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CEMENTED SANDSTONES OF THE DAKOTA AND KIOWA FORMATIONS IN KANSAS

By

ADA SWINEFORD

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ABSTRACT

Cemented sandstones in the Kiowa and Dakota formations in central Kansas have been quarried in considerable quantities for use of concrete aggregate, riprap, road metal, and building stone. This report presents the results of a study of calcite-, dolomitic calcite- and silica-cemented sandstones in Clay, Dickinson, Ellsworth, Kearny, Lincoln, McPherson, Ottawa, Rice, and Saline Counties, Kansas. These rocks are generally more durable than the other rocks of the region and, together with the more abundant iron oxide cemented sandstones, serve as cap rock of hills and form ledges along valley sides. At several places clusters of large carbonate-cemented concretions have been exposed at the surface by erosion, giving rise to spectacular features, such as "Rock City" near Minneapolis.

Thin sections of samples of indurated sandstones from 31 localities were studied; the results of physical tests and chemical analyses were furnished by the Corps of Engineers, War Department; and both chemical and mechanical analyses of the sand freed of cement were made in the laboratories of the State Geological Survey. The three major types of cement, their sequence and time of introduction, and minor constituents including barite, pyrite, and asphaltic material, are described. An analysis of the petrographic, chemical, and physical test data indicates that the carbonate-cemented sandstones described are good quality rocks, superior to other north-central Kansas rocks, for use as concrete aggregate, riprap, and some other purposes.

INTRODUCTION

Purpose of the study.—The increasing demand for suitable material for riprap, railroad ballast, road material, and concrete aggregate in Kansas has led to the present study of cemented sandstones in the Dakota formation and Kiowa shale of the State. In central and western Kansas, where surface deposits consist chiefly of clays, shales, chalk, silt, soft limestone, and friable sandstone of Permian to Recent age, hard durable rock is needed for construction, including the completion of Federal projects. Excellent construction material is known to occur in the Dakota formation of north-central Kansas, but it is distributed in isolated, lenticular deposits scattered throughout the area. The purpose of the present study is to determine the extent of some of these deposits and to describe some of their characteristics. The first part of the report concerns their stratigraphy, physiographic expression, and petrology. The second part describes the uses of the rock, presents the results of physical test data, and includes descriptions of individual localities in nine counties in central Kansas.

Distribution of cemented sandstones.—Cemented sandstones occur at many localities throughout the outcrop area of the Dakota and Kiowa formations. Although, as will be discussed, the cemented sandstones are restricted to certain types of depositional environments, stratigraphic position is only of slight value in prospecting for new deposits. The Dakota and underlying Kiowa formations of Cretaceous age crop out in north-central Kansas in a broad belt trending northeast-southwest (Fig. 1), and also in several small areas in the southwestern part of the State. The Kiowa shale in north-central Kansas unconformably overlies deposits of Permian age. The Dakota formation is overlain by the Graneros shale and is conformable on and interfingering with the Kiowa shale, although in the northernmost part of the area it overlaps directly on Permian rocks.

The Dakota formation consists for the most part of variegated clays, with a few relatively persistent thin siltstones and sandstones, and many thick, lenticular, channel sandstones. Most of these sandstones are soft and friable. Lenticular, well-indurated sandstones occur at several horizons within the formation and are widely distributed geographically. The Kiowa shale consists of dark shales and fine-grained white sandstones. Cementing materials in the two formations are of several types, including iron oxide, calcite, dolomitic calcite, silica, barite, and mixtures of two or more of these. Clay is the matrix in some of the resistant sandstones, notably in the upper siltstone marking the top of the Dakota formation, but this type of rock has not been studied for the present report.

Commercial uses.—The calcite-cemented sandstone is known locally as "Lincoln quartzite" because of its abundance near the town of Lincoln, Kansas, and has been used extensively as road material, railroad ballast, and high-quality concrete aggregate. It is also crushed and used in sewage disposal plants, as, for example, at Lindsborg, Kansas. The iron oxide cemented sandstone, which has a tendency to case-harden upon exposure to the atmosphere, has been used as building stone, road material, and riprap on stock-pond dams. The silica-cemented sandstone is restricted to small, scattered areas, but has been quarried for use on county roads. Barite-cemented sandstone is rare, and has been found associated with calcite cement. The occurrence and uses of dolomitic calcite-cemented sandstone are similar to those of calcite-cemented rock.

