and vermiculite are absent. Figure 34 shows a series of diffraction traces from a sample of relatively illitic Terra Cotta mudstone near the base of the Dakota where the Dakota rests on the Kiowa Formation. The presence of illite-montmorillonite mixed-layer clay is indicated by strong skewing of the illite 001 reflection in the low-angle direction, by expansion of the skewed reflection on

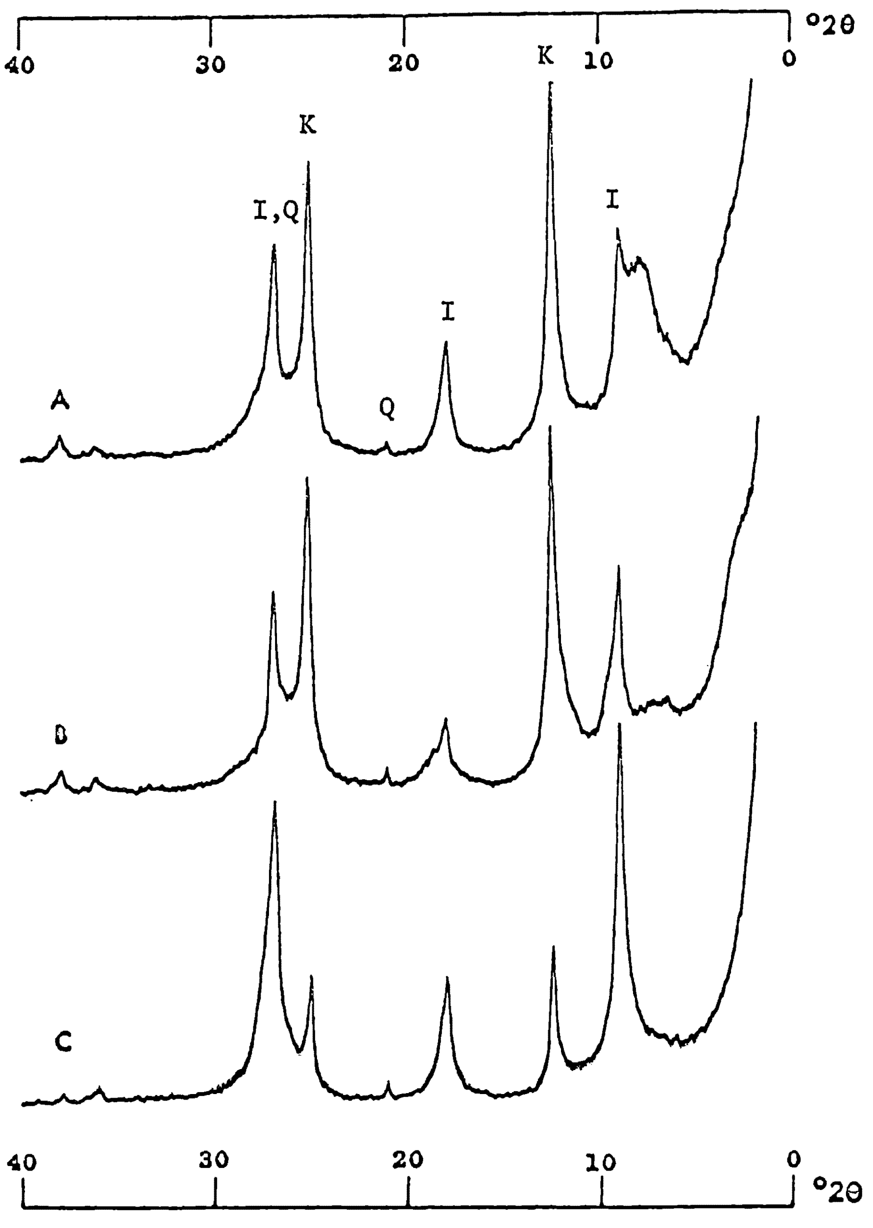


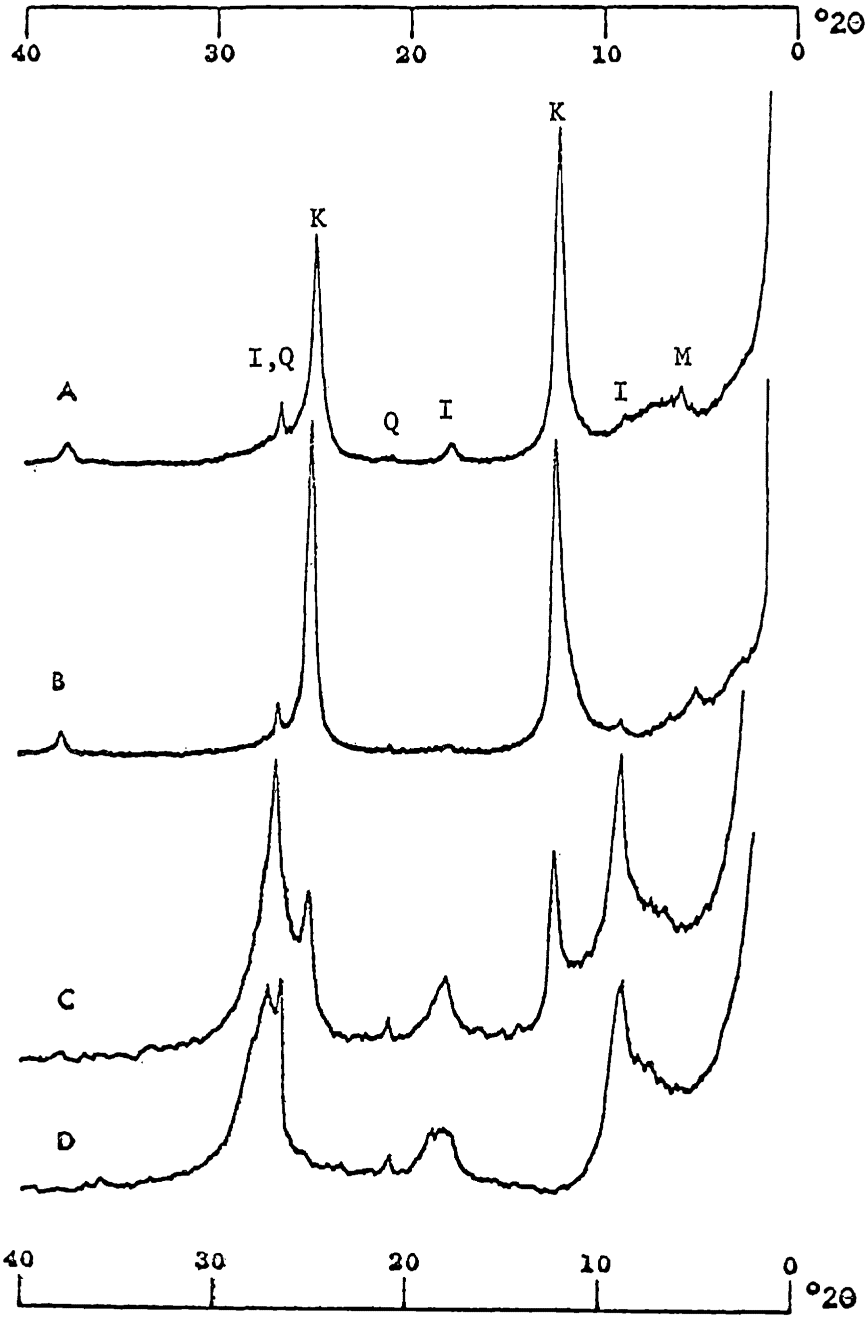
Fig. 34.--- Diffractometer patterns of fraction finer than 2 microns from red-mottled Dakota mudstone in lower part of Terra Cotta Clay Member, S½ SW¼ sec. 28, T. 15 S., R. 7 W., Ellsworth County, Kansas (unit 18, Measured Section 5, Appendix and Plate 4). The patterns illustrate the absence of chlorite and vermiculite and the abundance of kaolinite (K) in most Dakota rocks, and the presence of appreciable illite (I) and mixed-layer illite-montmorillonite in the basal part of the formation. A) air-dried, B) glycerated, C) heated to 450°C. Some quartz (Q) is present. In Pattern A, the illite 001 peak at 8.8°2θ (10A) is strongly skewed and a hump appears near 7.7°2θ. The shape of Pattern A indicates weak mixed-layer "superlattice" diffractions between 3° and 4°2θ. Pattern B shows shift of the mixed-layer hump and "superlattice" reflections. Pattern C only shows skewing that can be attributed to Lorentz polarization and angular effects. See Figure -B.

glyceration, and by complete collapse to a 10-Angstrom spacing on heating to 450°C. No chlorite or vermiculite can be detected in the patterns. Partial destruction of the kaolinite 001 and 002 reflections on heating may reflect poor crystallinity of the kaolinite or inadvertent maintenance of the sample at 450°C for a few minutes.

North of the Clay-Washington county line, where the Kiowa Formation is absent and the Dakota rests directly on Permian rocks, detectable amounts of chlorite and vermiculite are present in many samples collected at or near the base of the Terra Cotta Clay Member. Diffraction patterns from a highly kaolinitic sample are shown in Figure 35. The mudstone contains small amounts of montmorillonite and quartz. Illite is present in amounts not much greater than the limits of detection. Expansion of the montmorillonite and mixed-layer diffractions on treatment with glycerol revealed the presence of a 14-Angstrom component. Skewing of the 10-Angstrom reflection to the 14-Angstrom realm after heat treatment indicates that part of the mixed-layer clay is composed of chlorite or perhaps also vermiculite. Chlorite also seems to be present as a discrete mineral species.

Many samples collected from the upper part of the Janssen Clay Member contain appreciable illite and montmorillonite, either as distinct mineral species or as mixed-layer assemblages. The x-ray diffraction characteristics do not differ significantly from those shown in Figure 34; nor do the Janssen rocks generally contain either chlorite or vermiculite. Many samples from the upper parts of the Dakota Formation in Ellsworth and Russel counties, however, contain minor amounts of chlorite or vermiculite that commonly is interstratified with illite and montmorillonite (Measured Sections 3 and 4, Appendix and Plate 8). Locally, chlorite or vermiculite

Fig. 35.--- Diffractometer patterns of fraction finer than 2 microns from red-mottled Dakota mudstone in NE$\frac{1}{4}$ SE$\frac{1}{2}$ sec. 12, T. 2 S., R. 3 E., Washington County, Kansas (unit 1, Measured Section 17, Appendix and Plate 7). Patterns illustrate the presence of chloritic and vermiculitic components in mudstone and claystone in the basal part of the Dakota where it rests directly on Permian rocks. A) air-dried, B) glycerated, C) heated to 450°C, D) heated at 575°C for one-half hour. Pattern A shows the presence of abundant kaolinite (K) and sparse illite (I) and quartz (Q). A broad diffraction band joins the illite 001 reflection at 8.8°2θ (10A) to the peak (M) at 5.9°2θ. Pattern B shows shift of the montmorillonite peak (M) to 5°2θ (18A) and the broad diffraction band appears as a high-angle tail on the 18-Angstrom reflection. A stable 14-Angstrom peak is barely discernible at 6.3°2θ and a broad "superlattice" reflection is centered near 2.9°2θ. Heating produced collapse of the expansible components toward 10A, but the 10-Angstrom peak is skewed to 6.5°2θ or less. Persistence of a 14-Angstrom spacing on glyceration together with skewing of the 10-Angstrom peak toward 14A after heating indicates the presence of small amounts of chlorite. The mixed-layer clay that shows as a skewed reflection in Patterns C and D contains either chlorite or vermiculite in addition to illite and montmorillonite.

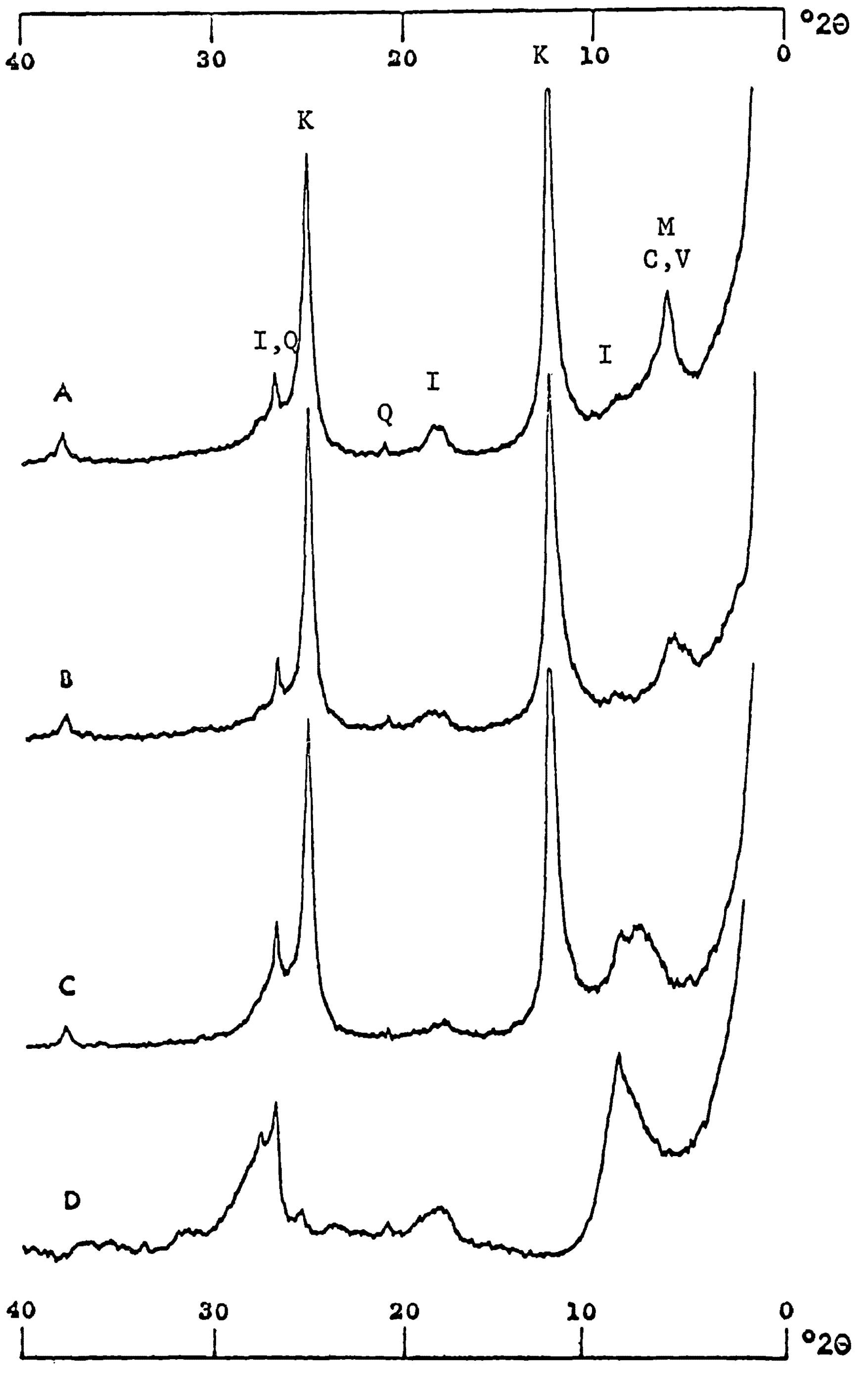

°2Θ
40
30
20
10
0
K
K
I,Q
M
A
I
Q
I
B
C
D
40
30
20
10
0
°2Θ

is present as a discrete mineral species and is not interlayered with either montmorillonite or illite. Figure 36 shows a series of diffractograms of the clay fraction from a sample of Janssen mudstone (unit 1, Measured Section 3) that illustrates the nature of the chloritic or vermiculitic component. The sample contains abundant kaolinite and very sparse illite, but a prominent 14-Angstrom diffraction is apparent. Part of the 14-Angstrom material is expansible and is thought to be montmorillonite. Collapse of the 14-Angstrom material to d-values near 13.2A could indicate the presence of vermiculite, but Brindley (1961b, p. 264) has noted that some chlorite has basal spacings in the range from 13.2A to 13.6A after dehydration rather than the more normal spacing of about 13.8A.

The massive, unlaminated character of much Dakota mudstone and claystone is suggestive of sedimentation by flocculation. Thin sections of some samples reveal poorly developed domain structure similar to that in the Longford Member of the Kiowa Formation (Fig. 26-B), but much Dakota mudstone and claystone also shows sharply defined plexoidal fabric (Fig. 33-B) in which the opposed directions of preferred orientation of individual flakes are at angles of 70 or 80 degrees. Where organic matter is abundant in the Dakota Formation, however, good preferred orientation of the clay particles parallel to lamination is common and in places is reflected in shaly parting.

The fabric developed by a clayey sediment prior to compaction is the product of many factors. The factors include not only the nature and concentration of organic compounds and electrolytes in the depositing medium, but also the rate of deposition, agitation or quiescence of the water in which the clay is deposited, particle size distribution of the sediment, and concentration of the clay particles in the water (Meade, 1964, p. B16).

Fig. 36.--- Diffractometer patterns of fraction finer than 2 microns from a sample of shaly mudstone, Janssen Clay Member, Dakota Formation, near cen. N½ sec. 6, T. 15 S., R. 10 W., Ellsworth County, Kansas (unit 1, Measured Section 3, Appendix and Plate 8). The sample exemplifies the occurrence of small amounts of chlorite (C) or vermiculite (V) in argillaceous rocks of the Janssen. A) air-dried, B) glycerated, C) heated to 450°C, D) heated at 575°C for one-half hour. Pattern A shows prominent kaolinite reflections (K) and the presence of small amounts of quartz (Q) and illite (I). On glyceration, the large peak at 6.1°2θ (14A) becomes skewed to 18A and a "superlattice" diffraction band centered near 2.3°2θ appears. Expansion to 18A indicates the presence of montmorillonite (M). Patterns C and D show intensification of the 10-Angstrom peak at 8.8°2θ and pronounced skewing in the low-angle direction. Intensification of the 10-Angstrom peak can be attributed to collapse of montmorillonite, but skewing toward 14A indicatcates the presence of either chlorite or vermiculite, most of which is interstratified with montmorillonite.



°2θ
40
30
20
10
0
K
K
I,Q
Q
I
I
M
C,V
A
B
C
D
40
30
20
10
0
°2θ

A dilute suspension of kaolinite in water may yield sediment with a well-defined preferred orientation or a laminated fabric whereas a concentrated slurry of kaolinite may yield sediment showing little or no preferred orientation of the clay flakes. Moreover, randomly oriented or plexoidal fabrics may develop in clay slurries in which the water is deficient in electrolyte owing to attractions between negatively charged basal surfaces and positively charged edges of the particles (Meade, 1964, p. B14) whereas turbostratic or domain colloidal structures may develop given the right concentration of an appropriate electrolyte (Aylmore and Quirck, 1962).

Thus, fabrics showing diverse orientation of the clay flakes or turbostratic groupings of clay particles probably are primary sedimentary features produced by flocculation during deposition. The same concept has been advanced by White (1961). The development of slickensided surfaces or fractures in claystone of the Dakota Formation may be related to development of synaeresis cracks similar to those described by White (1961) for flocculated clays. The laminated structures and fabrics seen in the upper and lowermost parts of the Dakota Formation may reflect the kind and abundance of organic compounds in the environment of sedimentation (Ingram, 1953; Meade, 1964). According to Meade (1964, p. B20) there is little evidence to indicate that laminated fabrics or preferred orientation of the clay flakes parallel to bedding in argillaceous rocks are produced by natural compaction.

The abundant spherulitic siderite or its iron-oxide pseudomorphs in Dakota mudstone and claystone may also have bearing on the environment of deposition. The siderite is found in red-mottled mudstone and claystone, in gray argillaceous rocks showing no sign of lamination, in fine-grained sandstone, and in highly carbonaceous argillaceous rocks that may or may not show lamination. It occurs in both the Terra Cotta Clay and Janssen Clay members. Waagé (1959, p. 55-58) has reviewed the character and genesis of spherulitic siderite, which is common in the Lakota Formation (Early Cretaceous) of the Black Hills. According to Waagé (p. 57),

> Although it is found in nonmarine deposits it appears to be found consistently only in terrains in which these nonmarine deposits are closely associated with marine deposits. This suggests that conditions optimum to its formation obtain in areas at or very close to sea level possibly within or on the landward sides of coastal swamps and salt marshes.

Citing Deans (1934) and Swain (1944), Waagé inferred that subaerial leaching may be an important factor in the genesis of spherulitic siderite. On the other hand, Boswell (1961, p. 92) not only noted that spherulitic siderite is widespread in freshwater clays and coals, but citing Spencer (1925), he attributed its development to precipitation at numerous centers in flocculated sediments in which supersaturation with respect to $FeCO_3$ of the entrapped and gradually expelled water obtained. Garrells (1960, p. 158) has observed that siderite can form either in strongly reducing or midly reducing environments depending on concentrations of bivalent sulfur and carbon dioxide. Although mildly reducing conditions might develop in argillaceous sediment subjected to mild subaerial leaching, it seems unlikely that strongly reducing conditions would be achieved. Occurrence of siderite spherules in relatively carbonaceous rocks indicates that leaching may not have been an important factor in genesis of the spherulites. Moreover, occurrence of siderite spherules in red-mottled Dakota argillaceous rocks indicates development under mildly reducing conditions inasmuch as the iron in the red mottles is in an unreduced oxidation state.

Sandstone

Sandstone is a relatively minor but conspicuous component of the Dakota Formation. Size analyses of 87 samples (Table 3) are not appreciably different from those of Kiowa sandstone. However, the results are biased inasmuch as coarse-grained to conglomeratic sandstone containing numerous clay pebbles and generally indurated by iron oxide (Fig. 32-A) were omitted from mechanical analysis. The sandstone analyzed ranges from medium or coarse grained to very fine grained but most is fine grained. Sorting mainly is good, but ranges from very well sorted to moderately sorted (Folk, 1954, footnote 3, p. 349; 1964, p. 45). Skewness generally is small and positive, but six samples showed slight negative skewness using Folk's (1964, p. 46) "inclusive graphic skewness," and five using Inman's (1952, p. 130) "phi skewness measure." Most samples showing negative skewness are from the Janssen Clay Member. As is true of the Kiowa Formation, the samples range from very platykurtic to leptokurtic and hence nearly all depart somewhat from lognormal distribution, but most samples are leptokuritic. No geographic variations in grain size were noted except those determined by stratigraphic position. As is indicated in Table 3, sandstone in the Janssen Clay Member tends to be appreciably finer grained than sandstone in the Terra Cotta Clay Member. The size data in Table 3 indicate that there is considerable overlap in the average properties of Kiowa and Dakota sandstone. Comparison of Figures 33-D and 16 bears out the point.

Quartz approximates 95 percent or more of the detrital components in much nonconglomeratic Dakota sandstone, most of which is mature (Folk, 1954). Polycrystalline quartz is sparingly present in very fine grained Dakota sandstone but may amount to as much as 5 percent of some coarse-grained sandstone, but in most Dakota sandstone it generally does not exceed 1 percent of the detrital components. Detrital feldspar approximates 3 percent of some samples, but generally it is less abundant. Untwinned potash feldspar is most common. Microcline is more common than plagioclase. Feldspar generally is not seen in coarse-grained or conglomeratic Dakota sandstone. Shredded and comminuted books of muscovite occur in trace amounts. Schistose and phyllitic rock fragments are equally scarce. The abundance of interstitial clay generally incrases as grain size decreases, except in coarse-grained to conglomeratic sandstone in which clay pebbles and interstitial clay commonly are major constituents (Fig. 32-A, 33-C). Glauconite pellets were seen in one sample of very fine grained sandstone from the Janssen Clay Member in the SW 1/4 NW 1/4 sec. 27, T. 11 S., R. 11 W., Russell County. Swineford and Williams (1945, p. 116-117) reported finding one or more zones of glauconitic sandstone cemented by calcite in the subsurface of southwestern Russell County. Although some of the sandstone assigned to the Dakota by Swineford and Williams (1945) perhaps is in the Kiowa Formation, examination of the sample logs in their report indicates that some of the glauconitic sandstone indeed is in the Dakota Formation. Spherulitic siderite or its iron-oxide pseudomorphs is present in some outcrops of fine-grained Dakota sandstone. Like spherulites in mudstone and claystone they measure as much as 2 mm in diameter.

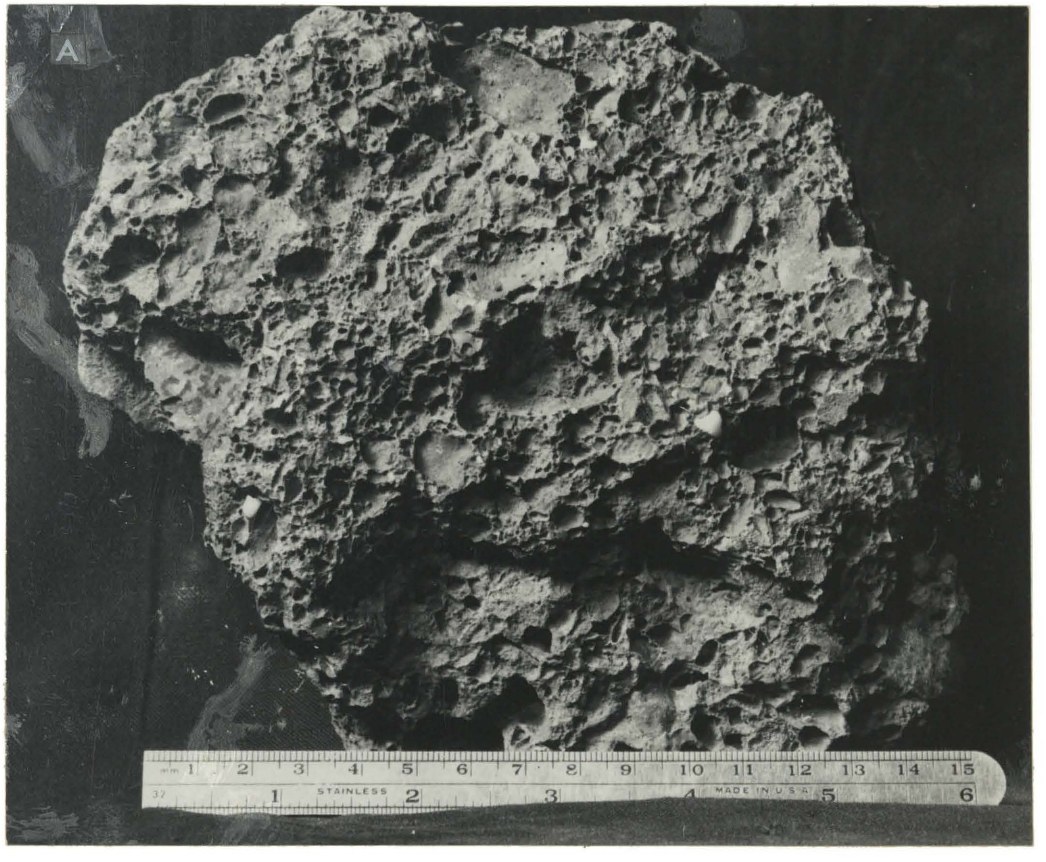
Granules and coarse grains of quartz, quartzite, and chert are common in most conglomeratic sandstone (Fig. 33-C). Many of the grains and granules of quartzite are yellowish orange to moderate reddish orange. The colors are similar to those of Precambrian Sioux Quartzite. Only locally do the coarse components of Dakota sandstone other than clay pebbles exceed 4 mm in long diameter. The penecontemporaneously reworked fragments of mudstone and claystone in the clay-pebble conglomerates generally measure less than 3 cm long, but locally fragments as much as 10 cm long are seen. Almost all coarse-grained and conglomeratic sandstone in the Dakota Formation is confined to the Terra Cotta Clay Member, particularly to its lower half.

Quartz grains in the Dakota sandstone are mainly subangular to rounded (Powers, 1953) and the mode of most samples approximates subrounded. Both sphericity and roundness, however, are dependent on grain size of the rock as well as of the individual detrital grains. Most fine-grained sandstone is angular to subrounded whereas coarse-grained and conglomeratic sandstone tends to be subangular to well rounded. Both roundness and sphericity increase together. Pebbles and granules in Dakota sandstone are mainly rounded and well rounded and have relatively high sphericity. The quartz grains in some fine- and medium-grained samples show sign of both etching and of subhedral to euhedral overgrowths. Some grains have rounded overgrowths.

Much Dakota sandstone is friable and only lightly stained by iron oxide except where iron-oxide cement has accumulated on hills and benches during post-Cretaceous weathering and erosion. Conglomeratic Dakota sandstone containing clay pebbles is much cemented by iron oxide in weathered exposures. A large part of the iron oxide probably was derived from the contained clay, or from siderite spherules within the clay. The abundant iron oxide, the peculiar cellular, nearly scoriaceous, aspect of weathered clay-pebble conglomerate (Fig. 37-A), and association with red-mottled Dakota mustone and claystone led Thorp and Reed (1949) to suggest that the conglomerates and associated red-mottled mudstone and

Fig. 37.--- Clay-pebble conglomerate, Terra Cotta Clay Member, Dakota Formation, north-central Kansas. A) "Vesicular" or scoria-like weathered clay-pebble conglomerate near cen. S½ sec. 36, T. 8 S., R. 1 E., Clay County. Note the well-rounded granules or pebbles of detrital quartz measuring as much as 6 mm long in right center and near left margin of sample. Rock of this type, together with associated red-mottled mudstone, has been interpreted as the product of penecontemporaneous lateritic weathering of Dakota sediments. Voids actually are produced by selective weathering and washing out of clay fragments whereas the sandy matrix became cemented by iron oxide during geologically young weathering.

B) Photomicrograph of thin section of clay-pebble conglomerate near cen. S line sec. 20, T. 14 S., R. 5 W., Saline County. Sample contains abundant iron-oxide cement (black) binding clay pebbles (gray) as much as 16 mm long and poorly sorted assemblage of quartz grains (white). The quartz grains range from silt-sized particles to granules, but most are about 0.8 mm in long diameter. The quartz grains range from subangular to rounded and include polycrystalline quartz that approximates 2 percent of the rock. Iron-oxide matrix amounts to nearly 40 percent of the rock and contains abundant disseminated and stained flakes of clay. Plane-polarized light.


A
STAINLESS
MADE IN U.S.A.


B
5 mm

claystone as well as various concretionary structures cemented by iron oxide were the product of penecontemporaneous lateritic weathering. Thorp and Reed did not recognize the fundamentally detrital nature of clay-pebble conglomerate in the Dakota Formation and equated the weathered product with the classic laterite of Buchanan. Figure 37-B is a photomicrograph of a thin section of a clay-pebble conglomerate near the south line sec. 20, T. 14 S., R. 5 W., Saline County. The clay pebbles are clearly discernible as are the abundant quartz grains that make up the bulk of the rock. The matrix is composed of admixed iron oxide and clay.

Concretionary structures produced by diffusion of iron oxide during post-Cretaceous weathering are similar in part to those seen in the Kiowa Formation (Fig. 18). Other iron-oxide cementation shows obvious control by jointing and forms distinct large-scale boxworks. Neither these nor weathered clay-pebble conglomerates can be attributed to penecontemporaneous lateritic weathering of the Dakota Formation.

Calcite and dolomite cement also are found in sandstone of the Dakota Formation, but are not as widely distributed as in the Kiowa Formation. Concretionary cement similar to that shown in Figure 19-A occurs in the lower part of the Terra Cotta Clay Member of the Dakota Formation in sec. 19, T. 12 S., R. 5 W., and in the SW 1/4 SE 1/4 sec. 20, T. 9 S., R. 2 W., Ottawa County (Plate 2). Large quantities of sandstone cemented by calcite or dolomite are present in Lincoln County (Swineford, 1947, p. 98-99) where the bulk of some sandstone lenses has been cemented without appreciable development of spheroidal concretions. The carbonate-cemented sandstone occurs both in the Terra Cotta Clay and Janssen Clay members. Large deposits are in T. 12 S., R. 8 W., and nearby in sec. 7, T. 12 S., R. 10 W., Lincoln County.

Sandstone in the Dakota Formation occurs in lenticular deposits of various sizes and shapes. As many as five or six prominent lenses of sandstone probably are exposed in the area of 7 square miles of Terra Cotta Clay Member represented in Figure 38. One lenticular deposit in the south half of sec. 33 apparently merges with a sandstone lens lower in the section. Most contacts between sandstone and underlying mudstone are disconformable and in many places, distinct scour-fill contacts can be seen. Only locally is there vertical gradation from argillaceous rocks upward into sandstone. Vertically gradational contacts are restricted almost completely to the upper parts of the Janssen Clay Member where sandstone overlies gray and carbonaceous shale. Thin beds of sandstone grade laterally into thick sandstone lenses or into argillaceous sections within short distances. Laterally persistent thin deposits of sandstone are practically nonexistent. Information on the size and shape of sandstone lenses in the Dakota Formation is scanty, but the mapping done for Figure 38 indicates that the extent of some lenses can be measured in miles. Thickness of some lenses locally exceeds 50 feet (15 m).

Sedimentary structures in Dakota sandstone are nearly as varied as they are in Kiowa sandstone. Transverse ripple marks (Fig. 32-B) were observed only locally near the base or near the top of the Dakota Formation. Micro-cross-stratification (Fig. 39-A) occurs in both the Terra Cotta Clay and Janssen Clay members but is scarce compared to other types of stratification. Linguloid ripple marks were seen in SE 1/4 sec. 29, T. 14 S., R. 7 W., Ellsworth County, in the Janssen Clay Member. Perhaps the apparent scarcity of ripple marks and micro-cross-stratification is related to the general lack of exposures showing bedding plane surfaces.

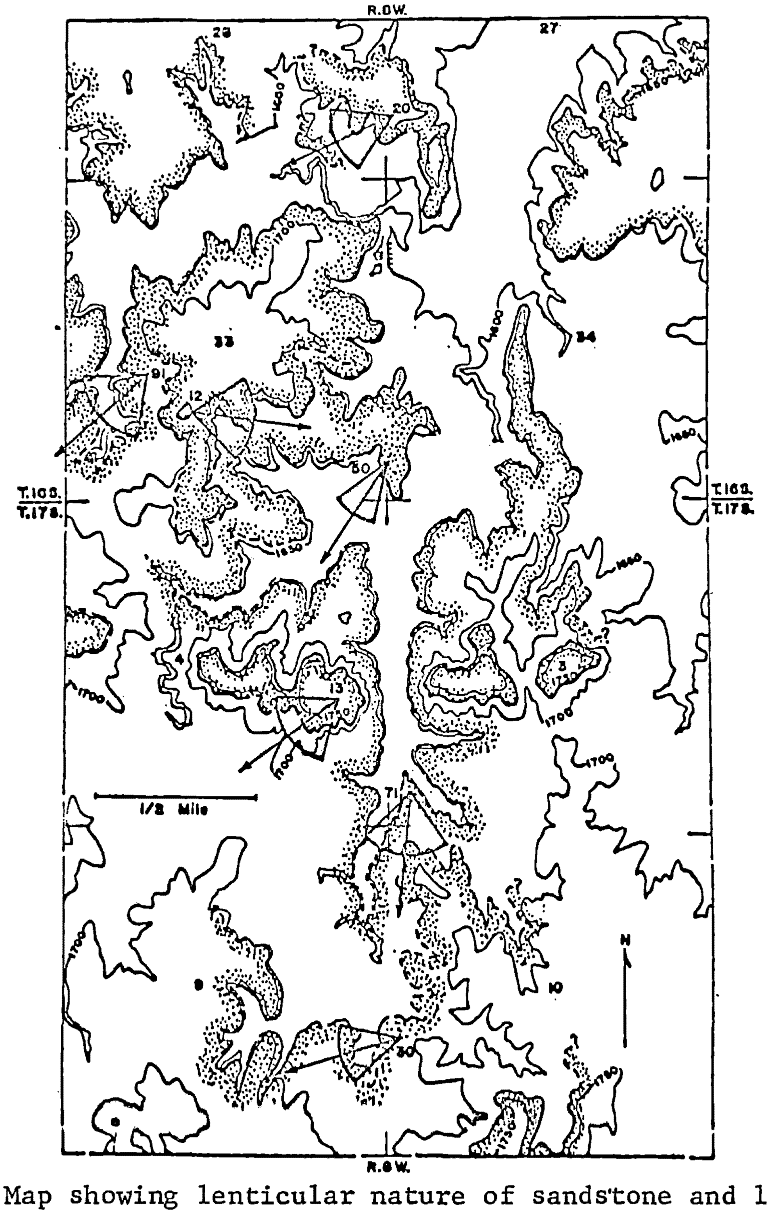


Fig. 38.--- Map showing lenticular nature of sandstone and local variability of cross-stratification trends in Dakota Formation in parts of T. 16 and 17 S., R. 8 W., Ellsworth County, Kansas. Bases of prominent sandstone lenses mapped from aerial photographs and shown by dark lines, long dash where approximately located, short dash where inferred. Stipples are on uphill side of contacts; queries mark areas where sandstone lenses pinch out within or grade laterally into sequences composed largely of mudstone and claystone. Light lines are contours; contour interval 50 feet (15 m). Arrows show vector resultants of dip bearings of cross-stratification. Arc delimited on each side of vector resultants is one standard deviation; numerals show number of measurements at each locality. The writer estimates that as many as 5 or 6 lenses of sandstone are shown in the seven square-mile area.