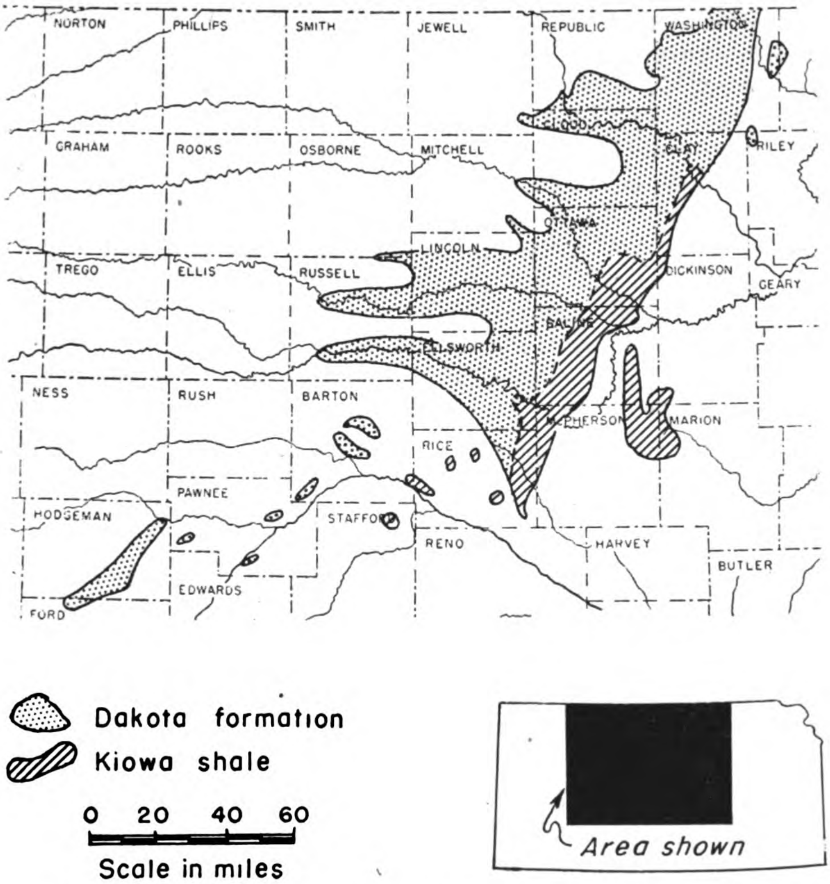

FIG. 1.—Outcrop areas of the Kiowa shale and Dakota formation in north-central Kansas.

Methods of investigation.—Six weeks were spent in the field locating and examining deposits, and samples were studied in the laboratory by means of thin sections, mechanical analyses, and chemical analyses.

Acknowledgments.—The study was made upon the instigation of Dr. John C. Frye, who supplied indispensable criticism and advice throughout its preparation. Thanks and appreciation are expressed to Colonel William E. Potter and Dr. Stafford C. Happ, Corps of Engineers, War Department, Kansas City, Missouri, who furnished chemical analyses and physical test data on the calcite- and dolomite-cemented sandstones. Thanks are also expressed to Mr. J. R. Carlgren of the Quartzite Stone Company, for information concerning carbonate-cemented sandstone in Lincoln County, and to many farmers in the area, especially Mr. R. G. Beil, Spearville, who supplied information concerning outcrop localities. Mr. Russell T. Runnels made chemical analyses of several samples in the laboratory of the State Geological Survey of Kansas. Mr. Norman Plummer supplied detailed stratigraphic information concerning the location and occurrence of many of the cemented sandstones. Dr. F. J. Pettijohn supplied helpful suggestions concerning the process of cementation. The manuscript has been read and criticized by D. H. McCoskey and Stafford C. Happ of the Corps of Engineers, War Department, Kansas City office, and Raymond C. Moore, Norman Plummer, and John C. Frye of the State Geological Survey of Kansas.

STRATIGRAPHY

The Kiowa shale and Dakota formation of north-central Kansas constitute the lowermost Cretaceous of that area. In south-central Kansas (Barber, Kiowa, and Comanche Counties) they are underlain by the Cheyenne sandstone (Latta, 1946). These Cretaceous formations lie unconformably on rocks of Permian age, and at the base in many localities there occurs a zone of water-worn pebbles imbedded in sand, silt, and clay. In the northernmost part of the State the Kiowa shale is absent, and the Dakota rests directly on Permian rocks. The Dakota is conformably overlain by, and transitional with, marine Graneros shale. The literature concerning the stratigraphy of the Dakota and Kiowa formations in Kansas has been reviewed in detail by Tester (1931, pp. 204-230), and more recently Plummer and Romary (1942) have classified the Dakota beds in stratigraphic units that they have correlated throughout central Kansas.

The Regional Dakota-Kiowa Contact

All geologists who have worked in the area in the past few years agree that the contact of the Dakota formation and Kiowa shale is conformable and interfingering, so that at any one locality the two formations may be interbedded, with typical marine Kiowa strata overlying the littoral or continental deposits of the Dakota. Latta (1946, p. 250) chose as an arbitrary line to mark the Kiowa-Dakota boundary the top of the uppermost marine stratum of the particular section being studied, and Frye and Brazil (1943) and Swineford and Williams (1945) chose the base of the lowermost nonmarine bed to mark the same formational boundary. In the present paper Dakota and Kiowa are used in a strictly lithologic sense, taking account of the interfingering of the two lithologies. Thus, sandstones in this part of the section that are characterized by marine fossils or thick deposits of dark-gray pyritic shale with selenite and cone-in-cone are classed as Kiowa, and sandstones associated with light-firing red and gray clays, leaf impressions, and siderite "shot" are classed as Dakota, even though locally rocks called Kiowa may overlie rocks called Dakota.

DAKOTA FORMATION

The resistant, most conspicuous beds of the Dakota are the dark-brown sandstones cemented with iron oxide which cap the hills and produce the irregular topography so common in the Dakota outcrop area. These lenticular sandstones, as shown by Plummer and Romary (1942), have no stratigraphic significance and may be found at any horizon within the formation. Iron oxide is the typical and predominant cement in the outcropping sandstones of the Dakota.

Carbonate-cemented sandstone in the Dakota formation occurs as concretionary bodies in beds of loose sand or iron oxide-cemented sandstone. It has been found by Plummer (personal communication) to occur at three or more horizons within the formation: (1) at the base, (2) near the middle of the Terra Cotta clay member, and (3) at or near the top of the Terra Cotta clay. This sandstone or "quartzite"* has been discussed at length by Plummer and Romary (1942, pp. 325, 329, 332, 333, 336, 340) from whose report the following discussion has been adapted.

In the generalized section of the Dakota formation in north-central Kansas Plummer and Romary (1942) describe 17 stratigraphic units designated as beds, and the carbonate-cemented

*Plummer and Romary use the term *quartzite* within quotation marks for convenience, as it is the local designation of this carbonate-cemented sandstone.

sandstone occurs in beds 1, 6, and 9. They describe bed 1 (basal Dakota formation) as siltstone and fine sandstone, mostly thin-bedded, but locally cross-bedded. This zone characteristically contains "quartzite" concretions, but where the sandstone is not quartzitic, it is commonly very friable. Fossil leaves, fragments of lignite, and nodules are common. Bed 1, which has a maximum thickness of 20 feet, is absent in some places, in which case Dakota clay (bed 2) rests directly on Kiowa shale or older rocks. The base of the Dakota is placed arbitrarily by Plummer and Romary at the base of the "quartzite"-bearing siltstone or sandstone described as bed 1. They state that the contact cannot be identified postively unless the dark fissile shale of the Kiowa can be found below the "quartzitic" bed 1, inasmuch as a series of beds resembling those from 1 to 5 occurs somewhat higher in the Terra Cotta member.