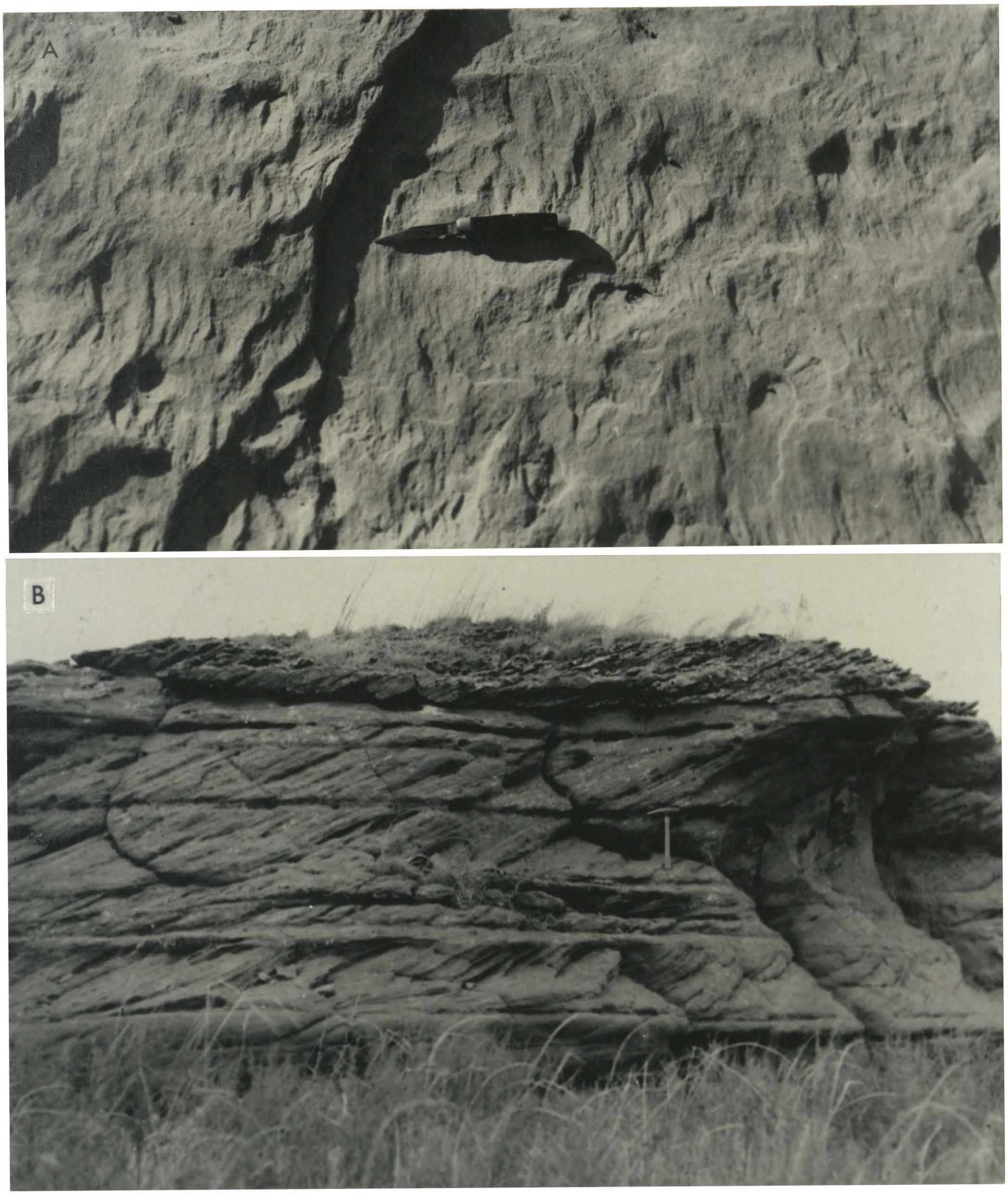


Fig. 39.--- Cross-stratification in Dakota sandstone, north-central Kansas. A) Micro-cross-stratification in fine-grained Terra Cotta sandstone near cen. N line NE¼ NW¼ sec. 21, T. 4 S., R. 2 E., Washington County. Pocket knife points in down-current direction and is about 6 inches (15 cm) long.

B) Tabular-planar cross-stratification in Terra Cotta sandstone in NW¼ SE¼ SW¼ sec. 34, T. 9 S., R. 2 W., Ottawa County. The topmost parts of this medium- to coarse-grained sandstone are cemented by calcite.

Small- to medium-scale tabular-planar high-angle cross-stratification is the most common type of cross-stratification in the Dakota Formation (Fig. 39-B). It occurs indiscriminately in fine-grained and coarse-grained sandstone. The tabular-planar cross-stratification is arcuate in plan view, but the width and curvature of individual sets is highly varied. Some sets are as little as 6 feet (1.8 m) wide, but others are nearly 50 feet (15 m) across. The broader the sets, the gentler is the degree of curvature of the cross-stratification. Small- to medium-scale wedge-planar high-angle cross-stratification also is common (Fig. 40) and commonly is intercalated with sets of tabular-planar cross-strata. Bounding surfaces of the wedge-planar sets dip as much as 10 degrees in the same direction as or in the reverse direction from the enclosed cross-strata. Trough cross-stratification in both members of the Dakota Formation is similar to that in the Kiowa (Fig. 19-B) and is found mainly in fine-grained sandstone. Medium- to large-scale wedge-planar low-angle cross-stratification similar to that in the Kiowa Formation is scarce in the Dakota Formation and is restricted chiefly to the Janssen Clay Member. Some is well exposed in SE 1/4 sec. 35, T. 2 S., R. 1 E., Washington County.

Other current-formed features include current crescents, which are built by washing out of sand from the upstream side of obstructions such as clay pebbles, and deposition of sand in "tails" on the lee side of the obstructions. Parting or current lineation also is common, but it seems to be restricted to the dipping faces of tabular- and wedge-planar cross-stratification. It generally pitches at small angles because of local divergence of currents flowing down the face of the cross-strata.

Horizontal stratification is much more common in thick deposits of Dakota sandstone than it is in thick deposits of Kiowa sandstone. In some

Fig. 40.--- Wedge-planar cross-stratification in near basal medium- to coarse-grained channel sandstone of Dakota Formation about 0.15 mile south of NE cor. sec. 14, T. 16 S., R. 5 W., Saline County, Kansas. Channel sandstone grades laterally to interbedded mudstone, siltstone, and fine-grained sandstone, but basal parts locally occupy scours cut into underlying Kiowa Formation. The exposure corresponds to the easternmost cross-stratification locality in Figure 42.

exposures of medium- to coarse-grained and even conglomeratic sandstone it is the only type of stratification seen, but it commonly is interbedded with cross-stratified sets. The horizontal stratification occurs as laminae and thin beds in sets as much as 2 feet (0.6 m) thick. Contacts of horizontally stratified sandstone lenses with underlying rocks, either argillaceous or arenaceous, commonly are erosive and the sandstone commonly contains clay pebbles and granules. Although horizontal stratification in sandstone commonly is ascribed to marine sedimentation (cf. Baars, 1961), Harms and others (1962, p. 576 - 577) have noted horizontal stratification in point-bar deposits where they have attributed it to shooting flow or upper regimen sedimentation. The extent to which deposits of horizontally stratified medium- to coarse-grained Dakota sandstone as much as 20 feet thick can be related to point bars is problematic, but their accumulation probably was governed by the upper phase of smooth traction and, depending upon grain size of the sandstone, may indicate current velocities on the order of 30 to 50 cm/sec (Nevin, 1946, p. 664, Plate 1). Horizontally stratified medium-grained and coarse Dakota sandstone probably was deposited under terrestrial conditions.

Fine-grained sandstone in the Dakota Formation locally forms horizontally stratified beds that are intercalated with siltstone, mudstone, and claystone. Bedding generally is thinly laminated but also includes micro-cross-stratification. Similar accumulations of fine-grained horizontally stratified and ripple-laminated sand have been noted by McKee (1939) in floodplain deposits of the Colorado River delta in Mexico and they occur in the floodplain deposits of modern rivers in Kansas. Harms and others (1962, p. 576) inferred that the micro-cross-stratification they found associated with point-bar deposits in the Red River of Louisiana formed during periods "...of decreasing flow velocity that led to deposition of suspended load and eventual emergence." commensurate with falling water depth.

Cross-stratification studies.---

The types of cross-stratification in the Dakota Formation are common to various environments of deposition. By itself cross-stratification might offer but little insight into the environments of deposition of the Dakota. However, recumbent fold structures and contorted cross-strata in tabular-planar high-angle cross-stratification in Terra Cotta sandstone (Fig. 41) seem particularly diagnostic of fluviatile sedimentation. McKee (1938) noted similar deformation of cross-stratification in deposits of sand along the Colorado River in Arizona. Deformed cross-strata have been described in some detail from the Chinle Formation of the Colorado Plateau by Stewart (1961) who attributed the deformation to flowage of water-saturated sand in river beds. Harms and others (1962) have observed recumbent cross-stratification in point-bar deposits of the Red River in Louisiana. McKee (1964) reported its generation under laboratory conditions whereby "...surface accumulations of sand are pushed forward by a sudden rush of water across the surface of a submerged set of foreset beds."

Locally, orientation of cross-stratification can be related to trend of sandstone deposits in the Dakota Formation, particularly in narrow pod-like deposits of sandstone in the Terra Cotta Clay Member that are on the order of 300 feet (91 m) wide and have lengths in excess of 1 mile (1.6 km). Figure 42 is a map of one such channel deposit that is well exposed in T. 16 S., R. 5 W., Saline County. The channel deposit is composed of medium- to coarse-grained sandstone near the base of the Terra Cotta. It is about 20 feet (6 m) thick, between 200 and 400 feet (60 and 120 m) wide, and occupies a scour that locally is cut into sandstone capping the upper part of the Kiowa Formation. In most places the sand-

Fig. 41.--- Overturned and contorted cross-strata in Terra Cotta sandstone near SE cor. sec. 17, T. 4 S., R. 3 E., Washington County, Kansas. The abundant contortions indicate that the sandstone was saturated with water at the time deformation took place prior to deposition of the succeeding bed.

stone is underlain by Dakota mudstone and grades laterally into flanking deposits of red-mottled and gray mudstone and sparse beds of fine-grained sandstone containing leaf fossils. Cross-stratification in the channel deposit is medium-scale wedge planar and high angle (Fig. 40). Measurement of cross-strata dip bearings at three localities along the channel deposit gave surprisingly uniform results and vector resultants computed for each locality shown in Figure 42 point almost directly down channel. The grand vector resultant calculated for all three localities also shows good correspondence with the overall trend of the channel deposit.

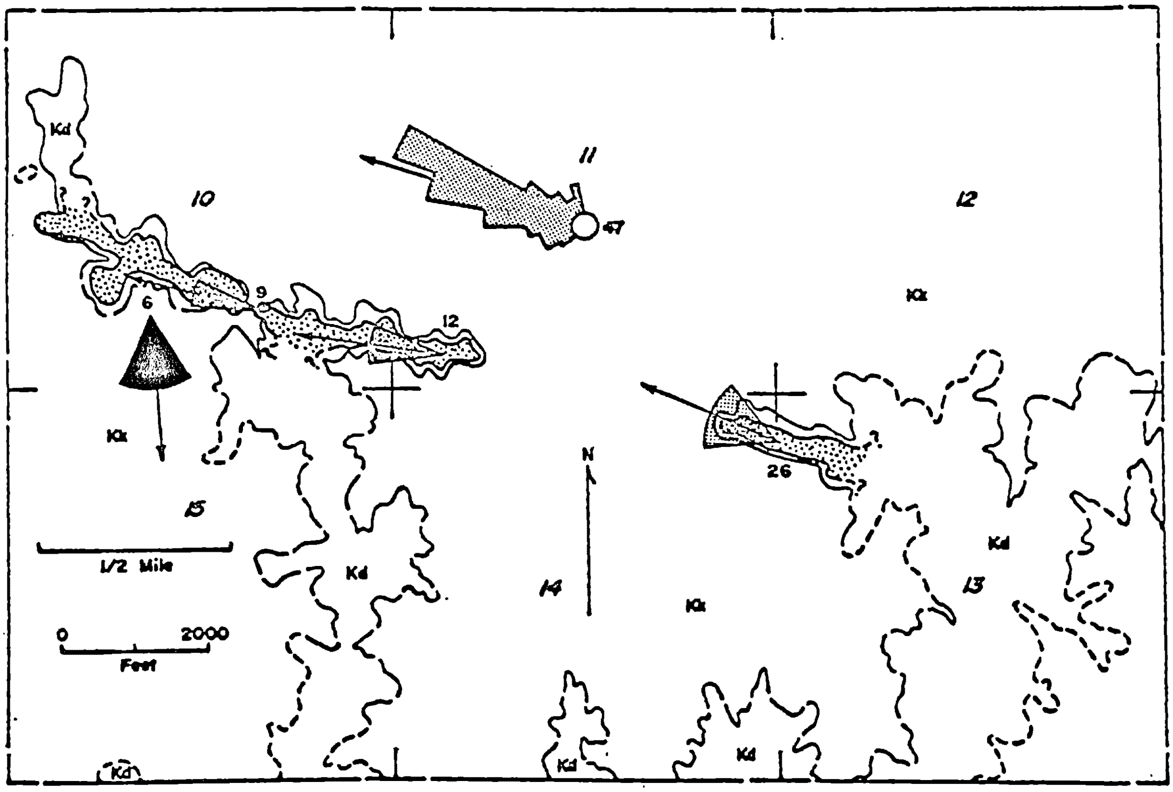


Fig. 42.--- Map showing configuration of channel sandstone near base of Dakota Formation on Schilling Air Force Base bombing range in T. 16 S., R. 5 W., Saline County, Kansas. Kiowa-Dakota contact shown as long dash where approximately located, short dash where inferred. Medium- to coarse-grained channel filling is shown by stipples; queries indicate areas where channel sandstone grades laterally to mudstone and fine-grained Dakota sandstone locally containing leaf fossils. Arrows show vector resultants of cross-strata dip bearings; arcs delimited on each side of vector resultants represent one standard deviation; stippled pattern indicates measurements made in channel sandstone; solid pattern, measurements in fine-grained sandstone capping Kiowa Formation. Rose diagram shows grand total of dip bearings measured in channel sandstone and plotted in 10-degree sectors; arrow is grand vector resultant. Channel sandstone is as much as 20 feet (6 m) thick and occupies a scour that locally is cut through basal Dakota mudstone into the Kiowa cap sandstone.

The pods of sandstone probably can be related to scour and fill along relatively straight reaches of small aggrading rivers. Large lenses of sandstone, such as the lower lens shown in Figure 38, commonly show somewhat less uniformity in the orientation of cross-strata vector resultants from place to place.

Locally it may be possible to relate the distribution of individual cross-strata dip bearings about their respective vector resultants to the type of stream flow. The distributions range from unimodal to multimodal and show variable degrees of skewing about the vector resultants (Franks and others, 1959, p. 232-235). The distribution of dip bearings shown in Figure 43-A is essentially unimodal and nearly symmetrical about the vector resultant. The dip bearings were measured in the medium-scale wedge-planar cross-stratification exposed in the narrow channel sandstone mapped in Figure 42 and photographed in Figure 40. The narrowness and straightness of the channel deposit and the unimodal nature of the circular histogram suggest that the extent to which the stream that deposited the sand meandered was relatively small.

In contrast, the distribution of dip bearings plotted in Figure 43-B is distinctly bimodal. Measurements were made in medium-scale tabular-planar cross-stratification in a relatively broad lens of sandstone. Meandering or other changes of current direction probably were important. Data presented by Potter and Pettijohn (1963, Fig. 4-9, p. 81) may support the suggestion. If the cross-bed data measured in point-bar deposits in the meandering Vermilion River, Indiana, and plotted in Potter and Pettijohn's map are replotted in 10-degree sectors (Fig. 44), a bimodal distribution is obtained. Differences between the rose diagram shown by Potter and Pettijohn and Figure 44-A are minor, but the larger sectors effectively mask the bimodality of the basic data (Fig. 44-B). One arm or mode of the distribution in Figure 44-B closely approximates the trend of the reach of the Vermilion River shown in Potter and Pettijohn's map. If it is assumed that the cross-bed measurements are representative of the currents that built the point bars studied by Potter

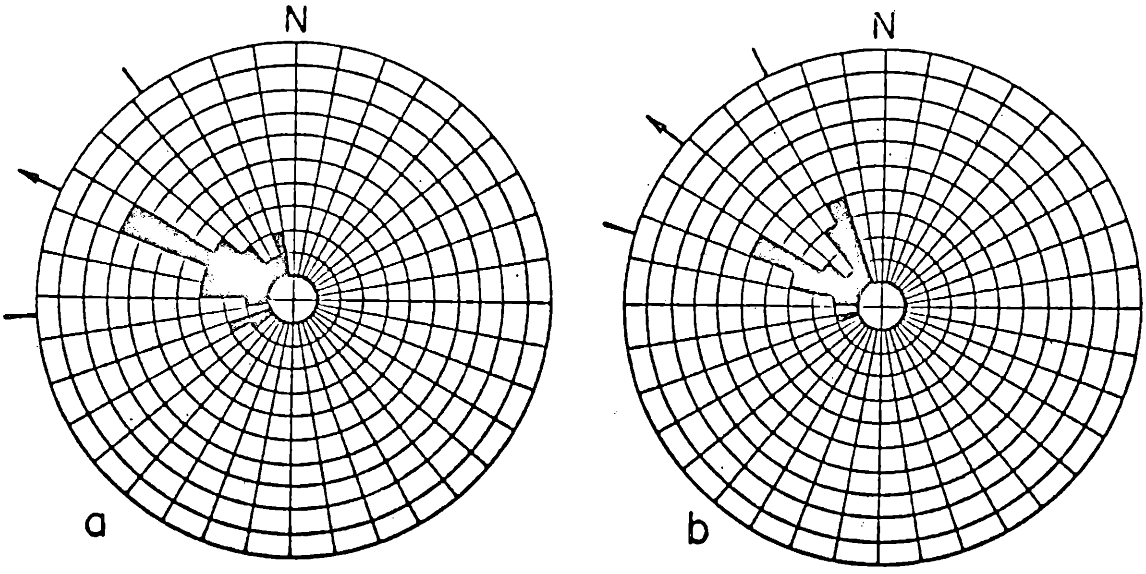


Fig. 43.--- Circular histograms of cross-strata dip bearings, Dakota sandstone, north-central Kansas. Arrow indicates direction of vector resultant; arc between lines is one standard deviation plotted on either side of vector resultant.

a) Channel sandstone deposit near cen. W line NW¼ NW¼ sec. 13, T. 16 S., R. 5 W., Saline County (See Fig. 40 and 42 .). Note the nearly symmetrical distribution of dip bearings about the vector resultant. Vector resultant is N66°W; consistency ratio, 0.89; standard deviation, 28°; 26 measurments.

b) Broad sandstone lens near cen. W½ SW¼ sec. 9, T. 10 S., R. 3 W., Ottawa County. Note the bimodal distribution of dip bearings about the vector resultant. Vector resultant is N51°W; consistency ratio, 0.93; standard deviation, 23°; 20 measurements.

and Pettijohn, the distribution not only is bimodal, but also is nearly centered about the vector resultant calculated for the directions plotted in their diagram. The similarity of Figures 43-B and 44-B is striking. As was suggested by Franks and others (1959, p. 237), depending on the degree of sinuosity of the channel pattern, "for the most part, directions of current flow in a braided or meandering stream will be at an angle to the over-all direction of flow, and only locally are current directions and the over-all trend likely to be coincident."

Close-spaced sampling of cross-strata dip bearings in the Dakota Formation in Ottawa County (Plate 2) gave vector resultants that show considerable local diversity in orientation. In T. 11 S., R. 5 W., for example,

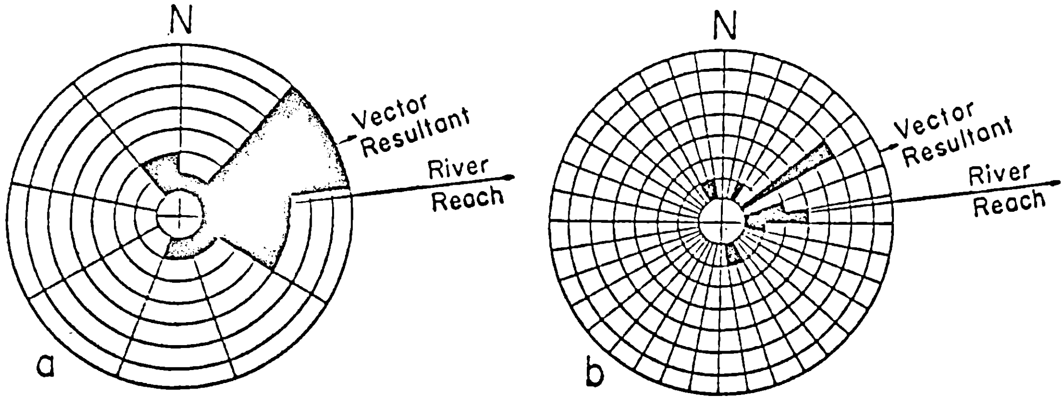


Fig. 44..--- Circular histograms of cross-strata dip bearings in point-bar deposits along a meandering reach of the Vermilion River, Indiana. Data from Potter and Pettijohn (1963, Fig. 4-9, p. 81). Dip bearings measured at 16 localities.

A) Circular histogram showing data plotted in 40-degree sectors modified after Potter and Pettijohn.

B) Circular histogram showing data plotted in 10-degree sectors. Bimodality of cross-stratification distribution is completely masked in (A), but is readily seen in (B). The reach of the river estimated from Potter and Pettijohn's map corresponds closely to one mode of the cross-strata dip bearings in (B). The vector resultant nearly bisects the angle between modes and probably reflects gross current directions that deposited the point bars but may not correspond to average current direction during low-water stages.

three vector resultants trend about N60°W; another trends about S50°W whereas the last trends about S10°W. Figure 23-C shows that dispersion of the vector resultants is much less marked than it is in the Kiowa Formation. Moreover, the distribution is strongly bimodal rather than markedly multimodal as is the distribution obtained for the Kiowa. One mode is centered near S40°W, the other near N70°W. Data from the relatively few localities in the Janssen Clay Member (Fig. 23-A) show considerably more dispersion than the vector resultants computed for the Terra Cotta (Fig. 23-B).

Variations in orientation of vector resultants computed for Dakota sandstone in Ellsworth County are apparent from place to place (Plate 3), but dispersion of the data is much smaller than in Ottawa County (Fig.

24-C). A bimodal distribution of the vector resultants can be inferred for the Terra Cotta Clay Member (Fig. 24-B). One mode is centered near S75°W and a lesser mode near S25°W. The vector resultants computed for the Janssen (Fig. 24-A) form a prominent westerly mode about which there is considerable dispersion of vector resultants in the northwest and northeast quadrants. The grand vector resultant of S67°W calculated for the Terra Cotta Clay Member in Ottawa County is in good agreement with the grand vector resultant of S64°W calculated for Ellsworth County. Because of the paucity of data available for the Janssen Clay Member in Ottawa County, comparison of a grand vector resultant of S36°W with the grand vector resultant of S83°W computed for Ellsworth County may not be valid (Table 5).

Comparison of data on the dispersion of individual cross-strata dip bearings about their respective vector resultants (Table 6) for Ottawa and Ellsworth counties shows that consistency ratios and standard deviations in the Terra Cotta do not differ appreciably from results calculated for the Kiowa Formation, but that the high dispersion of vector resultants in the Janssen is accompanied by high dispersion of individual cross-strata dip bearings about their corresponding vector resultants.

The orientations of vector resultants calculated for the Terra Cotta Clay Member for the whole of the area studied (Plate 1) basically are similar to the arrays of vector resultants shown on Plates 2 and 3. The spread of individual vector resultants about the grand vector resultant of S65°W computed for the Terra Cotta in the area shown on Plate 1 compares favorably with the dispersion of individual vector resultants about the grand vector resultants in both Ottawa and Ellsworth counties (Table 5). Moreover, the grand vector resultants of S65°W, S67°W, and S64°W computed for the Terra Cotta of north-central Kansas, Ottawa County, and Ellsworth County respectively are in excellent agreement. Figure 25-B also shows a markedly bimodal distribution of the vector resultants computed for the Terra Cotta in north-central Kansas. Modes centered near S35°W and west are in fair agreement with modes shown in Figures 23-B and 24-B. In addition, a small but distinct mode centered near S25°E is apparent in the data for the Terra Cotta Clay in Figure 25-B. The latter mode is close to the southeasterly mode detected in the Kiowa Formation. It is noteworthy that the multimodal distribution of the data is lost in the circular histogram for the Terra Cotta Clay Member shown on Plate 1 because of plotting in 30-degree sectors rather than 10-degree sectors.

Although local differences in orientation of individual vector resultants computed for the Janssen Clay Member and plotted on Plate 1 do not seem particularly different from the array of vector resultants plotted on Plates 2 and 3, considerable difference is detected in the circular histograms (Fig. 23-A, 24-A, and 25-A). Most of the differences in the histograms doubtless relate to the small number of data involved for Ottawa and Ellsworth counties. A combination of the results for Ottawa and Ellsworth counties (Table 5) forms a much better approximation of the distribution of vector resultants obtained for the area shown on Plate 1. Figure 25-A shows a multimodal distribution of the vector resultants. Two prominent modes are centered near S85°W and S55°W. Lesser modes seemingly are developed near N35°W and S15°E. The latter mode is similar to the southeasterly modes in the Kiowa Formation. The grand vector resultant calculated for the Janssen Clay Member in the area shown on

Plate 1 is S70°W, which is in reasonable agreement with the grand vector resultant of S79°W calculated for both Ottawa and Ellsworth counties (Table 1).

The vector resultants plotted in Figures 23-C, 24-C, and 25-C for the Dakota Formation show prominent westerly and southwesterly modes that give the data strong degree of bimodality. Franks and others (1959, p. 235-237) suggested that some of the bimodality detected in Ottawa County could be attributed to grouping of the data at three different levels (grouping in the field, grouping for calculation of individual vector resultants, and finally grouping of vector resultants for plotting of the circular histograms). However, the bimodal distributions of vector resultants obtained in conjunction with this study generally seem too persistent to be attributed to various levels of grouping. Franks and others (1959, p. 237) also recognized that the bimodality of the vector resultants might be inherent in the cross-strata and entertained the possibility that it might "...reflect meandering or braiding of streams that deposited most Dakota sandstone." However, it seems more likely that the bimodality of the vector resultants reflects preferred orientation of stream courses rather than details of meandering or braiding superimposed on the general directions of stream flow. Although a precise cause for the bimodality of the vector resultants is obscure, the distribution perhaps could be due to stream patterns developed in a system of shifting distributaries on a low-lying deltaic coastal plain.

The southeasterly mode of vector-resultant dip bearings in the Terra Cotta in Figure 25-B and perhaps also in Figure 24-B could stem in part from misidentification of Kiowa sandstone during mapping, but some of the vector resultants are from sandstone stratigraphically high in the Dakota (as in sec. 21, T. 12 S., R. 8 W., Lincoln County, Plate 1). Other localities in the Terra Cotta that show southeasterly or southerly vector resultants are near the base of the Dakota Formation and may have been controlled by topography on top of the Kiowa Formation, by structure, or by both together. Greatest thickness of the Kiowa Formation commonly is in areas of thick lenticular deposits of sandstone and the elevation of the Kiowa-Dakota contact is higher in those areas than in surrounding areas where the bulk of the Kiowa Formation is made up of shale. Sedimentation and stream flow during deposition of sandstone near the base of the Dakota therefore may have been controlled by thick lenticular deposits of Kiowa sandstone that were elongate in the southeasterly direction. On the other hand, the basal Dakota sandstone on Coronado Heights in the SW 1/4 sec. 31, T. 16 S., R. 3 W., and in SE 1/4 sec. 36, T. 16 S., R. 4 W., Saline County (Plate 1) is on the west flank of the north-trending Lindsborg Anticline in an area where the Kiowa Formation seems abnormally thin (Measured Section 9, Appendix and Plate 4). The trend of cross-stratification in the basal Dakota sandstone and the thinness of the Kiowa may have been influenced by movement along the anticline during or prior to deposition of the basal Dakota sandstone. The same may be true of the area encompassed by T. 5 and 6 S., R. 3 and 4 E. in Washington and Clay counties, but information on structural geology is lacking except insofar as it can be inferred from surface mapping (Plate 1).

The increased dispersion of both vector resultants and of individual cross-strata dip bearings about them (Tables 5 and 6) in the Janssen Clay Member in part reflect lessened stream gradients that would be in accord with the fine grain size of Janssen sandstone (Table 2). A decrease in stream gradients could have been controlled by rising base levels of sedimentation induced by the transgressing Graneros sea. However, marine fossils found in the Janssen Clay Member (Stanton, 1922; Hattin, 1965a) indicate nearshore or perhaps littoral sedimentation for part of the Janssen. Although it remains to be demonstrated in the field, some sandstone lenses having southeasterly or northwesterly vector-resultant dip bearings may be elongate in the same direction and hence analogous to bar deposits inferred in the Kiowa Formation.

Heavy minerals.---

The heavy minerals in Dakota sandstone are similar to those in Kiowa sandstone and generally amount to less than 0.5 percent by weight of the rock. Compared to separations from the Kiowa Formation, the fine fractions of the heavy mineral concentrates from Dakota sandstone contain increased proportions of zircon and correspondingly reduced proportions of staurolite. The change is most marked in the Janssen Clay Member of the Dakota Formation (Table 7). Rounded grains of barite and one or two grains of topaz were noted among the heavy minerals of the Dakota but were not seen in samples from the Kiowa Formation. Separations of heavy minerals from Dakota sandstone commonly contain abundant siderite spherulites or their goethite pseudomorphs. The spherulites were not counted because of their authigenic origin.

The upward increase in proportions of zircon and corresponding decrease in abundance of staurolite from the Kiowa Formation to the Janssen Clay Member of the Dakota Formation probably is due to differences in source areas. Graphs of median grain size of sandstone vs. composition of the contained heavy mineral suites show no trends whatever in either the Kiowa or the Dakota formations. Perhaps continued development of eastward flowing drainage systems in the Appalachian region (Groot, 1955), which probably supplied most of the staurolite, combined with the decreasing westward gradients indicated by cross-stratification trends and fine grain size of Janssen sandstone, effectively reduced the supply of staurolite. Decrease in abundance of staurolite perhaps also stems from the increasing importance of sedimentation in the Mississippi Embayment during the Late Cretaceous (cf. Pryor, 1960; Potter and Pryor, 1961), which doubtless served to siphon off sedimentary debris being transported from east to west across the stable interior. As is true for the heavy mineral assemblage of the Kiowa Formation, the suites in Dakota sandstone indicate derivation mainly by reworking of older sedimentary rocks.

Thickness of the Dakota Formation

The thickness of the Dakota Formation in north-central Kansas is difficult to determine because of the lack of continuous exposures and because of the width of the outcrop belt. Estimation of thickness also is complicated by structural features, e.g., the Ellsworth and Ellsworth-Kanopolis anticlines. Mack (1962, p. 28) indicated that the Dakota Formation of Ottawa County is as much as 350 feet (106 m) thick and estimates based on differences in elevation of the upper and lower contacts of the Dakota in southwestern Ottawa County indicate values on the order of 300 feet (91 m). Swineford and Williams (1945, p. 116) reported thicknesses from 213 to 300 feet (65 to 91 m) in the subsurface of southwestern Russell County, but most values recorded in the drill logs (p. 154-156) are nearer to 250 feet (76 m) than to 300 feet (91 m). Estimates made by subtraction of approximate elevations of the upper and lower contacts in Ellsworth County are as small as 170 feet (51 m), but they seem grossly unrealistic and probably reflect steepened dips induced by structure. Similar estimates in Washington County approximate 300 feet (91 m). In proportion to overall thickness of the formation and width of the outcrop belt, any variations in thickness that can be attributed to scour and fill along the Kiowa-Dakota contact probably are relatively minor, but there may be considerable local variation in thickness where the Dakota rests on Permian rocks. Moreover, regional variations in thickness owing to intertonguing with or lateral gradation into the Graneros Shale can be expected. Thickness of the Dakota Formation approximates 250 feet (76 m), but in some areas may be as little as 200 feet (61 m) or as great as 300 feet (91 m).

Paleontology of the Dakota Formation

The Dakota Formation of Kansas and Nebraska is noted for its profusion of fossil leaves of deciduous trees. The leaf fossils are found mainly in fine-grained sandstone, but locally are found in gray mudstone and claystone, and in medium- to coarse-grained sandstone. They have been described in detail by Lesquereux (1874, 1883, 1892), but many of the specimens he described probably came from the Kiowa Formation. There probably is considerable similarity in the fossil leaf assemblages found in both formations, although careful stratigraphic work coordinated with studies of speciation might reveal distinct differences. The varieties found in the Dakota Formation include sassafras, oak, willow, laurel, poplar, walnut, and other upland plants. Fig and cycad remains reported from the Dakota may represent part of a lowland flora. Lesquereux (1892, p. 256) inferred that the fossil flora indicates an equitable temperate realm locally verging on the subtropical. Leaves in the Dakota Formation are not associated with stumps and logs and it is likely that the assemblage has been transported by water to accumulate in relatively quiet ponds and backwaters.

Fossil vertebrates reported from the Dakota Formation include an armored herbiverous dinosaur (ankylosaur) from the Terra Cotta Clay Member in northeastern Ottawa County (Eaton, 1960), and a trachodont from northeastern Burt County, Nebraska (Barbour, 1931). Crocodile (?) tracks have been reported from the Dakota Formation near Sylvan Grove, Lincoln County, Kansas (Vaughn, 1956), but the locality is poorly specified in the older literature and could be either in the Dakota Formation or the Graneros Shale. A plesiosaur found near Delphos in Ottawa County has been referred to the Dakota (Williston, 1903), but it seems more likely that the find was in the Graneros Shale.

Hattin (1965a) reported on the occurrence of marine and brackish-water pelecypods and gastropods in the upper parts of the Janssen Clay Member of the Dakota Formation. The fossils are found mainly as molds and casts in sandstone in various parts of Lincoln, Russell, and Ellsworth counties. Hattin (1965b, p. 74-80) also found various foraminifers in the upper parts of the Dakota Formation. The writer has seen molds and casts of pelecypods in the uppermost sandstone of the Dakota Formation in the SW 1/4 sec. 31, T. 2 S., R. 1 E., Washington County, just below the contact with the overlying Graneros Shale. An assemblage of reworked high-spired gastropods in sandstone in the SW 1/4 NW 1/4 sec. 15, T. 11 S., R. 2 W., Russell County, is particularly striking and shows superficial resemblance to the "Mentor beds" of the Kiowa Formation. Stanton (1920, p. 260) listed fossils found in localities in Mitchell and Lincoln counties. He noted that the assemblages were unlike those in the "Mentor" and were related to fossil assemblages reported from the type area of the Dakota Formation in northeastern Nebraska. The locality in Lincoln County visited by Stanton was in shaft lignite mines in T. 11 S., R. 8 and 9 W., about two miles north of Denmark. According to Hattin (1965b, p. 65),

> ...the earliest Late Cretaceous marine lithologic succession in Kansas bears a close resemblance to the Woodbine-Eagle Ford beds of northeastern Texas....Conformability of the Graneros on the Dakota in Colorado indicates inception of Graneros deposition earlier in that State than in Kansas. The shoreline lay in the central Kansas area during the time the uppermost Dakota beds were laid down in that part of the State, and the shoreline continued to migrate progressively eastward or northeastward as Graneros sediments were deposited.

Terra Cotta Clay Member

The lower member of the Dakota Formation is characterized by kaolinitic light-gray to light greenish-gray mudstone and claystone showing abundant red mottles (Fig. 29). The measured sections shown on Plates 4, 6, and 7 span either the Kiowa-Dakota contact or the Permian-Dakota contact and show the lower parts of the Terra Cotta Clay Member, but none spans the full thickness of the member. The relative proportions of claystone, mudstone, and siltstone to sandstone are significant and emphasize the extent to which the Dakota Formation chiefly is an argillaceous unit.

Discontinuous thin beds of mudstone and siltstone up to one foot (0.3 m) thick form prominent ledges (so-called "marker beds") in weathered exposures of the Terra Cotta Clay Member (Fig. 31-A). They are much encrusted by iron oxide and have resistant, ragged, burr-like surfaces. Thin section examination of relatively fresh samples dug from the ledges shows that they contain numerous pellets of spherulitic siderite that are largely oxidized to goethite and hematite. Many also contain abundant fine-grained calcite cement. Locally, several such "marker beds" are present (unit 23, Measured Section 6, Appendix and Plate 4). They serve as useful guides for mapping the lower parts of the Dakota Formation. The admixed silt and clay, abundance of siderite, and local abundance of calcareous cement may indicate that the beds accumulated rapidly in ponded areas or local ephemeral lakes.