Bed 6 is described as follows: Clay, mottled gray and red, massive, of the fire-clay type, obliquely jointed irregularly, and breaking out with a conchoidal fracture. This bed contains economically important zones of gray fire clay having a high alumina and low iron content. Some seemingly persistent zones of concretionary iron in the form of limonite, siderite, or hematite pellets, or of granular hematite, occur in this bed. There are also some thin zones of sandstone and silt, not channels or bars, in which "quartzite" concretions are commonly found. The thickness of bed 6 ranges from 100 to 150 feet.

Bed 9, the top of which is 10 feet or less below the base of the Janssen clay member, consists of silt and sandstone, very fine, gray or yellow, generally thin-bedded and containing lignite particles. In many places this bed is "quartzitic," or contains ellipsoidal concretions of "quartzite." Where present, it is as much as 10 feet thick. The contact between the Terra Cotta and Janssen members is drawn at the top of a bed containing a marked concentration of concretionary "iron." In many places the "quartzitic" silt or fine sand underlies the concretionary "iron" bed. Plummer and Romary thought that the presence of the "quartzite" is due to the fact that the conditions favorable to cementation are distributed at definite horizons and that a "quartzite" is formed wherever there is a bed of sufficient permeability.

A fourth horizon, not specifically referred to in the report by Plummer and Romary, was observed to contain carbonate-cemented sandstone. It is at or near the top of the Janssen member (uppermost Dakota) and contains such sandstone in at least two localities. (1) In western Lincoln County, near Sylvan Grove (sec. 7, T. 12 S., R. 10 W.) it contains a large lenticular mass, one-half mile in diameter, which is being quarried by the Quartzite Stone Company of Lincoln, Kansas. (2) In a small area in eastern Jewell County (SW¼ sec. 12, T. 5 S., R. 6 W.) outcrops were studied along the bluff which forms the south wall of Buffalo Creek Valley. This locality was brought to my attention by A. R. Leonard, who measured the section and found this rock to be at or very near the top of the Dakota formation (personal communication).

In the Jewell County locality the cemented sandstone is less than 3 feet thick, and the upper surface of some of it is a fairly coarse, shark-tooth conglomerate. Several types of teeth are present, among which seem to be *Corax curvatus* Williston and at least two species of *Ptychodus*. Williston (1900, p. 242) described a similar conglomerate in Ellsworth County as follows:

> Three small teeth . . . from the conglomerate containing specimens of *Corax curvatus*, appear to belong to this species *Ptychodus janewayii*. The horizon of the conglomerate is near the line of contact between the Dakota and Benton, in Ellsworth County. Cope's type was from a bed of Conglomerate containing *Lamna* and *Isurus* teeth of small size near Stockton. It is probable that the horizon is the same in both.

Cretaceous rocks which crop out in the vicinity of Stockton are Niobrara chalk and upper Carlile shale, so that the two exposures of conglomerate described by Williston cannot be considered correlatives. The presence of the conglomerate in Jewell County, however, may provide a clue to the environmental conditions of deposition of the sandstone. If it is a marine conglomerate, it should probably be referred to the base of the Graneros shale.

Silica is the cementing material in a sandstone of the upper bed of the Janssen clay member of the Dakota formation, exposed for three-fourths mile on the south side of the Arkansas River southwest of the town of Hartland in Kearny County (sec. 17, T. 25 S., R. 37 W.). The sandstone, or quartzite, of this area is 3 to 5 feet thick (Pl. 1C) and in a few places contains the vertical holes or channels resembling worm borings or root and stem molds which are reported by Plummer and Romary (1942, p. 339) to be characteristic of the same unit in north-central Kansas. McLaughlin (1942, pp. 77, 79) reports massive ledges of sandstone cemented by pale-gray quartz in the Dakota formation (Cockrum sandstone) of Morton County, but he does not give their stratigraphic position. Iron oxide is the only other cementing material referred to by him in the Dakota of that county.

Calcite-cemented glauconitic sandstone occurs in the subsurface Dakota of southwestern Russell County in a zone about 50 feet above the base of the formation (Swineford and Williams, 1945, pp. 116-117), but it was not noted in the Kiowa shale of this area. This zone is thought to be contained in bed 6 of the generalized section by Plummer and Romary (1942, p. 329), but it may represent a late readvance of the Kiowa sea.

The upper siltstone of the Dakota forms a resistant ledge in Hodgeman and Ford Counties (Pl. 2B) and other areas. This bed was observed to be white or light gray to yellowish brown in color, noncalcareous, and softer than quartzite. It is thought to be a clayey siltstone impregnated with finely divided silica.

Calcite- and silica-cemented sandstones in deposits of the Dakota Stage in Iowa and Nebraska.—Tester's (1931) report on the Dakota Stage of the type locality contains many references to calcite-cemented sandstones, and the descriptions and illustrations of these rocks, which occur both in the Dakota formation and the Graneros shale, indicate their similarity to those in Kansas. Tester (1931, pp. 237, 241, 245, 249, 250) describes calcite-cemented sandstones in the Dakota of the following localities. (1) Pits of the Sioux City Brick Company at Riverside, west part of Sioux City, Iowa, along the South Dakota branch of the Chicago, Milwaukee, St. Paul & Pacific Railroad; E. side sec. 23, T. 89 N., R. 48 W., Woodbury County, Iowa; sandstone at the top of the Dakota and at one lower horizon. (2) Sec. 11, T. 89 N., R. 48 W., Woodbury County, Iowa, west of Sioux City in the bluff facing Big Sioux River at old quarry site south of west entrance to Stone Park; sandstone about 45 feet below top of Dakota. (3) At Sergeant Bluff, sec. 30, T. 88 N., R. 47 W., Woodbury County, Iowa; in pits of Ballou Brick Company; sandstone at three horizons. (4) In the bluff 2½ miles southeast of Homer, sec. 20, T. 27 N., R. 9 E., Dakota County, Nebraska; calcite-cemented sandstone in one small exposure. (5) SW¼ sec. 23, T. 27 N., R. 8 E., and NE¼ sec. 26, T.

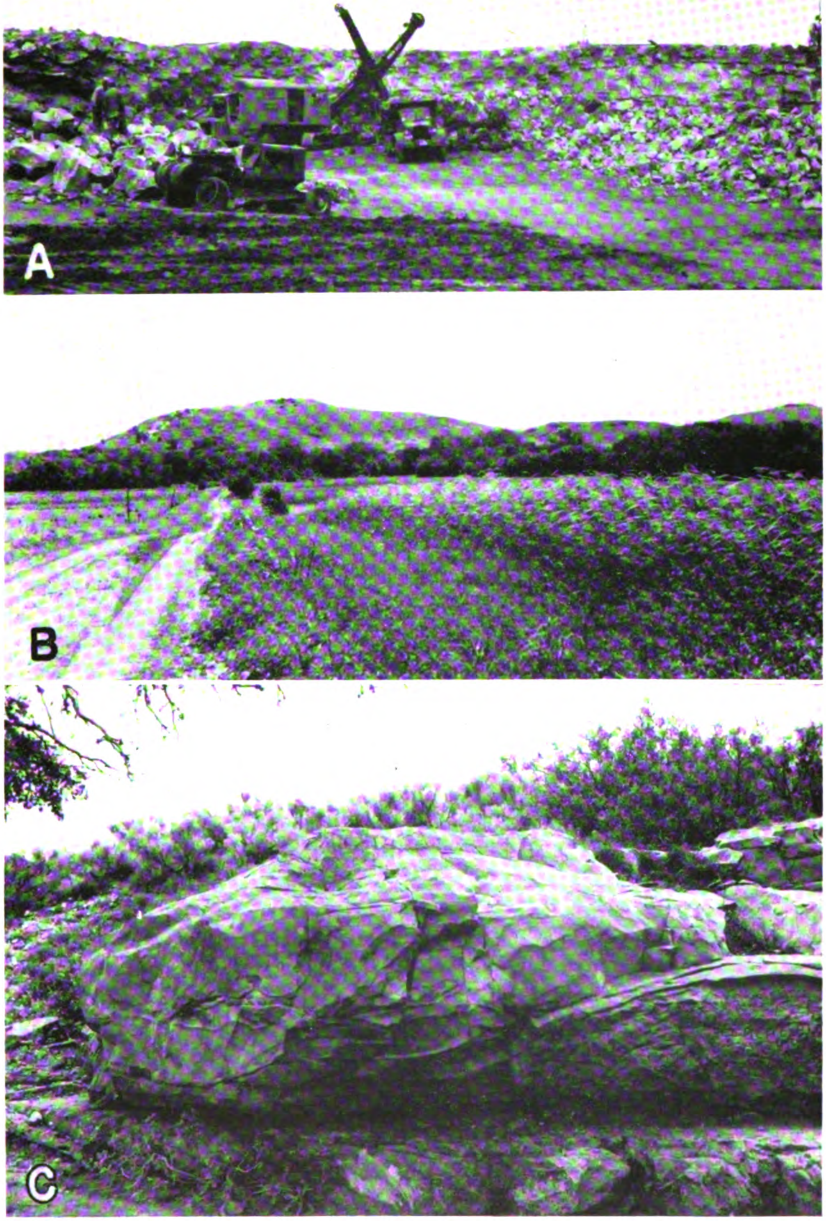

PLATE 1.—*A*, Dolomite-cemented sandstone in the Sylvan Grove quarry, sec. 7, T. 12 S., R. 10 W., Lincoln County. *B*, Twin Mounds, capped with silica-cemented sandstone; NW cor. sec. 1, T. 18 S., R. 2 W., McPherson County. *C*, Quartzite in yellow-brown sandstone at top of Dakota formation, sec. 17, T. 25 S., R. 37 W., Kearny County. Note lenticular nature of the quartzite.