Below the "marker beds" the Terra Cotta Clay Member commonly contains abundant gray and dark-gray mudstone and claystone as well as beds of lignite and kaolinitic siltstone. Partly because of its economic significance and partly because of lithologic (though not necessarily mineralogic) similarity to the Janssen Clay Member, Plummer, Edmonds, and Bauleke (1963, p. 4) designated the sequence informally as the "Andrews section." It is named for its excellent development on the Andrews Ranch 1 to 2 miles east of Kanopolis, Ellsworth County, where it is exposed in sec. 28, T. 15 S., R. 7 W., at the Acme Brick Company clay pit and in nearby natural exposures (See Measured Section 5, Appendix and Plate 4). Siltstone in the Andrews section commonly contains abundant carbonaceous plant debris. Imprints of carbonized leaves occur in gray mudstone and claystone as well as in siltstone. Pyrite and marcasite are common. Locally the Andrews section contains relatively few lenses and beds of red-mottled mudstone and claystone, but in many places it grades laterally into sequences composed largely of red-mottled material. Much of the gray argillaceous rock of the Andrews section is thinly laminated and fissile. Although the clayey rocks of the Andrews section generally are relatively illitic compared to higher parts of the Terra Cotta, shaly gray claystone and mudstone in many places contain laminae and beds of white to very light gray porcelaneous nearly pure kaolinite as much as one foot (0.3 m) thick (Fig. 33-A). The seams are hard and the kaolinite seems to have formed by alteration of beds of volcanic ash (See section on "Mudstone and claystone.").

The sequences described in Ellsworth, McPherson, and Ottawa counties (Measured Sections 5, 6, 8, and 11, Appendix and Plate 4) span rocks some of which can be referred to the Andrews section. A definite contact between the Andrews section and the higher parts of the Terra Cotta Clay Member cannot be selected, however, because of lateral and vertical gradation of the Andrews section into rocks more characteristic of the Terra Cotta.

The upward increase in abundance of kaolinite in the clay fraction of argillaceous rocks in the Kiowa Formation continues into the basal parts of the Terra Cotta Clay Member of the Dakota Formation, which locally contain as much illite and "degraded" illite as the upper parts of the Kiowa Formation (Plates 4 and 6). Thus, although the contact is lithologically sharp and distinct in many areas, mineralogic changes across the contact are relatively gradational. Where illite disappears as a prominent constituent in the Terra Cotta, the clay fraction of the argillaceous rocks is composed almost completely of b-axis disordered kaolinite (Fig. 10).

Small amounts of montmorillonite and vermiculitic or chloritic mixed-layer clay are almost universally present in the basal parts of the member where the Terra Cotta Clay Member rests directly on Permian rocks (Plate 7), but proportions of illite generally are less than where the Terra Cotta overlies the Kiowa Formation. Locally, however, either illite or montmorillonite may be surprisingly abundant where the Terra Cotta Clay Member rests on Permian rocks (unit 6, Measured Section 16, and unit 9, Measured Section 14, Plate 7). As proportions of illite and montmorillonite relative to kaolinite change, corresponding variations in the abundance of vermiculitic and chloritic clay also take place.

The correspondence outlined above between the clay mineralogy of the basal parts of the Terra Cotta Clay Member and that of the underlying rocks;

whether they belong to the Kiowa Formation or to the Permian, suggests that the gradational changes in clay mineralogy across the Kiowa-Dakota contact may not represent gradation between Kiowa and Dakota sedimentation. Rather, the correspondence in clay mineralogy suggests that reworking of underlying deposits was a factor in controlling the mineralogy of the basal argillaceous rocks of the Dakota Formation.

Sandstone in the basal parts of the Terra Cotta Clay Member commonly contains large rounded grains of quartz in a silt matrix (Fig. 45) where the Dakota rests directly on Permian rocks or is close to the area of disappearance of the Longford Member of the Kiowa Formation in southeastern Washington County. The texture of the sandstone is similar to the bimodal grain-size distribution in Middle and Upper Permian siltstone described by Swineford (1955) as well as to the fabric in siltstone of the Longford Member of the Kiowa Formation (Fig. 26-A). The bimodal grain-size distribution possibly stems from reworking of Permian rocks, but perhaps more likely results from reworking of siltstone belonging to the Longford Member of the Kiowa Formation.

The origin of red-mottled mudstone and claystone in the Terra Cotta Clay Member has bearing on the origin of the abundant kaolinite in the Dakota Formation. Test-holes logged by Swineford and Williams (1945, p. 154-165) in southwestern Russell County and by Mack (1962, p. 112-114) in Ottawa County reveal the presence of red-mottled mudstone and claystone in the subsurface. The test-holes and exposures in clay pits demonstrate that red mottles are not the product of modern or geologically young weathering but are first order features of the Dakota Formation. Geologically young weathering may produce some redistribution of iron oxide and augment the red coloration of red-mottled mudstone and claystone (Fig. 29), but it does not generate the red mottles.

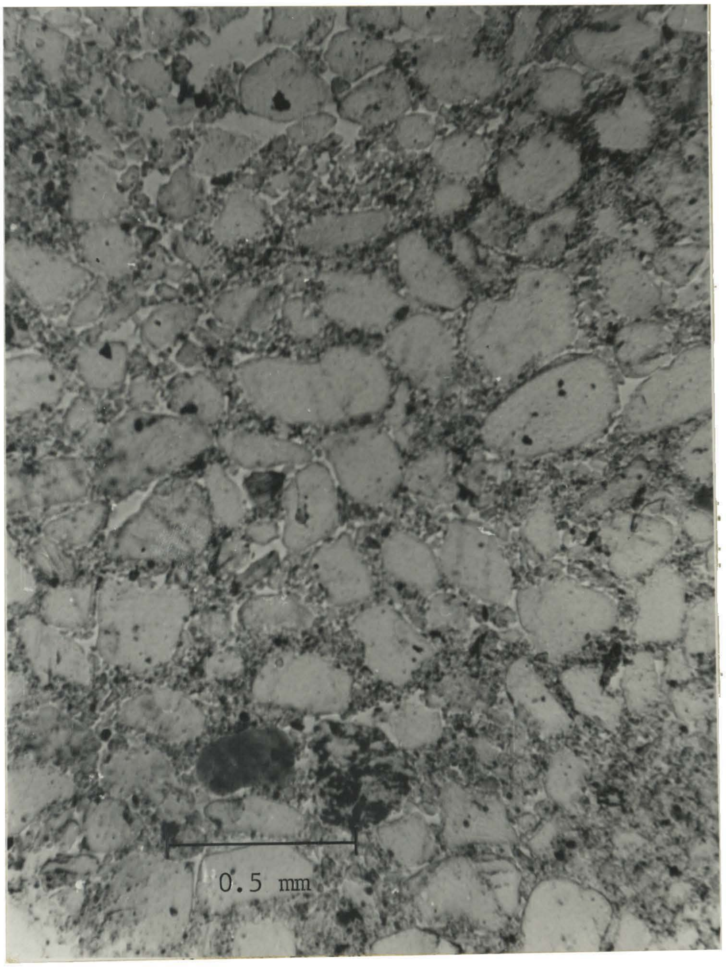


Fig. 45.--- Photomicrograph of thin section of basal Dakota sandstone near cen. S½ sec. 26, T. 5 S., R. 3 E., Washington County, Kansas (unit 4, Measured Section 14, Appendix and Plate 7) showing bimodal grain size distribution having rounded grains of quartz in a silt matrix and similar to the distributions in the Longford Member, Kiowa Formation. See Fig. 26-A. Dark-gray grain is tourmaline. Black and light-gray grain adjoining tourmaline is chert. Remaining black material is carbonaceous matter. Plane-polarized light.

Microscopic and x-ray examination of the nonclay fraction of red-mottled mudstone and claystone from the Terra Cotta Clay Member shows that either siderite or its goethite and hematite pseudomorphs are present as spherulites in the interareas between red mottles. Whether spherulitic siderite, goethite, or hematite is present depends only on the freshness of the sample. A mudstone sample from the Acme Brick Company clay pit in the W 1/2 sec. 28, T. 15 S., R. 7 W., Ellsworth County, contained microcrystalline calcite and ankerite in the interareas between red mottles and in the mottles. The interareas contained spherulitic siderite and microscopic blebs of pyrite. The red mottles contained mainly hematite and sparse siderite. The distribution of the siderite in the red mottles could not be determined but no spherulites were observed. The major clay mineral both in the mottles and in the interareas was b-axis disordered kaolinite. Some red-mottled mudstone and claystone contain disseminated carbonaceous matter between the red mottles, and the common occurrence of gypsum in many samples of red-mottled mudstone indicates that pyrite or marcasite may have been original components that have been destroyed by weathering. Some samples of red-mottled mudstone in the Andrews section of the Terra Cotta Clay Member have a dark-gray background on which red mottles are superimposed, and locally the interareas between the mottles also contain siderite.

Siderite spherulites and blebs of pyrite in the interareas of light-gray to light greenish-gray mudstone and claystone between the red mottles indicate that red-mottled mudstone and claystone in the Terra Cotta Clay Member is the product of incomplete reduction of originally red sediment. Garrells (1960, p. 158) observed that siderite may form in either strongly reducing or moderately reducing environments depending upon concentrations of bivalent sulfur and carbon dioxide. That reduction did not proceed far enough to displace all of the ferric oxide from its high oxidation state and left irregular areas or mottles of the originally red sediment indicates that reducing conditions were mild. Local crystallization of pyrite in the sediment could have been controlled by micro-environments related to the distribution of blebs of carbonaceous matter.

Plummer and Romary (1942, p. 341) suggested that the kaolinite in the Dakota Formation was produced by subaerial leaching and weathering that altered various clay minerals (mainly illite and montmorillonite) to kaolinite. Thorp and Reed (1949) suggested that the Dakota Formation was the product of penecontemporaneous laterite genesis. Evidence of the detrital nature of some of the supposed laterite, namely the clay-pebble conglomerate, was discussed in the section on Dakota sandstone. Other features of supposed lateritization discussed earlier seem to be products of post-Cretaceous weathering, e.g., iron-oxide diffusion structures and boxworks in Dakota and Kiowa sandstone. Thorp and Reed (1949) also indicated that red-mottled kaolinitic clay associated with much of the cellular sandstone enriched in iron-oxide was a common "companion material" in laterites. Intercalation of red-mottled mudstone and gray sulfide-bearing carbonaceous mudstone and claystone as lenses one within the other controverts pervasive oxidation and leaching that should be associated with laterite genesis.

As Keller (1964, p. 17-20) has indicated, dissolution and removal of silica is essential to kaolinization and lateritization, but the abundance of unetched detrital silt-sized quartz in red-mottled mudstone controverts leaching as a means of generating either the kaolinite or the red mottles during lateritization. Moreover, chemical analyses of mudstone and claystone form the Terra Cotta Clay Member indicate that they contain roughly the same amounts of silica, alumina, and iron oxide as does Kiowa shale (Table 2). Lateritic concentration of iron oxide does not seem to have taken place in Dakota mudstone and claystone. The small smounts of K_2O, Na_2O, CaO, and MgO indicated in Table 2 are in accord with the kaolinitic nature of Terra Cotta mudstone and claystone.

Red-mottled Dakota mudstone and claystone therefore are the products of partial diagenetic reduction of an initially red sediment. Colloidal siderite precipitated about numerous centers in the flocculated sediment as reduction progressed and water was gradually expelled or supersaturation relative to $FeCO_3$ obtained. Reduction spread from numerous centers but was incomplete. The unreduced areas between coalescing realms of reduction remain as red mottles. Presence of red-mottled mudstone and claystone as penecontemporaneously reworked fragments in clay-pebble conglomerates indicates that development of red mottles was an early diagenetic process. The presence of b-axis disordered kaolinite in both red mottles and the gray to greenish-gray interareas of Terra Cotta mudstone and claystone indicates that the kaolinite was not the product of leaching, but was part of an initially red sediment transported by Dakota streams and rivers. As James (1966, p. W40) has pointed out, "...there seems little doubt but that much iron is transported as oxide films on clays."

Grand vector resultants calculated for cross-strata dip bearings in sandstone of Terra Cotta Clay Member indicate that transport was from northeast to southwest. The average direction of transport, and hence the direction inferred for inclination of the regional slope was about S65°W. Coarse grains and granules in much Terra Cotta sandstone indicate that gradients were steeper than those of the overlying Janssen Clay Member. The shape of some sandstone lenses and data on orientation of cross-stratification indicate that some streams followed relatively straight reaches for distances in excess of one mile (Fig. 42). Considerable diversity of trend is indicated for other, perhaps larger streams (Fig. 38). The streams seemingly supplied red kaolinitic sediment from highly weathered source areas composed largely of sedimentary rock lying to the east and northeast.

Locally channel sandstone deposits in the Terra Cotta are associated with deformation of a type that Williams and others (1965) have attributed to development of stream valleys, channel cutting, and subsequent slumping of previously deposited sediment. Mention has been made of the fault in T. 7 S., R. 1 E., Clay County in which upper Kiowa rocks show evidence of slumping induced by erosion and differential loading prior to or penecontemporaneously with deposition of basal Dakota sandstone. The fault near the common corner of sec. 20, 21, 28, and 29, T. 16 S., R. 7 W., Ellsworth County (Plates 1 and 2) is truncated by Dakota sandstone (Fig. 46). Ver Wiebe (1937) thought that the deformed beds beneath the sandstone were "Comanche rocks" but the presence of appreciable red-mottled mudstone in the section exposed in the roadcut shows that the beds belong to the basal parts of the Terra Cotta. The deformed section of mudstone, claystone, and sandstone beneath the truncating sandstone shows dips as steep as 70°. Faulting was penecomtemporaneous with deposition of basal Dakota rocks. Ver Wiebe (1937) attributed the deformation to solution and collapse of salt in the Wellington Formation in the subsurface of Ellsworth County. Intimate association of the fault with a channel sandstone in which cross-strata dip nearly parallel to the strike of the fault seems to support the premise that the faulting is due to rotational slumping that took place during the development of a local disconformity by stream erosion.

The contact between the Terra Cotta Clay Member and the overlying Janssen Clay Member is not a fixed stratigraphic datum. Although the Janssen is characterized by gray and dark gray mudstone and claystone as

Fig. 46.--- Deformed beds near the base of the Dakota Formation near SE cor. sec. 20, T. 16 S., R. 7 W., Ellsworth County, Kansas. Truncation of the deformed beds by the sandstone (dark gray) and only partial involvement of the sandstone show that deformation was penecontemporaneous with sedimentation.

well as beds and seams of lignite, the Janssen does contain beds typical of the Terra Cotta Clay Member. Plummer and Romary (1942, p. 336) placed the contact at the top of a "marked concentration of concretionary 'iron'." In many places, the contact can be placed conveniently at the top of beds or zones enriched in iron oxide, most of which seems to have been derived from oxidation of spherules and concretionary masses of siderite. Swineford and Williams (1945, p. 116) reported penetration in 9 out of 16 test holes of one or more zones of concentrated concretionary siderite "below gray massive clay 40 to 81 feet below the base of the Graneros shale." The contact between the Janssen and Terra Cotta therefore differs in stratigraphic position from place to place and the beds or zones most conveniently marking the separation are not everywhere present.

The thickness of the Terra Cotta Clay Member can only be approximated, but is estimated to be about two thirds the thickness of the Dakota Formation, or about 160 or 170 feet (49 or 52 m). Thicknesses as great as 200 feet (60 m) may be common in some areas.

Janssen Clay Member

The Janssen Clay Member of the Dakota Formation, the upper parts of which are facies of, grade westward into, and interfinger with the overlying Graneros Shale (Eicher, 1965; Hattin, 1965b), is composed mainly of gray and dark-gray kaolinitic mudstone and claystone and contains lenticular beds and seams of lignite and lignitic shale or claystone. Carbonaceous siltstone is prominent in many areas and locally lenticular beds of red-mottled mudstone and claystone are common, particularly along the gradational contact with the Terra Cotta Clay Member. In places, however, red-mottled mudstone is found near the top of the Janssen (Measured Section 4, Appendix and Plate 8). Sandstone generally is less prominent in the Janssen than it is in the Terra Cotta, although the "Rocktown channel sandstone" (Rubey and Bass, 1925) comprises a thick assemblage of lenticular sandstone bodies most of which are in the Janssen Clay Member of northern Russell County.

Thin lamination and shaly parting are much more common in the argillaceous rocks in the Janssen Clay Member than they are in the Terra Cotta. The abundance of laminated mudstone and claystone or shale probably reflects the high content of organic matter in the depositional environment and consequent particle-by-particle settling rather than flocculation of the clay micelles (Ingram, 1953; Meade, 1964). Like the basal parts of the Terra Cotta Clay Member, the Janssen Clay locally contains seams of porcelaneous kaolinite as thick as 0.5 foot (15 cm). Spherulitic siderite is common not only in mudstone and claystone, but also in fine-grained Janssen sandstone. Siderite also forms close-spaced concretionary beds as thick as 0.2 foot (6 cm) intercalated with dark-gray shale or silty shale in the uppermost parts of the Janssen, as near the cen. sec. 25, T. 14 S., R. 15 W., Russell County. Pyrite and marcasite together with jarosite stain and gypsum abound in the carbonaceous and lignitic beds of the member.

Although beds of mudstone, claystone, and siltstone in the Janssen are laterally persistent compared to similar beds in the Terra Cotta, lateral change also is characteristic of the Janssen Clay Member. The two sections measured in Ellsworth County and the one measured in Washington County (Plate 8) have very little in common except for kaolinitic mudstone and claystone. The sequence shown in Measured Section 15, in the NW 1/4 SW 1/4 sec. 31, T. 2 S., R. 1 E., Washington County, changes to a sequence of fine-grained sandstone containing molds and casts of pelecypods in its topmost part within one-fourth mile to the west. Similar abrupt change is common in other areas.

Schoewe (1952) found that lignite occurs as shaly beds as much as 3 feet (0.9) thick within the upper 25 feet (7.6 m) of the Janssen Clay Member. The pelecypod assemblages described by Stanton (1922, p. 260) were in part from a lignite mine near Denmark in Lincoln County. Foraminifers reported by Hattin (1965b, p. 77) also are associated with lignitic material. Much of the lignite in the Janssen probably accumulated in swampy areas bordering the transgressing Graneros sea, perhaps in lagoonal or estuarine environments as well as in fresh-water swamps. The abundance of carbonaceous trash in much siltstone and mudstone in the Janssen suggests sedimentation under somewhat similar swampy conditions.

The clay fraction of mudstone and claystone in the Janssen Clay Member, whether fissile or massive, is composed mainly of b-axis disordered kaolinite (Fig. 10-B). Local presence of red-mottled mudstone and claystone in the Janssen (Measured Section 4, Appendix and Plate 8) indicates that the sediment also was initially red because of colloidal iron-oxide coatings on the clay micelles. The abundance of carbonaceous matter and its contained iron sulfide in the Janssen, siderite spherules in some gray mudstone and claystone, and local occurrence of concretionary beds of siderite in some shaly sequences indicate that the environment of deposition was reducing. Chemical analyses of channel samples of Janssen mudstone and claystone have averages close to values obtained for channel samples of Terra Cotta mudstone and claystone (Table 2), but the mean content of ferric oxide is much less than it is in the Terra Cotta Clay Member. If the pH of water in the swampy environments was acid, perhaps because of abundant organic compounds in solution, reduction and dissolution of colloidal iron-oxide films on clay particles could have taken place rapidly during sedimentation (Carroll, 1958). Ferrous iron perhaps was carried off in solution to be redeposited as siderite beds in marginal environments of sedimentation, or perhaps also was carried off to the Graneros sea.