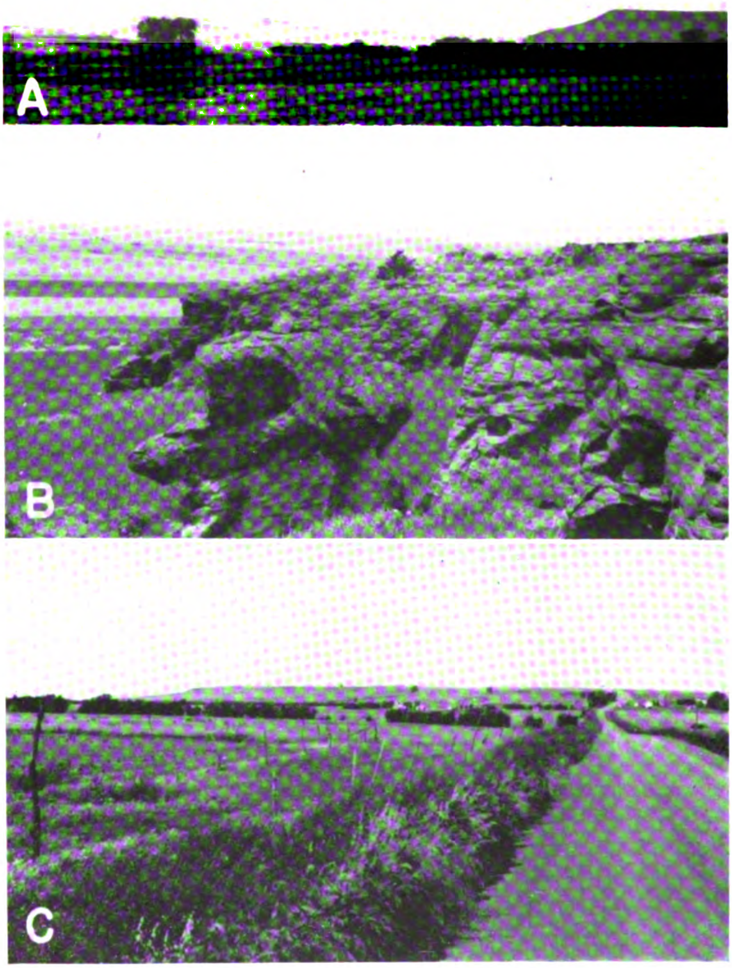

PLATE 4.—*A*, Hills of the Dakota formation capped by ferruginous sandstone, sec. 14, T. 15 S., R. 6 W., Ellsworth County, looking southeast from Highway U. S. 40. *B*, Erosion remnants of ferruginous sandstone in S½ sec. 4, T. 13 S., R. 11 W., near "Rocktown," Russell County; upper parts cemented by hematite, lower parts by limonite. *C*, South end of hill of calcite-cemented sandstone capped with quartzite; sec. 25, T. 17 S., R. 2 W., McPherson County.

27 N., R. 8 E. about 2 miles south of Homer, Dakota County, Nebraska; sandstone at one horizon. At all except one of these localities the sandstone contains either glauconite or marine fossils or both, which Tester interprets as indicating a marine invasion. They may mark one or more early invasions of the Graneros sea.

Gould (1900, p. 430) describes one locality of quartzite in the Dakota of Nebraska. This occurs about 5 miles northwest of Fairbury, near Whiskey Run, as a ledge about 3 feet thick. Gould does not describe its stratigraphic position but writes,

> It differs from anything seen elsewhere in the State except somewhat similar ledges found near the old mission on the Omaha Reservation and along the bluffs to the north, although quartzite boulders similar in character are found in Saline and McPherson counties, Kansas.

Whiskey Run is a short, southward-flowing tributary to the Little Blue River. I was unable to find any Cretaceous quartzite in the area, but a small ledge of dense, gray, calcite-cemented sandstone at or near the top of the Dakota formation occurs near the stream in sec. 33, T. 3 N., R. 2 E.

Kiowa Shale

The Kiowa shale consists of dark-gray to black shale with thin beds and lenses of fine-grained sandstone and thin beds of fossiliferous limestone. Pyrite, gypsum, and cone-in-cone are abundant in the formation. The sandstones are more persistent than are those of the Dakota, but they cannot be traced over long distances. Carbonate-cemented sandstone occurs at several horizons in the Kiowa, and silica-cemented sandstone has been observed in the formation at isolated localities in McPherson and Rice Counties (Williams and Lohman, in press). Iron oxide-cemented sandstone is common in the "Black Hills" of southwestern Dickinson County. This is believed to be in the Kiowa shale, but some of it may occur in the Terra Cotta clay member of the Dakota formation. A small quantity of carbonate-cemented sandstone also occurs in this area.

In Rice County, O. S. Fent (personal communication) noted that sandstone with carbonate cement occurs in at least three zones within the Kiowa shale. He also observed cone-in-cone in the shale at the same horizon at other localities where the sandstone is absent. In the basal part of some of the exposures of calcite-cemented sandstone he noted numerous fragments of shells.

In McPherson County, carbonate-cemented sandstone associated with cone-in-cone caps a 4-mile north-south discontinuous ridge in the northeastern part of T. 18 S., R. 2 W. Other small areas of carbonate-cemented sandstone occur in northeastern McPherson County. Near Battle Hill school, 5 miles south of Roxbury, sandstone with silica cement cropped out in four low hills. This sandstone, most of which has been removed for road material, occurred not far above Permian rocks of the Sumner group. Twenhofel (1924, p. 40) writes, "The sandstones of the 'Dakota' [sic] form a compact quartzitelike rock on the hills south of Roxbury"; but elsewhere in the same report (p. 12, pl. 1) he maps these rocks as marine strata and by implication calls them Comanchean. In the usage of this paper it would probably be classed as Kiowa formation. It is referred to the Kiowa shale by Williams and Lohman (in press). Silica-cemented sandstone tentatively classed a Kiowa is observed capping Twin Mounds (Pl. 1B), about 5 miles southwest of Roxbury. A thin lens of silica-cemented reddish-brown sandstone also occurs a few feet above some carbonate-cemented sandstone 3 miles west of Roxbury (NE¼ sec. 25, T. 17 S., R. 2 W.).

Calcite-cemented sandstone in the Kanopolis quarry, sec. 19, T. 16 S., R. 6 W., Ellsworth County, is thought to occur in the Kiowa shale because it overlies black shale containing gypsum and pyrite and because it is associated with cone-in-cone. The cone-in-cone at this locality curves around the lower sides of concretionary bodies of cemented sandstone and above more of the same sandstone. Cone-in-cone has not been described from the Dakota formation of Kansas, although it is reported by Tester (1931, p. 261) from a few feet below the base of the Graneros shale in one locality in Nebraska. Liesegang banding is well developed on the upper weathered surface of some of the sandstone in this quarry.

Carbonate- and silica-cemented sandstone in sec. 33, T. 15 S., R. 7 W., about 2.5 miles east of Kanopolis, on the east side of the Smoky Hill River, is described by Twenhofel and Tester (1926, p. 558) as follows.

> Sandstone, gray, fine to medium grained; usually in massive beds, making principal ledge of bluff; variously cross-bedded. The member is essentially calcareous, though considerable silicification has occurred in the upper part. In many respects this sandstone resembles some phases of the Mentor of the Salina region, and is considered to be the equivalent of the Mentor.

The bed is reported by them to be 6 to 7 feet thick.