Near the Dakota-Graneros contact, appreciable amounts of illite and montmorillonite occur locally in Janssen mudstone and claystone (Plate 8), although the clay fraction of most mudstone and claystone in the Janssen is composed largely of kaolinite. The illite and montmorillonite in the upper parts of the Janssen Clay seemingly reflect transition into the overlying and laterally equivalent Graneros Shale. Shale in the Graneros, which is composed largely of montmorillonite (cf. diffraction trace opposite unit 9, Measured Section 15, Plate 8), locally contains appreciable kaolinite and illite in its basal parts where much of whatever montmorillonite present commonly is interstratified with illite (Measured Sections 3 and 4, Plate 8).

Detectable chlorite and vermiculite are scarce in argillaceous rocks of the Dakota Formation in north-central Kansas, except in the northern part of the area where the basal parts of the formation rest on Permian rocks. Much mudstone and claystone near the Dakota-Graneros contact also contains vermiculitic and chloritic clay in Ellsworth and Russell counties (Fig. 36). Most samples from Measured Sections 3 and 4 (Appendix and Plate 8) showed the presence of vermiculite and chlorite in the clay fraction, either as mixed-layer structures with montmorillonite and illite or as independent components. In contrast, no chlorite or vermiculite was detected in Measured Section 15 (Appendix and Plate 8). The clay fraction of practically every sample from subsurface equivalents of the Dakota Formation in northwestern Kansas studied by x-ray methods by Franks and Plummer (_in_ Merriam and others, 1959) also contained small amounts of chlorite or vermiculite.

The chloritic and vermiculitic mudstone and claystone in the upper part of the Janssen Clay Member in Russell and Ellsworth counties perhaps are part of a marginal marine to littoral facies that expands westward to encompass the bulk of the chloritic and vermiculitic equivalents of the Dakota Formation in the subsurface of western Kansas. The whole of the basal Cretaceous section examined by Merriam and others (1959) seems to be chiefly marine. Few beds, even in the section spanning supposed Dakota equivalents, seemed to be nonmarine and the brackish-water to marine aspect of numerous beds in the upper part of the Janssen Clay Member in north-central Kansas already has been noted. Measured Section 3, in which chloritic and vermiculitic clay was found, is in the same general part of sec. 6, T. 15 S., R. 10 W., Ellsworth County, where Hattin (1965b, p. 77) reported finding foraminifers in the upper parts of the Janssen.

Calcareous beds and concretions showing cone-in-cone structure occur locally in the Janssen Clay Member, but the beds and concretions generally are unlike those in the Kiowa Formation. Near the cen. S line SE 1/4 sec. 8, T. 1 S., R. 3 E., Washington County, subspherical highly argillaceous calcareous concretions about 4 feet (1.2 m) in diameter in gray claystone showing sparse dark-red mottles have outer fringes of fibrous cone-in-cone about 3 inches (8 cm) thick. The floor of the Cloud Ceramic Company clay pit in SE 1/4 NW 1/4 sec. 13, T. 6 S., R. 3 W., Cloud County, is cut in part on a lenticular concretionary bed of argillaceous calcium carbonate containing sparse siderite and dolomite and abundant detrital silt-sized quartz. The bed, which is as much as 3 feet (0.9 m) thick, shows indistinct cone-in-cone structure in which cones are as much as 1 cm long. The cones are composed both of conelets of fibrous calcite and of microcrystalline calcite that is thought to be the product of partial recrystallization of fibrous calcite. Cone-in-cone structure in the Janssen is thought to be the product of early diagenesis similar to that which took place in the Kiowa Formation although the depositional environment differed.

A prominent ledge-forming siltstone bed is found near the top of the Janssen Clay Member in many parts of north-central Kansas (unit 9, Measured Section 4, Appendix and Plate 8). Locally the siltstone bed is as much as 5 feet (1.5 m) thick, but in most places it is between 1 and 2 feet (0.3 and 0.6 m) thick. It is laminated to thinly laminated and weathers very light gray to pale grayish orange, or even white. Siliceous cement may impart some of its resistance to weathering. Locally it contains carbonaceous debris, argillaceous films, and mica flakes on bedding surfaces. Practically everywhere it contains nearly vertical tubules as much as 6 inches (15 cm) long and between one-fourth and one-half inch (about 1 cm) in diameter. In places the tubules are filled with "limonite," but in other places they contain carbonaceous matter, or are empty. The tubules have been interpreted as worm burrows, root impressions, or molds of reeds. In light of their general straightness and local carbonaceous filling, the last interpretation, proposed by Hattin (1965b, p. 65), seems most likely.

The ledge-forming siltstone grades downward into Janssen mudstone and claystone or into similar less resistant siltstone. The upper part of the siltstone commonly interfingers with an intercalated sequence of siltstone, sandstone, and brownish-gray shale as thick as 6 feet (1.8 m). The sequence above the ledge-forming siltstone commonly is much stained by iron oxide and is capped by a concentration of "limonite" in many places. The iron oxide marking the top of the intercalated sequence probably stems from oxidation of concretionary siderite. The intercalated sequence of siltstone, sandstone, and shale supports a generally covered slope and is overlain by the Graneros Shale. The ledge-forming siltstone is not continuous. In places it is replaced laterally by interbedded shaly claystone, lignite, and sandstone (Measured Section 3, Appendix and Plate 8). Elsewhere it is replaced by sandstone.

A large concentration of sandstone found along the Saline River and Wolf Creek in northern Russell County extends from the upper part of the Terra Cotta Clay Member to the top of the Janssen Clay Member. It is composed of a series of intercalated lenses of sandstone as much as 50 feet

(15 m) thick that are separated by sequences of mudstone and siltstone in many places. Rubey and Bass (1925, p. 57) defined this sequence as the "Rocktown channel sandstone member" of the Dakota Formation. The designation, however, is inappropriate owing to the general lenticular nature of sandstone in the Dakota Formation, although the name does serve informally to distinguish an uncommonly large concentration of sandstone in Russell County. Rubey and Bass (1925, Plate 3) inferred from studies of cross-stratification that the deposits were formed by a shifting meandering stream system and tried to reconstruct the actual drainage courses and meanders for part of the sandstone. Their interpretation has been cited often in the literature, but the writer suspects that the pattern of the meander loops is not so susceptible to deciphering as their work might indicate. Cross-stratification trends measured for this report commonly are antithetic or at right angles to the channels inferred by Rubey and Bass.

Southeasterly trends of vector-resultant cross-strata dip bearings may indicate that longshore currents were operative in deposition of sandstone in the upper parts of the Janssen in parts of Russell County (Plate 1) inasmuch as the depositional slope seems to have been inclined to the southwest. Many of the molds and casts of marine and brackish-water pelecypods reported by Hattin (1965a, 1965b) from the uppermost parts of the Janssen are in the general area of the "Rocktown channel sandstone." Moreover, Rubey and Bass (1925, p. 62) concluded that even-bedded sandstone at the top of the sequence may have been deposited as "beach sands," although they were unaware of the pelecypod fossils. The area of the "Rocktown channel sandstone" probably was a realm of deltaic sedimentation on the margins of the advancing Graneros sea, but it seems unlikely that individual deltaic components or analogues from the classic Gilbert delta can be deciphered from the stratigraphic record exposed in Russell County.

The thickness of the Janssen Clay Member is difficult to determine. It is thought to approximate the upper one third of the Dakota Formation and thicknesses on the order of 75 to 100 feet (23 to 30 m) are inferred for most places. Vertical and lateral gradation into the Terra Cotta Clay Member of the Dakota Formation and into the overlying Graneros Shale probably account for appreciable differences in thickness from place to place. Plummer and Romary (1942, p. 336) stated that the Janssen approaches its minimum thickness in its type area in Ellsworth County where it may be as little as 50 feet (15 m) thick.

Dakota-Graneros Contact

The fossils found in the topmost parts of the Dakota Formation and the lateral gradation between the upper Janssen and the lower Graneros described by Eicher (1965) and Hattin (1965b) point up the transitional nature of Janssen and Graneros sedimentation. Hattin (1964, p. 206) reported that reference to marker beds higher in the Graneros section shows that the position of the contact is nonuniform and "...reflects intertonguing of adjacent parts of the two units." Because selection of a contact between the Janssen Clay Member of the Dakota and the overlying basal parts of the Graneros Shale in many places depends on the characteristics of argillaceous rocks in both units, brief description of the lithology and mineralogy of basal Graneros rocks is included in this section of the report. The clay mineralogy of basal Graneros rocks also provides background for evaluation of the transitional variations in clay mineralogy in the upper part of the Janssen. However, a relatively sharp separation of the Dakota and Graneros formations can be made in most areas.

The ledge-forming siltstone containing molds of reeds that is close to the top of the Janssen Clay Member constitutes a convenient reference in many areas in north-central Kansas. The interval above the siltstone is somewhat variable from place to place, but generally only a few feet of transitional deposits separate the siltstone from the Graneros Shale (unit 10, Measured Section 4, Appendix and Plate 8). However, in sec. 31, T. 2 S., R. 1 E., Washington County (Measured Section 15, Appendix and Plate 8) a resistant ledge-forming siltstone containing molds of reeds is about 28 feet (8.5 m) below typical montmorillonitic Graneros shale. Where only a few feet of transitional rocks separate the siltstone from the overlying Graneros, concretionary iron oxide commonly is concentrated at the top of the transitional sequence of siltstone, sandstone, and shale overlying the ledge-forming siltstone. In many places a bench that is formed by the ledge-forming siltstone and the overlying transitional rocks precisely marks the base of the Graneros Shale. The Graneros shale above the bench commonly forms slopes that are marred by landslips.

Where the ledge-forming siltstone has been replaced by sandstone, the top of the Dakota Formation commonly can be drawn at the top of the sandstone. Siderite spherules or their goethite relicts are common in fine-grained sandstone in the upper part of the Janssen. The spherules and the relative abundance of carbonaceous debris aid in distinguishing topmost Dakota sandstone from fine-grained sandstone in the lower part of the Graneros. In many areas sandstone in the upper part of the Janssen is replaced laterally in short distances by characteristic Janssen argillaceous rocks, siltstone, and lignite.

At those places where the ledge-forming siltstone or prominent sandstone beds are absent in the upper part of the Janssen, shaly argillaceous rocks of the Dakota commonly are overlain directly by shale belonging to the Graneros. The clay fraction of most Graneros shale is composed chiefly of montmorillonite, as is shown by x-ray diffraction studies by Franks and Plummer (<u>in</u> Merriam and others, 1959), Hattin (1965b), and by the writer. The diffraction trace of a relatively representative air-dried preparation is shown on Plate 8 opposite unit 9, Measured Section 15. The strong montmorillonite peak at $6.6^{o}2\theta$ expanded to 18A on glyceration and collapsed to 10A or less on heating to $450^{o}C$. Only small amounts of illite and kaolinite were detected. Where similarly montmorillonitic Graneros shale overlies the argillaceous rocks of the Janssen, the olive weathering characteristics, high plasticity, and consequent tendency of the Graneros shale to slump contrast with the relatively neutral gray or brownish-gray tones and comparatively low plasticity of weathered Janssen rocks even though the Janssen rocks commonly are fissile.

In many areas along the Dakota-Graneros contact, however, the basal parts of the Graneros Shale contain relatively abundant illite and kaolinite, particularly in parts of Ellsworth, Russell, and Lincoln counties. The x-ray diffraction and other physical properties of the shale contrast sharply with those of more typically montmorillonitic Graneros shale. Figure 47 shows diffractometer patterns obtained from the fraction finer than two microns obtained from a sample collected near the base of the Graneros that contains abundant kaolinite and appreciable illite and mixed-layer illite-montmorillonite (unit 15, Measured Section 3, Appendix and Plate 8). Collapse of the mixed-layer clay to 10A on heating to $450^{o}C$ shows the absence of detectable chlorite and vermiculite. The clay mineralogy of the sample is similar to that of many Janssen rocks near the Dakota-

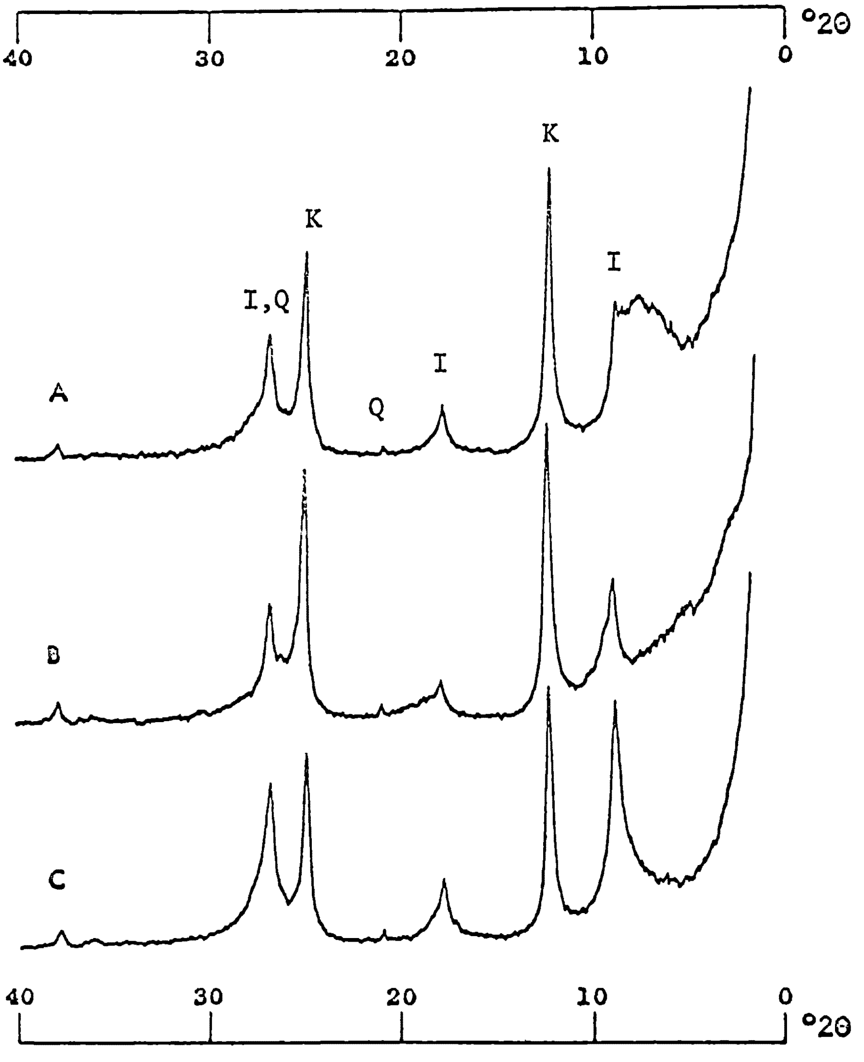


Fig.47 .--- Diffractometer patterns of fraction finer than 2 microns of a sample of kaolinitic and illitic shale from the Graneros Shale near cen. N½ sec. 6, T. 15 S., R. 10 W., Ellsworth County, Kansas (unit 15, Measured Section 3, Appendix and Plate 8). A) air-dried, B) glycerated, C) heated to 450°C. Pattern A shows strong kaolinite peaks (K) and weaker reflections from illite (I). Small amounts of quartz (Q) are present. The illite 001 reflection at 8.8°2θ is strongly skewed and shows a prominent hump near 7.6°2θ. On glyceration, the skewed mixed-layer reflection is displaced to about 5.1°2θ (about 17A) and a "super-lattice" diffraction maximum appears near 3°2θ. Swelling of the mixed-layer material to about 17A indicates the presence of montmorillonite. Collapse to 10A (Pattern C) on heating and little or no sign of skewing except for that which can be attributed to Lorentz polarization and angular effects verifies the presence of montmorillonite in the mixed-layer structure and demonstrates the absence of detectable chlorite or vermiculite.

Graneros contact, but differs from underlying Janssen rocks in N 1/2 sec. 6, T. 15 S., R. 10 W., Ellsworth County (Measured Section 3), in the absence of chloritic or vermiculitic components (cf. Fig. 36).

The Graneros Shale contains numerous seams of relatively pure calcium and sodium montmorillonite (bentonite) in many areas (cf. Franks and Plummer, p. 42, in Merriam and others, 1959; Hattin, 1965b). However, a sample from a "bentonite" seam in the N 1/2 sec. 6, T. 15 S., R. 10 W., Ellsworth County (unit 15, Measured Section 3, Appendix and Plate 8), contained only sparse montmorillonite. The major diffractions were from relatively well crystallized kaolinite (Fig. 10-A), and the rock is very similar to porcelaneous kaolinite seams in the Dakota Formation. The kaolinite seams in both formations are inferred to have formed by alteration of volcanic ash. The seams of kaolinite and the brackish-water fossils reported by Hattin (1965b) in the basal parts of the Graneros Shale also emphasize the transitional nature of Janssen and Graneros sedimentation. Keller (1964, p. 23) observed that the alteration of volcanic ash to montmorillonite requires high concentrations of divalent cations, but that given the right pH, low concentrations of cations give rise to kaolinite.

Where relatively kaolinitic and illitic shale as well as layers of kaolinite occur in the basal parts of the Graneros, placement of the Dakota-Graneros contact commonly is difficult. However, the relative abundance of carbonaceous debris and presence of lignitic seams in shaly sequences of Janssen claystone and mudstone allow relatively easy separation of the two formations in most places. Moreover, the brown and brownish-gray tones and relatively poor fissility of the shaly rocks in the upper part of the Janssen are a useful guide in separating them from the more-or-less kaolinitic rocks of the overlying Graneros.

Sedimentation, Diagenesis, and Source Areas of Dakota Formation

Sedimentation and diagenesis

The Dakota Fromation of north-central Kansas is believed to have been deposited mostly in a low-lying nonmarine coastal or deltaic plain bordering the Cretaceous sea that extended from the Gulf Coast region into the Western Interior of the United States (Tester, 1931; Plummer and Romary, 1942; Reeside, 1957). The sea probably connected with the sea that transgressed southward into the Western Interior from Canada during Dakota time (Haun, 1963, p. 128). The dominantly marine character of subsurface equivalents of the Kiowa and Dakota formations in northwestern Kansas described by Merriam and others (1959) testifies to westward gradation of the Dakota Formation into marine sediments. Similar relationships are indicated by the marine and brackish-water fossils found in the upper parts of the Janssen Clay Member (Hattin, 1965a, 1965b) and by the presence of one or more zones of glauconitic sandstone in the Dakota in the subsurface of southwestern Russell County, Kansas (Swineford and Williams, 1945). These gross regional relationships are in accord with an overall transport direction near S65^{o}W calculated from cross-strata dip bearings (Fig. 25). The depositional slope was inclined in about the same direction.