In Saline County calcite-cemented sandstone is well exposed in the Camp Phillips quarry (NW¼ sec. 36, T. 14 S., R. 4 W.). Its stratigraphic position is near the base of the Dakota formation; it contains barite sand-crystals, which have not been noted in unquestioned Dakota, and cone-in-cone. It therefore is tentatively placed in the upper part of the Kiowa shale.

PHYSIOGRAPHIC EXPRESSION

Carbonate-cemented sandstone.—Most exposures of carbonate-cemented sandstone are small and occur as groups of spheroidal concretions 20 feet or less in diameter. At several localities such concretions have prominant physiographic expression owing to the more rapid weathering and removal of the softer rocks enclosing the concretions. Of these perhaps the best known is "Rock City," a group of 200 or more sandstone concretions about 3 miles southwest of Minneapolis in Ottawa County (Bell, 1901; Schoewe *et al.*, 1937). Shoewe (Schoewe *et al.*, 1937, p. 181) made a detailed plane-table map of "Rock City," showing the elongate nature of the outcrop area and the linear strings of individual concretions, trending about N. 83° W. Similar linear groups of concretions occur elsewhere in central and north-central Kansas, but "Rock City" is better known because of its greater accessibility. In topographic position these features may be found along uplands, in stream valleys, and at the up-slope edges of terraces. They do not in themselves modify the topography.

Larger masses of carbonate-cemented sandstone form minor ledges along otherwise gentle slopes, or, if dissected by streams, they form steep-walled valleys. A lentil of dolomitic calcite-cemented sandstone in western Lincoln County (sec. 7, T. 12 S., R. 10 W.) is dissected by Wolf Creek and has been a popular picnic ground locally called "The Gorge." The sandstone cliffs in this area are more than 50 feet high and rise abruptly above a low terrace of Wolf Creek (Pl. 3B). The cliffs are characterized by many reentrants which are probably localized by differences in degree of cementation. The upper surfaces of the large masses are lowered chiefly by solution (Frye and Swineford, 1947), and in very few places does this sandstone hold up prominent hills.

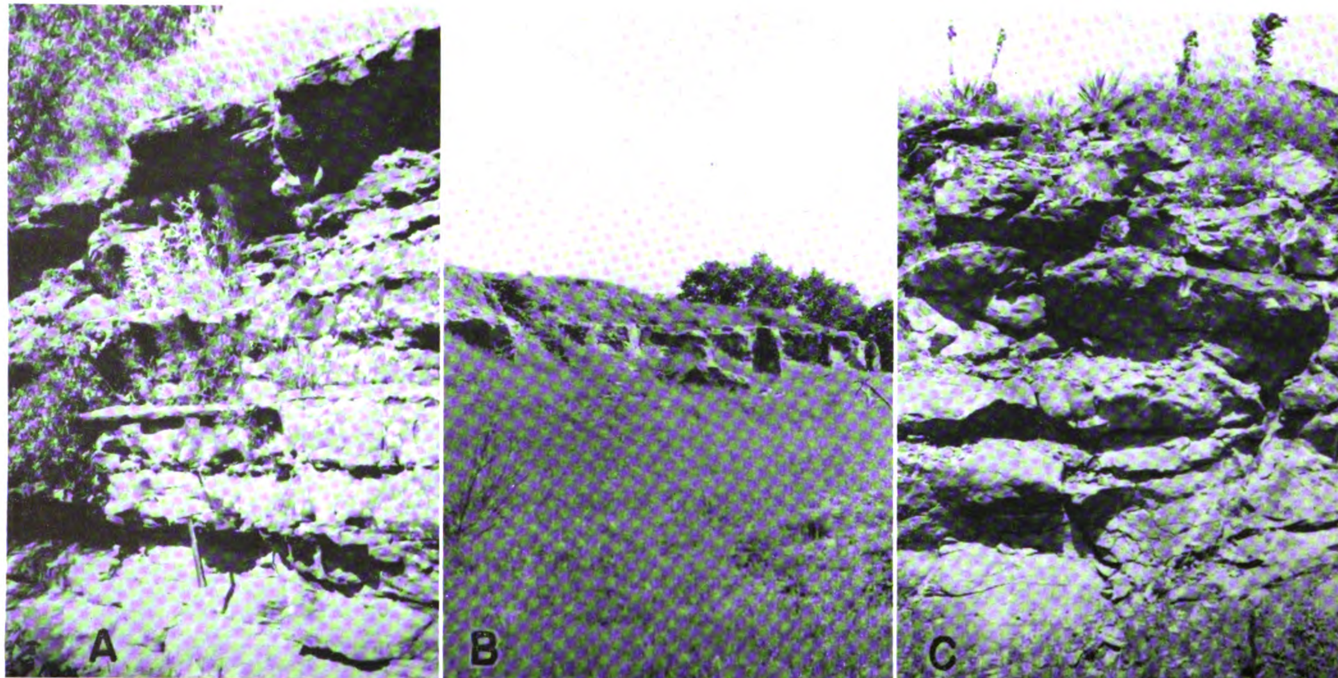

PLATE 2.—*A*, **Interbedded ferruginous sandstone and calcite-cemented sandstone in cut-bank of small stream in SW¼ SW¼ sec. 28, T. 18 S., R. 7 W., Rice County. Hammer hangs on lowermost calcareous lentil; above it are five other protrud**ing ledges of calcareous sandstone. Topmost massive bed is case-hardened ferruginous sandstone. *B*, Natural exposure of upper siltstone member of the Dakota formation, SE¼ sec. 12, T. 25 S., R. 24 W., Ford County. The matrix consists of siliceous clay. *C*, Small quarry in calcite-cemented sandstone, NW¼ sec. 14, T. 18 S., R. 2 W., McPherson County.

Silica-cemented sandstone. — Silica-cemented sandstone is more resistant to corrasion and weathering, and in many areas caps rounded or conical hills. The largest of these are Twin Mounds in eastern McPherson County (NW cor. sec. 1, T. 18 S., R. 2 W.), at or near the tops of which are a few feet of quartzite (Pl. 1B). Quartzite caps part of a long ridge 3 miles west of Roxbury, McPherson County, which is underlain by calcite-cemented standstone (Pl. 4C). Quartzite in Kearny County (sec. 17, T. 25 S., R. 37 W.) forms a low ledge under coarse gravels near the Arkansas River. A few potholes are observed on the water-worn surface of this ledge (Pl. 3A).

Iron oxide-cemented sandstone.—Ferruginous sandstone is ubiquitous in the Dakota and is responsible for the rugged topography characteristic of this formation in Kansas (Pl. 4A). Plummer and Romary (1942, pp. 327-328) describe it as follows.

> The more resistant sandstone caps the hills and covers the slopes with residual sand and slumped fragments. . . . In some places the coarser sandstone has the appearance of being relatively thin and horizontally persistent. This seems particularly true of sandstone that caps a series of hills. Where such occurrences have been studied in detail, it was found that the capping sandstone occupies different stratigraphic positions, although the dark, case-hardened sandstone on the hill top has the appearance of being thin, horizontally persistent "sheets."

Rubey and Bass (1925, pp. 57-64) describe and illustrate the weathering of upper sandstones of the Dakota into groups of "hoodoos," isolated irregular cones or blocks 5 to 15 feet high and resulting from slight irregularities in cementation. The cementing material is iron oxide. These groups of "hoodoos" are known as Rocktown, and are situated in the NW¼ sec. 4, T. 13 S., R. 11 W. Plate 4B shows similar erosion remnants in the southern part of the same section. The upper parts of these blocks are cemented with hematite, and the lower parts with limonite.

Relative resistance to weathering and erosion.—Resistance to weathering is greatest in the quartzite and least in the carbonate-cemented sandstones, which are more readily dissolved by rain water. The ferruginous (limonitic) sandstones, because of their tendency to case-harden, are intermediate in resistance.

The quartzite is probably most resistant to stream erosion, although a good opportunity for comparison did not present itself. A cut-bank in a small stream in the SW¼ SW¼ sec. 28, T. 18 S., R. 7 W., Rice County, shows the relative resistance of calcite- and iron oxide-cemented sandstones to stream action. In this exposure thin lenses (less than 3 inches thick) of calcite-cemented sandstone protrude as much as a foot beyond dark-brown ferruginous sandstone (Pl. 2A), which has been case-hardened only at the top.

PETROLOGY

Thin sections of indurated sandstones from the Dakota formation and Kiowa shale were examined from samples from 31 localities in 10 counties in Kansas—Clay, Ellsworth, Kearny, Lincoln, McPherson, Ottawa, Rice, Russell, Saline, and Washington. Some mechanical analyses were made of the sand freed of cement (Table 1), chemical analyses were studied (Tables 2 and 3), and a few staining tests were made. The cementing materials show a wide range in composition and petrographic character, and in some instances the sand grains themselves show alteration related to the cement.

The indurated sandstones of the Dakota formation and Kiowa shale are grouped, on the basis of their cement, into four categories: iron oxide-cemented sandstone, calcite-cemented sandstone, dolomitic calcite-cemented sandstone (here designated simply as dolomite-cemented sandstone), and silica-cemented sandstone. A few miscellaneous types are also discussed. In all the samples herein described, unless otherwise noted, the clastic grains are predominantly quartz, with minor quantities of feldspar (plagioclase, microcline, orthoclase), chert, and quartzite.

Iron Oxide-Cemented Sandstone

Iron oxide is the most abundant cementing material of the sandstones in the Dakota formation; it is also common in the Kiowa shale. On outcrops it occurs chiefly in a case-hardened crust, which

Table 1.—*Size distribution of sand in carbonate-cemented sandstones.* (Analyses by Carrie B. Thurber)

County	Location	Size distribution in mm (percent by weight) .71-.5	.5-.35	.35-.25	.25-.177	.177-.125	.125-.088	.088-.062	.062	Type of cement
Lincoln	7-12- 7W			1.9	40.1	41.7	13.6	1.1	1.6	Calcite
Lincoln	7-12-10W		0.0	73.9	20.0	2.8	2.3	0.4	0.5	Dolomite
McPherson	19-17- 2W		0.0	0.1	0.8	33.8	55.9	5.5	3.8	Dolomite
Ellsworth	19-16- 6W	0.0	0.0	88.3	9.5	0.5	0.8	0.2	0.7	Calcite

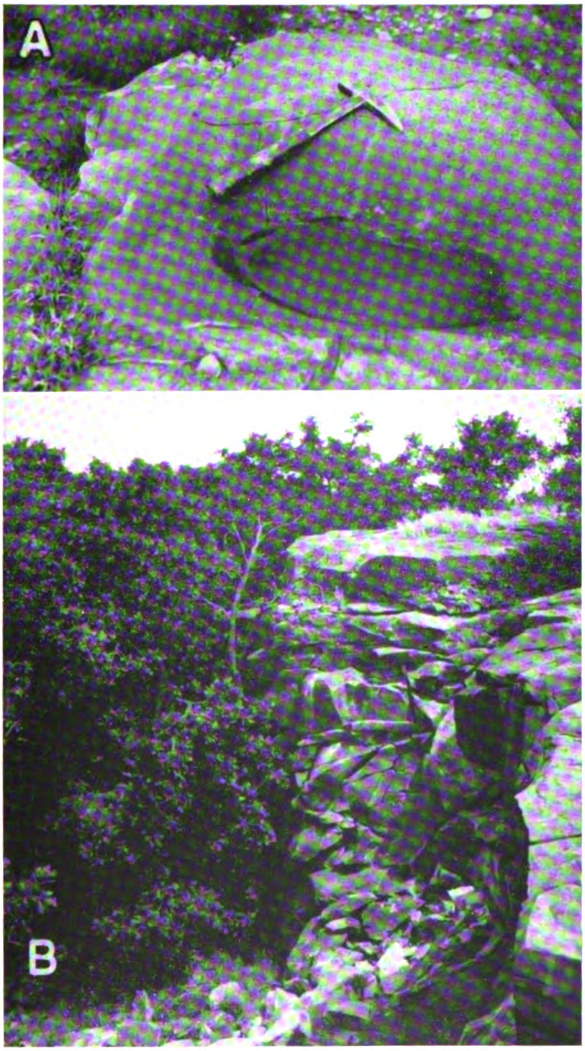

Plate 3.—*A*, Water-worn surface and pothole in quartzite south of Arkansas River, sec. 17, T. 25 S., R. 37 W., Kearny County. *B*, Fifty-foot cliff of dolomite-cemented sandstone at site of Sylvan Grove quarry, sec. 7, T. 12 S., R. 10 W., Lincoln County. July 1946.