Lignitic beds near the base and top of the Dakota Formation and local abundance of leaf fossils might be suggestive of a terrestrial environment of deposition. The leaf fossils, however, are found mainly in fine-grained sandstone and are not associated with fossilized logs, stumps, or roots. The general lack of fossilized wood in the Dakota Formation may mean that the environment not only was unfavorable for preservation of wood but perhaps also that it was inhospitable to growth of trees.

Most fossil leaves in the Dakota Formation seem to have been transported to their present sites of preservation by water from uplands lying to the east and northeast. The ankylosaur found in the Dakota Formation in Ottawa County, Kansas (Eaton, 1960), and the parts of a trachodon found in Burt County, Nebraska (Barbour, 1931), are stronger evidence of a terrestrial environment.

The dominantly kaolinitic character of the Dakota Formation can be interpreted as evidence of terrestrial or nearshore sedimentation. According to Weaver (1958a, p. 258) "...kaolinite is dominant mainly in fluviatile environments..." although it may occur in abundance in nearshore sediments (p. 259). The abundance of kaolinite and dearth of illite and montmorillonite in most Dakota rocks contrasts sharply with the general abundance of illite in the Kiowa and with the general abundance of montmorillonite in the Graneros. Occurrence of recumbent and contorted tabular-planar cross-stratification in Terra Cotta sandstone (Fig. 41) also indicates fluviatile sedimentation.

Some of the uppermost parts of the Dakota Formation, however, were deposited in a brackish-water or nearshore marine environment, as is indicated by the fossils described by Hattin (1965a, 1965b).

Gradation of both the Kiowa and Dakota formations into a dominantly marine sequence in northwestern Kansas combined with local evidence of slumping along the contact in north-central Kansas perhaps indicates relatively rapid withdrawal of the Kiowa sea prior to the start of Dakota sedimentation in north-central Kansas. Truncation of sandstone lenses of the Kiowa Formation and evidence of the truncation of the siltstone bed marking the top of the Longford Member of the Kiowa Formation along the Clay-Washington county line in north-central Kansas suggest a disconformable contact between the two formations, as does the localized concentration of iron oxide along the contact in parts of north-central Kansas (Measured Sections 5, 6, 8, and 11, Appendix and Plate 4). The relationships of the clay mineralogy of the basal parts of the Dakota Formation to the mineralogy of the underlying Kiowa and Permian rocks may be further evidence for erosion and reworking of the underlying sediments during the early stages of Dakota sedimentation. Throughout a large part of the continental interior, including the type area of the Kiowa Formation in southweatern Kansas, similar conditions seem to have prevailed upon withdrawal of the Early Cretaceous sea (cf. Baker, 1962; Gries, 1962).

The concept of a disconformable contact between the Kiowa and Dakota formations is not without drawbacks. Local evidence of continuation of Kiowa-like sand sedimentation into the depositional realm of the Dakota Formation suggests that any disconformity separating the two formations may have been only partially developed. The extent to which disconformable relationships persist into the dominantly marine section in the subsurface of western Kansas remains problematic.

Following or during the rapid withdrawal of the Kiowa sea, the drainage systems of the stable interior extended themselves southwestward over the previously deposited Kiowa sediments. Locally drainage courses were controlled by structural movement, as along the Lindsborg Anticline, and followed more southerly and even southeasterly directions of flow. Other streams may have been controlled partly or influenced by gentle topography established by the distribution of thick lenticular deposits of sandstone within the Kiowa Formation. Rivers and streams flowed down a relatively steep gradient and deposited relatively coarse clastics including penecontemporaneously reworked mud and clay along their channels. The streams formed an alluviating system in which many of the small streams followed relatively straight reaches but larger rivers tended to meander or otherwise change course. Mud, clay, silt, and fine-grained thin-laminated sand, some of which shows micro-cross-stratification, accumulated on the flanks and interfluves of the streams.

Initial Dakota sediments included the gray and carbonaceous mudstone, claystone, and shaly rocks of the Andrews section, which are intercalated with red-mottled mudstone and claystone more characteristic of the Terra Cotta Clay Member. The gray rocks and sparse lignitic beds of the Andrews section seem to have been deposited in a more strongly reducing and more poorly drained environment than was the bulk of the Terra Cotta. The abundance of organic matter associated with Andrews sediments probably permitted developemnt of shaly parting and thin lamination by favoring particle-by-particle settling of the clay.

As deposition continued, an alluvial plain became established and large amounts of clayey sediment accumulated on the interfluves and on the flanks of stream channels. Plexoidal and domain fabrics in red-mottled Terra Cotta mudstone and claystone point to sedimentation by flocculation. Flocculation is attributed to deposition in a fresh-water environment in which edge-to-face attractions of clay particles were effective (Meade, 1964). Spherulitic siderite in red-mottled mudstone and claystone shows that mildly reducing conditions prevailed within the sediment. The mottles are judged to be relict from an initially red sediment that, once deposited, underwent only partial reduction. Penecontemporaneous reworking of red-mottled mudstone and claystone into clay-pebble conglomerates indicates that reduction took place early during diagenesis. Presence of _b_-axis disordered kaolinite within both the gray and red parts of red-mottled mudstone and claystone is taken as evidence that kaolinite was not generated in situ but was supplied from highly weathered source areas to the east and northeast. The near sameness of chemical composition of Kiowa and Dakota argillaceous rocks (Table 2), alkali and alkaline-earth oxides excepted, indicates that strong leaching and argillation did not take place during or after deposition of the red-mottled Terra Cotta claystone and mudstone.

As the Graneros sea transgressed from the western seaway eastward toward the continental interior, the shoreline migrated toward north-central Kansas (Hattin, 1959b), and the Janssen Clay Member of the Dakota Formation was deposited. Gradually, the slope of the depositional surface in north-central Kansas was lessened, partly owing to alluviation, but in part concomittantly with transgression of the sea. In north-central Kansas, deposition of the dominantly gray to dark-gray and carbonaceous sediments of the Janssen was initiated and increasingly smaller amounts of red-mottled mudstone and claystone accumulated. The fine grain size of Janssen sandstone compared to the Terra Cotta Clay Member indicates either a decreasing abundance of coarse material or a decline in the transporting ability of the streams that supplied the sand. Greater divergence in the direction of flow of rivers and streams ensued, as is indicated by both increased spread of vector resultants and increased dispersion of individual cross-strata dip bearings about their respective vector resultants (Tables 1 and 7).

During deposition of the Janssen Clay Member, the northern parts of Russell County, and perhaps other areas, became the site of concentrated deposition of fine-grained sandstone. With continued advance of the Graneros sea, a complex transitional zone developed in that area. The deltaic complex involved deposition of sand not only along rivers, but also perhaps in various marginal environments. Marine and brackish-water pelecypods in sandstone and foraminifers in associated argillaceous rocks (Hattin, 1965a, 1965b) indicate that some of the sand was deposited under nearshore marine conditions. Northwesterly and southeasterly trends of cross-stratification may spell the formation of offshore bars and low-angle wedge-planar cross-strata suggest that beach or related deposits were built. Unequivocable evidence of either beaches or bars is wanting, however. Doubtless, the transgressing sea reworked and destroyed many of the shoreline deposits.

Lignitic beds and highly carbonaceous silts and clays are thought to have been deposited in either estuarine or lagoonal environments associated with the deltaic sandstone complex in Russell County. The dominantly reducing nature of the environment is indicated not only by the abundance of carbonaceous debris, but also by accompanying spherulitic siderite in sandstone, mudstone, and claystone, as well as by iron sulfide in the carbonaceous deposits. Intercalation of beds and lenses of red-mottled mudstone and claystone with the gray argillaceous rocks of the Janssen indicates that Janssen sediments also were initially red and that they underwent early diagenetic reduction. The low concentrations of iron oxide in most Janssen mudstone and claystone (Table 9) indicate that much of the iron oxide originally present as ferric oxide coatings on clay particles was reduced and taken into solution. Some of the iron was concentrated during diagenesis to form concretionary beds of siderite within shaly sequences near the top of the Janssen, but much of the iron oxide may have been transported to the Graneros sea after dissolution. Early diagenetic processes probably generated the sparse concretions and concretionary beds showing cone-in-cone structure in the Janssen.

The prominent ledge-forming siltstone showing molds of reeds close to the top of the Janssen Clay Member was deposited in areas where little sandstone accumulated. It may have formed in tidal marshes that fringed swamps in which lignite accumulated. Not until the advancing sea transgressed over the region was deposition of kaolinite overwhelmed by deposition of the montmorillonite that is so characteristic of the Graneros.

The deciduous leaf fossils of the Dakota Formation indicate a mild climate, locally perhaps verging on the subtropical (Lesquereux, 1892, p. 256), similar to that postulated for the Kiowa. The climatic conditions indicated by the leaves seem to be in accord with conditions under which clay particles coated with red colloidal iron oxide would have been transported to the realm of Dakota sedimentation in north-central Kansas.

Source areas and mineral distributions

The heavy mineral suite of the Terra Cotta Clay Member of the Dakota Formation basically is similar to the heavy mineral suite of the Kiowa Formation (Table 3). Greater differences are apparent in the heavy mineral suite of the Janssen Clay Member of the Dakota. All three heavy mineral assemblages indicate that the dominant source area was an older sedimentary terrain, but as seems true for the Kiowa Formation, much of the staurolite in the heavy mineral suites is thought to have been derived from the central Appalachians. The changes in the Dakota heavy minerals, which show as decreased proportions of staurolite and increased proportions of zircon, would mean that inferred source areas in the central Appalachian Mountains became less important as time progressed: the source of sediment increasingly became the weathered Paleozoic or older rocks of the interior regions of North America.

Decrease in amount of sediment supplied from the central Appalachian Mountains could have been brought about by several factors. According to Groot (1955) the heavy mineral assemblages of Upper Cretaceous rocks of the Atlantic Coastal Plain of Deleware indicate increasing headward extention of east-flowing drainage systems so that eventually sediment was partly derived from the Folded Appalachians. Thus, areas that formerly supplied sediment to the interior regions of North America would have been captured. Decreased stream gradients related to the advance of the Graneros sea also may have reduced the prominence of the central Appalachians as sources of sediment for the Dakota Formation. Increasing sedimentation along the Gulf Coast and in the Mississippi Embayment may have siphoned off sediment originally destined for the Dakota Formation.

The kaolinite of the Dakota Formation probably was derived from highly weathered Paleozoic and perhaps also Precambrian rocks of the craton. Appreciable thicknesses of kaolinitic mantle overlie Precambrian rocks and underlie basal Cretaceous rocks in Minnesota (Grout, 1919; Goldich, 1938; Schwartz and Thiel, 1963). The basal Cretaceous Baylis Formation of western Illinois overlies mildly weathered Pennsylvanian sedimentary rock and contains appreciable kaolinite. According to Frye, Willman, and Glass (1964) kaolinite, montmorillonite, and mixed-layer clay in the Baylis Formation were derived from weathered source rocks to the east and north of western Illinois, but they also suggested that some of the montmorillonite may have been an alteration product of volcanic ash. The basal Cretaceous Windrow Formation of Wisconsin, Minnesota, and Iowa also overlies intensely weathered Paleozoic rock, some of which has been incorporated in the Windrow Formation (Andrews, 1958). Intense weathering of the Paleozoic and older rocks during the long interval of erosion and nondeposition represented by the unconformity separating Permian and Cretaceous rocks in Kansas seems to have been the ultimate source of most of the kaolinite in the Dakota Formation. Local reworking of Permian rocks accounts for the presence of vermiculitic and chloritic clay in the basal parts of the Dakota Formation in Washington County, Kansas. Similar reworking of Kiowa sediment may account for the relative abundance of illite in the basal parts of the Dakota Formation elsewhere in north-central Kansas and in the vicinity of type Kiowa in southwestern Kansas.

Beds and laminae of procelaneous well crystallized kaolinite in the Dakota Fromation that contrast sharply with the b-axis disordered kaolinite of the enclosing rocks are thought to be the product of alteration of volcanic ash derived from source areas in the Nevadan orogenic belt, most likely from volcanic centers in western Montana. The clay fraction of the Graneros Shale is dominantly montmorillonitic (Hattin, 1965b; Plummer and Romary, 1942), and Weaver (1958b, p. 168-169) pointed out that volcanic material generally has been accepted as the source of much of the montmorillonite in Cretaceous marine formations in the Western Interior. The Graneros also contains numerous seams of bentonite and one persistent bed that Hattin (1965b, p. 33-38) considered to be products of alteration of volcanic ejecta from sources in the Nevadan orogenic belt of Idaho. Slaughter and Early (1965) and Knechtel and Patterson (1962) suggested source areas in eastern Idaho or western Montana for Cretaceous bentonite in eastern Wyoming and the Black Hills area, although Gilluly (1965, Fig. 5, p. 15) indicated volcanic activity occurred only in northern Washington, northeastern Nevada, and western Montana during the Cretaceous.

Variations in clay mineralogy in the marginal sediments of the Janssen Clay Member of the Dakota Formation and of the Graneros Shale may be explained best in terms of differential transport and sedimentation, differences in source areas, and in terms of flooding and dilution. The abundance of kaolinite in the Janssen where the argillaceous rocks are closely associated with sandstone containing marine and brackish-water fossils is not so readily explained by subaerial leaching or weathering as by a flood of kaolinite being contributed to and deposited in saline or brackish-water environments by Dakota streams. Similarly, the variations in the lower parts of the Graneros Shale, where some samples contain nearly as much kaolinite as underlying and facies equivalent Dakota rocks (Plate 8), are readily explained in terms of sources and conditions of sedimentation.

If the bulk of the montmorillonite in shale belonging to the Graneros was derived from alteration of ejecta supplied by volcanic activity in the Western Interior, most likely western Montana, widespread distribution of the montmorillonite could have been accomplished in part by currents in the transgressing Late Cretaceous sea. Hjulström (1939) has shown that clay-sized quartz spheres can be suspended and transported almost indefinitely by currents having velocities less than 0.1 cm/sec. Clay mineral particles, particularly fine-grained montmorillonite, may be suspended even more easily owing to their flaky habit and tendency to form open coacervates. Whitehouse and others (1960) also have shown that montmorillonite settles much more slowly than other clay minerals over a considerable chlorosity range. Hence, variations in proportions of montmorillonite and kaolinite in the facies equivalent upper parts of the Dakota and lower parts of the Graneros can be interpreted in terms of local and unsystematic flooding by kaolinite derived from easterly sources and supplied by Dakota streams.

The appearance of appreciable amounts of illite in Janssen rocks close to the Dakota-Graneros contact is analogous to changes in mineralogy between Kiowa shale and the kaolinitic and montmorillonitic mudstone and claystone of the Longford Member of the Kiowa Formation. It too can be understood in terms of the work by Griffin (1962) and by Whitehouse and others (1960). Whereas the bulk of the kaolinite in the Dakota Formation was flocculated in a fresh-water alluvial plain environment, illitic clays were differentially bypassed and sedimented under more saline conditions than those that prevailed for the larger part of the formation. The same model can be extended to account for the local abundance of illite in the more kaolinitic basal phases of the Graneros Shale. The model also applies to explanation of the illitic and chloritic or vermiculitic character of the dominantly marine subsurface extensions of the Dakota in northwestern Kansas (Franks and Plummer, in Merriam and others, 1959).

The differential transport and sedimentation model, however, lacks strength in evaluating the appearance of chloritic and vermiculitic components in the upper parts of the Janssen Clay Member of Ellsworth and Russell counties, but not in associated Graneros sediments. Similar distribution of chlorite and vermiculite is found in the subsurface of northwestern Kansas: the subsurface extensions of the Dakota contain chlorite and vermiculite but not the overlying Graneros shale, part of which probably was deposited while Janssen sediments accumulated farther east. Chloritic and vermiculitic clays seem to have been by-passed during deposition of the bulk of the Dakota Formation in north-central Kansas and deposited with the dominantly marine extensions of the Dakota in the subsurface, but little or no chlorite or vermiculite was transported to the transgressing Graneros sea. The chloritic or vermiculitic clay mineral assemblage of the upper part of the Janssen in north-central Kansas seems to be associated with marginal sediments that may extend into the subsurface as a distinct marginal marine or nearshore facies. It seems unlikely that the environment was saline enough for diagenetic formation of either illite or chlorite inasmuch as volcanic ash seems to have altered under conditions entailing low concentrations of cations to form seams of porcelaneous kaolinite in both the Janssen and the overlying facies equivalent Graneros shale. Some special combination of environmental factors must have acted to bring about deposition of sparsely chloritic or vermiculitic clay mineral assemblages in uppermost Janssen rocks in Ellsworth and Russell counties. Weaver (1958b, p. 163) has suggested "...that chlorite may be more abundant in clays deposited in brackish and freshwater environment than in those deposited under open marine conditions...," although Griffin (1962) found that chloritic clays occur far off shore in northeastern Gulf of Mexico.

Summary

Proximity to marine sediments in the subsurface of northwestern Kansas and to one or more zones of glauconitic Dakota sandstone in the subsurface of southwestern Russell County indicates that the Dakota Formation of north-central Kansas was deposited near the margins of a shallow inland sea. Local evidence of erosion of the topmost regressive deposits of the Kiowa Formation combined with the abrupt change in lithology in most places along the Kiowa-Dakota contact suggests that the Dakota Formation was deposited disconformably on the Kiowa Formation upon relatively rapid withdrawal of the Kiowa sea from north-central Kansas. Locally, however, deposition of sand in some marginal or nearshore environments may have persisted contemporaneously with terrestrial deposition of the basal parts of the Dakota Formation.

Contemporaneous with or not long after retreat of the Kiowa sea, streams extended themselves westward and southwestward to deposit sandstone and conglomeratic sandstone at or near the base of the Dakota Formation. The coarseness of some sandstone in the lower part of the Terra Cotta Clay Member may be indicative of relatively steep gradients and perhaps also of relatively rapid though limited uplift of the source areas. Low areas between and bordering streams received the dominantly argillaceous sediments that make up the bulk of the Dakota Formation. Local swampy areas allowed accumulation of vegetative debris that eventually was converted to lignite in the Andrews section at the base of the Terra Cotta Clay Member. Volcanic activity, perhaps in western Montana, may have led to deposition of volcanic ash that locally was reworked and altered to porcelaneous seams composed almost completely of well-crystallized kaolinite in basal Dakota mudstone and claystone.

An alluvial plain environment seemingly became established with deposition of the sandstone and red-mottled mudstone and claystone of the Terra Cotta Clay Member. Kaolinitic mudstone and claystone were flocculated on the flanks of and in the interfluves of streams. Locally beds of kaolinitic siltstone were deposited. Some sedimentation may have taken place in lakes and ponds, but swampy conditions did not prevail. The environment within the sediments was reducing enough to be favorable for colloidal precipitation of spherulitic siderite during early diagenesis. But the intensity of reduction was not enough to destroy completely the red coloration of the kaolinite-rich sediment that originated in the highly weathered source areas. Red mottles have persisted in the rocks since Dakota time. The sediments of the alluvial plain may have been relatively well drained, but leaching probably was not important.

Dip bearings of cross-stratification indicate that the streams that deposited the sediments of the Terra Cotta Clay flowed in the general direction of S65°W, but the streams showed considerable local diversity in trend. Vector-resultant dip bearings with southerly trends calculated for sandstone in some areas at the base of the Dakota may stem from structural or topographic control of directions of stream flow. Upward increase in dispersion of both vector resultants and individual cross-strata dip bearings about the vector resultants in the Dakota Formation probably was caused by decreased stream gradients and consequent greater tendency to meander. Northwesterly and southerly to southeasterly vector resultants calculated for sandstone deposits in the upper parts of the Janssen Clay Member perhaps are due to the action of longshore currents operating in a marginal marine environment indicated by occurrence of brackish-water and marine pelecypods and foraminifers in the upper parts of the Janssen.

The advance of the Graneros sea across Kansas coincided with a decrease in the slope of the depositional surface and a decrease in the size of sand deposited in the Janssen Clay Member of the Dakota Formation. Kaolinite, however, continued to be the main clay mineral supplied from the source areas to the east and northeast. The abundance of iron oxide that seems to mark an approximate contact between the Janssen Clay and Terra Cotta Clay members may indicate the onset of stagnant conditions favorable to accumulation of colloidal iron oxides, siderite, or iron oxide-organic complexes. As the Graneros sea advanced, the proportions of red-mottled clay preserved in the sediments decreased and deposition of argillaceous rocks containing carbonaceous material and diagenetic pyrite or marcasite predominated. Sporadic ash falls probably account for the seams of porcelaneous kaolinite in the Janssen Clay Member.

Beds of plant debris accumulated in swamps near the margins of the Graneros sea. Eventually they were converted to lignite. Some of the lignitic material may have been deposited in localized lagoons and estuaries, and some in swamps. Deltaic deposits locally extended into the encroaching sea and spits and offshore bars probably were formed. The advancing Graneros sea, however, probably destroyed most strand line deposits. Siltstone beds with imprints of nearly vertical reeds may be all that remains of deposition in tidal marshes on the shoreward side of the advancing sea. Locally, fingers or small deltaic complexes of sand perhaps extended out into the sea, and the penecontemporaneously reworded sand may have been the home for brackish-water and marine pelecypods found in the topmost part of the Dakota Formation. Or the sand may have accumulated in brackish-water estauries, embayments, or lagoons that were from time to time hospitable to the more hardy forms of Late Cretaceous pelecypods and gastropods. Under the influence of the marine transgression, terrestrial sedimentation finally was superseded by deposition of the Graneros Shale, and montmorillonite rather than kaolinite became the dominant constituent of detrital deposits.

Cross-stratification studies, the composition of heavy mineral suites, and the clay mineralogy indicate that the dominant source area for the Dakota Formation lay to the east and northeast and comprised chiefly highly weathered sedimentary rock. Staurolite in the heavy mineral suites may have been contributed from the central Appalachians, but the importance of this source disminished in time, for sandstone in the Janssen contains appreciably less staurolite than sandstone in either the Kiowa Formation or the Terra Cotta Clay Member of the Dakota. Lateral variations in clay mineralogy in the Janssen Clay Member and in the basal parts of the Graneros

Shale seem to reflect differential transport and sedimentation that permitted local accumulation of somewhat illitic, chloritic, or vermiculitic clays in the upper parts of the member. Abundant kaolinite entering the nearshore realms of the Graneros sea flooded the normally montmorillonitic Graneros sediment to produce shale relatively enriched in kaolinite in some areas.

The environment was either unfavorable to the growth of trees or unfavorable to the preservation of stumps and logs. Fossil leaves found in sandstone probably were transported into the depositional realm of the Dakota Formation. Imprints of oak, willow, walnut, sycamore, magnolia, laurel, and sassafras leaves, among others, indicate that the climate in uplands to the east and northeast was mild. Cycads and figs may have grown at lower elevations and indicate that the climate verged on subtropical (Lesquereux, 1892, p. 256). Few remains of land-dwelling dinosaurs have been found in the Dakota Formation.

CONCLUSIONS

1. The unconformity separating Permian rocks from the overlying basal Cretaceous Kiowa and Dakota formations in north-central Kansas is part of a mature erosion surface. Compressed weathering profiles preserved along the unconformity show upward gradation from illitic and chloritic or vermiculitic Permian rocks through zones enriched in montmorillonite into uppermost parts enriched in kaolinite. Locally, metahalloysite is found in the kaolinitic parts of the profiles. The compressed character of the soil profiles and generation of kaolinite and halloysite in their upper parts suggests that the terrain was water logged and that the climate was warm and humid. Climatic conditions during development of the soil profiles were similar to those that prevailed during deposition of the Kiowa and Dakota formations.

The pebbles of chert, "vein" quartz, and quartzite in the basal parts of the Kiowa and Dakota formations are thought to have been reworked from an originally widespread mantle of gravel that blanketed the Permian rocks. The pebbles were derived from the east and northeast.

Occurrence of the pebbles in Cretaceous rocks overlying or on the flanks of topographic highs on the Permian surface and preservation of the ancient soil profiles on the topographic highs suggests that a period of erosion preceded or was partly contemporaneous with deposition of the basal Cretaceous beds.

2. The Kiowa Formation and the overlying Dakota Formation are lithologically distinct mappable units separated throughout much of north-central Kansas by a sharp contact dividing contrasting assemblages of argillaceous and arenaceous rocks. The contact is disconformable at least locally as is shown by truncation of beds in the Kiowa Formation in Ottawa County and

near the Clay-Washington county line where the Kiowa Formation pinches out. Disconformable contacts also show in areas where basal Dakota conglomeratic sandstone rests directly on the Kiowa Formation. Areal extent of the disconformity (or disconformities), particularly into the subsurface, remains to be demonstrated.

In much of north-central Kansas, the contact is placed at the base of mudstone or claystone that is either gray with red mottles or contains lenses of red-mottled mudstone or claystone. Elsewhere it is placed at the base of medium- to coarse-grained sandstone that commonly contains clay pebbles and granules of quartz, quartzite, and chert. In many places the top of the Kiowa Formation is marked by fine-grained sandstone that grades downward into gray Kiowa shale or into carbonaceous beds that pass downward into gray Kiowa shale. In places, sandstone at the top of the Kiowa Formation grades laterally into thick lenticular deposits of sandstone. The contact is useful for delineation of surface structure and also marks a distinct change in lithogenesis.

A contact corresponding to the contact between the Kiowa and Dakota formations in north-central Kansas is recognizable in the vicinity of the type area of the Kiowa Formation in Kiowa County, Kansas. Recognition of this contact eliminates evidence of vertical and lateral gradation between the two formations in the type area of the Kiowa Formation.

No evidence was found for large-scale or wholesale intertonguing of the Kiowa and Dakota formations. Gradational contacts between the two formations are restricted to small areas. The extent to which gradation is real or the product of reworking of Kiowa sandstone by depositional agencies of the Dakota Formation is problematic. If lateral gradation or intertonguing of Kiowa and Dakota rocks does occur, gradation is restricted to a narrow zone along the contact that could not be detected in mapping.

3. The Longford Member (new name) of the Kiowa Formation is a distinctive unit at the base and eastern fringes of the formation. It contains terrestrial and nearshore facies equivalents of the shallow neritic and littoral deposits of the Kiowa Formation. The member is capped by a distinctive siltstone.

4. The Kiowa Formation, including its Longford Member, pinches out near the Clay County-Washington County line in north-central Kansas and does not crop out in eastern Nebraska or at the type area of the Dakota in northeastern Nebraska.

5. The upper part of the Janssen Clay Member of the Dakota Formation is laterally and vertically transitional with the overlying Graneros Shale, but a mappable contact can be selected in the field. In many places, the contact is within a few feet of a distinctive siltstone in the upper part of the Janssen Clay Member. Where the siltstone bed is absent, the contact is chosen on the basis of characteristic lithologies (e.g., carbonaceous mudstone and lignite in the Dakota vs. gray montmorillonitic shale in the Graneros). As is the Kiowa-Dakota contact, the Dakota-Graneros contact is useful for surface mapping of structural features.

6. The Terra Cotta Clay and Janssen Clay members of the Dakota Formation extend across north-central Kansas to the Kansas-Nebraska boundary, whence lithologic equivalents extend northward to the type area of the Dakota. The Dakota Group of Nebraska and the Dakota Formation of Kansas span essentially the same lithostratigraphic interval. The Janssen Clay Member in Kansas is the approximate lithogenetic equivalent of the Omadi Formation of Nebraska. The Terra Cotta Clay Member is the approximate lithogenetic equivalent of rocks classed as "Skull Creek and Fall River equivalents" on the outcrop in eastern Nebraska. Inasmuch as the Dakota Formation is the mapping unit in Kansas, retention of the name is justi-

fied and expansion of the name to encompass the Cheyenne and Kiowa formations is unwarranted. Elevation of the members of the Dakota Formation in Kansas to formational units would be impractical. Review of the nomenclatural history of the Kiowa and Dakota formations indicates that the practice of restricting the name "Dakota" is nearly as old as the name itself.

7. The age of the Kiowa Formation is Early Cretaceous (Twenhofel, 1924; Loeblich and Tappan, 1950). The age of the Dakota Formation is less certain, but recent paleontological evidence shows that the upper parts of the Dakota are of Late Cretaceous age (Eicher, 1965; Hattin, 1965a). The position of the Upper Cretaceous-Lower Cretaceous boundary is problematic but the boundary probably lies within the Dakota Formation, which unit is referred therefore to the Lower (?) and Upper Cretaceous. Restudy of the fossil flora of the Kiowa and Dakota formations might clarify the problem provided that sufficient attention were paid to the stratigraphic distribution of the species.

8. The Kiowa and Dakota formations are heterogeneous units composed of argillaceous rocks, siltstone, and sandstone. The Dakota Formation, particularly the Terra Cotta Clay Member, is characterized by abundant gray mudstone and claystone showing red mottles. The Kiowa Formation is characterized by olive-weathering gray shale containing discoidal concretions of impure siderite and beds and concretions of calcareous cone-in-cone structure. Dakota mudstone and claystone are composed mainly of b-axis disordered kaolinite, whereas Kiowa shale is composed largely of illite that is partly weathered to montmorillonite in most exposures. The Longford Member of the Kiowa Formation also contains red-mottled mudstone, but much of it is highly montmorillonitic. Where the Dakota rests on the Longford Member of the Kiowa Formation in Clay and Washington counties,

Kansas, the two formations can be separated by recognition of the distinctive siltstone that caps the Longford Member.

9. Numerous fossils testify to the generally marine or brackish-water nature of Kiowa sedimentation. Fossils indicate that the uppermost parts of the Janssen Clay Member of the Dakota Formation also were deposited locally in a nearshore brackish-water environment. One ankylosaur found in Kansas (Eaton, 1960) indicates terrestrial sedimentation for the Terra Cotta Clay Member of the Dakota Formation. That evidence is augmented by recumbent or overturned tabular-planar cross-stratification that is thought to be indicative of fluviatile sedimentation. The generally kaolinitic character of the Dakota and of parts of the Longford Member of the Kiowa Formation also can be interpreted as indicating fluviatile sedimentation.

The Kiowa Formation is thought to have been deposited in a shallow shelf sea in which waves and currents disturbed the bottom, the Longford Member near and on the landward side of that sea, and the Dakota Formation on an alluvial plain that developed on relatively rapid retreat of the Kiowa sea. The alluvial plain environment of the Dakota Formation persisted until the transgressive Graneros sea advanced across north-central Kansas during Late Cretaceous time. The invasion of the Graneros sea established littoral or marginal marine environments for the upper parts of the Janssen Clay Member of the Dakota Formation, and in time submerged them.

10. Measurement of cross-strata dip bearings and calculation of vector resultants shows that the depositional slope was inclined about S65°W during deposition of the Kiowa and Dakota formations. However, modality of cross-stratification must be taken into account, particularly in the Kiowa Formation where a strong southerly to southeasterly mode can be

attributed to operation of longshore currents. Similar modes in the Janssen Clay Member of the Dakota Formation also may reflect longshore currents, but the evidence is not as conclusive as it is for the Kiowa Formation where sedimentary structures allow recognition of littoral or beach deposits. A southerly to southeasterly mode in cross-strata vector resultants in the Terra Cotta Clay Member of the Dakota Formation may be partly controlled by the distribution of thick lenticular deposits of sandstone in the upper part of the Kiowa Formation and partly by uplift along north-trending anticlines at about the time the basal beds of the Dakota were being deposited.

A southwesterly inclination of the paleoslope during deposition of the Kiowa Formation is in accord with the distribution of rock types within the Longford Member and in accord with grain size variations within the formation. Grain size of Kiowa sandstone increases irregularly to the east and northeast. Transport of sediment supplied to the Kiowa and Dakota formations chiefly was from the east and northeast.

11. Studies of heavy minerals in sandstone show basic similarity in the suites in both the Kiowa and Dakota formations. In conjunction with studies of cross-stratification, they indicate derivation of Kiowa and Dakota sediments from weathered Paleozoic and older rocks lying to the east and northeast of the outcrop belt in north-central Kansas. The major source of the heavy minerals was older sedimentary rock. The maturity of Kiowa and Dakota sandstone also is in accord with such a source. Staurolite in the heavy mineral suite probably was derived from the central Appalachian Mountains. Decrease in abundance of staurolite in the Janssen Clay Member of the Dakota Formation indicates decreasing importance of Appalachian sources later in the depositional sequence. Mass properties of grain size distributions of Kiowa and Dakota sandstone show considerable overlap and

probably reflect similarities of their provenance.

12. Differences in clay mineralogy between the Longford Member and the bulk of the Kiowa Formation and between the Kiowa Formation and its subsurface equivalents in northwestern Kansas are attributed to differential transport and sedimentation. Kaolinite and montmorillonite, together with chloritic and vermiculitic components reworked from underlying Permian rocks, were flocculated in fresh-water or marginal marine environments to form the Longford Member. Illite and some chlorite and vermiculite were bypassed so that the marine to brackish-water Kiowa Formation is dominantly illitic and its subsurface equivalents contain appreciable amounts of chlorite and vermiculite. The same model serves to explain differences in mineralogy between the dominantly kaolinitic Dakota Formation and its illitic and chloritic or vermiculitic subsurface equivalents. The abundance of montmorillonite in the Graneros Shale stems from volcanic activity in western Montana or eastern Idaho. Local high content of kaolinite near the Dakota-Graneros contact is due to flooding of montmorillonite by kaolinite derived from Dakota streams.

The sedimentary differentiation model does not adequately explain the localized occurrence of vermiculitic and chloritic clay in the uppermost parts of the Janssen in parts of Ellsworth and Russell counties, but other explanations are equally weak. The presence of vermiculitic or chloritic components in the Janssen can be viewed as part of a general facies that extends into the subsurface to encompass the subsurface equivalents of the Dakota Formation, which are, like parts of the Janssen Member, of brackish water to marine origin. Alteration of volcanic ash is thought to account for thin layers of nearly white well-crystallized kaolinite near the base and near the top of the Dakota Formation. Similar seams within the lower part of the overlying Graneros Shale probably have a similar origin, namely alteration under conditions of relatively low pH without abundant divalent cations in solution to permit formation of montmorillonite.

13. Variations in clay mineralogy near the base of the Terra Cotta Clay Member of the Dakota Formation in north-central Kansas are attributed to reworking of underlying rocks during deposition of the Dakota. Where the Dakota Formation rests directly on Permian rocks, its basal phases contain detectable amounts of vermiculitic and chloritic clay. Where the Dakota rests on the Kiowa Formation, its basal phases contain appreciable amounts of illite, but no detectable vermiculitic or chloritic clay. These variations are taken as supporting evidence for disconformable separation of the Kiowa and Dakota formations in north-central Kansas.

14. Ample evidence of reduction within the sediments that now make up the Kiowa Formation and local persistence of red coloration indicate that the clayey sediment supplied to the Kiowa sea initially was red. Siderite spherules, sparse pyrite or marcasite, and trace amounts of carbonaceous matter in the interareas between red mottles in Dakota claystone and mudstone is evidence that the muddy sediment supplied to the Dakota Formation also was red. Similar reasoning also applies to red mottles in the Longford Member of the Kiowa Formation. It is inferred that the source areas for the muddy sediments were intensely weathered or that the parent rocks themselves were red. The fossil leaves in both the Kiowa and Dakota formations indicate that a warm humid climate prevailed to the east and northeast of north-central Kansas. The source areas probably were intensely weathered and may have been mantled partly by lateritic soils. Evidence of intense leaching or of penecontemporaneous lateritic weathering to account for <u>in situ</u> generation of <u>b</u>-axis disordered kaolinite in the

Dakota Formation is lacking.

15. Discoidal ironstone concretions and calcareous cone-in-cone structure in the Kiowa Formation and in the Janssen Clay Member of the Dakota Formation are thought to be products of early diagenesis, as are siderite spherules in Dakota mudstone and claystone. Development of cone-in-cone structure in calcite-cemented sandstone in the Kiowa Formation indicates that introduction of calcite cement into sandstone also took place during early diagenesis.

SUGGESTIONS FOR FURTHER STUDY

Several lines of research offer opportunity for additional work on the Kiowa and Dakota formations and associated stratigraphic units. The topics suggested below should provide additional insight into the conditions under which the rocks were formed.

1. Detailed study of the fossil flora and palynology of the Kiowa and Dakota formations in order to aid in determining more precisely the stratigraphic position of the Upper Cretaceous-Lower Cretaceous boundary.

2. Stratigraphic and petrologic study of the subsurface equivalents of the Kiowa and Dakota formations in western Kansas with particular emphasis on facies relations with the surface section.

3. Stratigraphy and petrology of the Cheyenne Sandstone and the Kiowa Formation of southwestern Kansas and subsurface work to determine the extent to which the Cheyenne has rock-stratigraphic and genetic equivalents in the subsurface of western Kansas and beyond.

4. Geochemical study of trace elements and of the distribution and oxidation states of iron in the Kiowa and Dakota formations to provide additional insight into the environments of sedimentation.

5. The organic geochemistry of the Kiowa and Dakota formations and its bearing on the distribution of iron in the argillaceous rocks.

6. Investigation of the distribution of and factors controlling the distribution of chlorite and vermiculite in the Janssen Clay Member of the Dakota Formation and in the subsurface equivalents of the Kiowa and Dakota formations.

7. Detailed mineralogic and geochemical study of the weathering profiles developed in Permian rocks along the Permian-Cretaceous unconformity.

8. The provenance of staurolite in the heavy mineral suites of the Cretaceous rocks of the Midcontinent and Western Interior.

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