TABLE 2.—*Chemical composition of eight samples of indurated sandstones from the Dakota and Kiowa formations in Kansas*

(Analyses by Russell Runnels)

County	Location	*Chemical analysis (percent)*										Type of cement
		Loss on ignition	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	$BaSO_4$	SO_3	Sol. in HCl	
Lincoln	13-12-8W	16.60	58.02	1.49	0.08	0.59	21.05	0.44	0.00	0.03	39.74	Calcite
Washington	11-3-4E	14.17	62.56	2.12*	1.49		16.71	0.72	0.00	0.00	34.28	Calcite
Rice	26-20-10W	13.99	62.57	1.06	0.90	0.21	20.39	0.20	0.00	0.00	34.58	Calcite
Lincoln	7-12-10W	16.73	60.95	0.76	0.25	0.82	13.74	6.31	0.00	0.00	37.13	Dolomite
McPherson	19-17-2W	16.48	61.61	1.31	0.52	0.18	16.07	5.75	0.00	0.00	36.08	Dolomite
McPherson	1-18-2W	18.35	55.88	2.37*	0.50		13.51	6.92	0.00	0.07	41.34	Dolomite
McPherson	25-17-1W	13.61	60.29	2.07*	0.19		17.82	1.42	2.95	0.36	35.45	Calcite-barite
Ellsworth	14-15-6W	2.04	83.76	4.06	8.69	0.48	0.00	0.94	0.00	0.00	2.69	Ferric oxide

*Includes TiO_2.

makes the sandstone extremely resistant to abrasion and further weathering. However, a few inches or feet in from the surface, most of the sandstones are probably soft and friable. Limonite is the predominant form of iron oxide in the case-hardened sandstone, but there are also small quantities of hematite. Hematite is much more prevalent in the subsurface Dakota than in outcropping sandstones, but it is well developed in a branch of Horsethief Canyon, in the Cen. sec. 9, T. 16 S., R. 6 W., Ellsworth County, and at Rocktown, sec. 4, T. 13 S., R. 11 W., Russell County.

Sands cemented with iron oxide are fine- to coarse-grained, and well- to poorly sorted. Many contain pellets of impure iron oxide slightly larger than the quartz grains, and small hollow concretionary nodules of limonite. Two thin sections of ferruginous sandstone were examined. One is case-hardened dark-brown sandstone from a channel sand of the Terra Cotta clay, NE¼ sec. 2, T. 3 S., R. 4 E., Washington County (Pl. 5D). The cement is chiefly limonite, which fills more than half the space between the sand grains; this matrix is further characterized by pore spaces of about the diameter of coarse silt particles. Some of these pore spaces have a roughly rhombohedral shape, and the cement is judged to have been derived from siderite, because there are a few remnants of siderite rhombs in various stages of alteration. The sand grains themselves are well sorted but poorly packed. Many of the grains have been etched so that they exhibit extremely irregular boundaries. There are also small micro-clay-balls, or pellets, about 2 mm in diameter, which consist of impure limonite and hematite and contain much silt. As silt particles are not present elsewhere in the thin section, these clay balls must have been deposited as units.

The second thin section of ferruginous sandstone is from the Terra Cotta clay near the type locality in Ellsworth County (SW¼ sec. 14, T. 15 S., R. 6 W.), and was cut from somewhat friable sandstone below the case-hardened surface. It differs from the dark case-hardened sandstone described above, chiefly in the smaller quantity of iron oxide cement. The cement is limonite, but occurs as scattered patches or grains, and as coatings on the quartz particles. Many of the grains are probably pseudomorphs after pyrite, but their uniformly rhombohedral shape in thin section suggests that they may be pseudomorphs after siderite or ankerite. The sand grains are poorly sorted, but little or no silt is present. Heavy accessory minerals (tourmaline and zircon) are not coated with iron oxide, and are not etched, as are most of the quartz grains.

Calcite-Cemented Sandstone

The calcite-cemented sandstone is hard, dense, quartzitelike rock which is gray to creamy gray on fresh surfaces and buff-colored or brown when weathered. Liesegang banding is developed on some of the weathered surfaces, but is not visible in thin sections or on freshly broken rock. The sand is fine- to coarse-grained, and in nearly every case extremely well sorted (Table 1). Thin sections show that the calcite cement occurs as large interlocking crystals, each enclosing several quartz grains. The diameter of the crystals may be observed in the hand specimen by reflection of sunlight from cleavage planes. If the crystals did not interlock, much of this sandstone would be similar in general appearance to the famed calcite "sand-crystals" of the White River Oligocene in South Dakota and Wyoming (Penfield and Ford, 1900; Ziegler, 1914, pp. 126-128; Wanless, 1922) and to the Fountainebleau sandstones of France. There are a few localities in the Dakota of Kansas where cement crystals are not entirely in contact with each other, notably in the SE¼ sec. 13, T. 12 S., R. 8 W., Lincoln County; and also in the S½ sec. 20, T. 9 S., R. 2 W., Ottawa County, where small sand-crystals occur in a partly cemented zone between two spheroidal concretions.

The optical orientation of the calcite crystals seems to be random in most samples examined, but in others the orientation of

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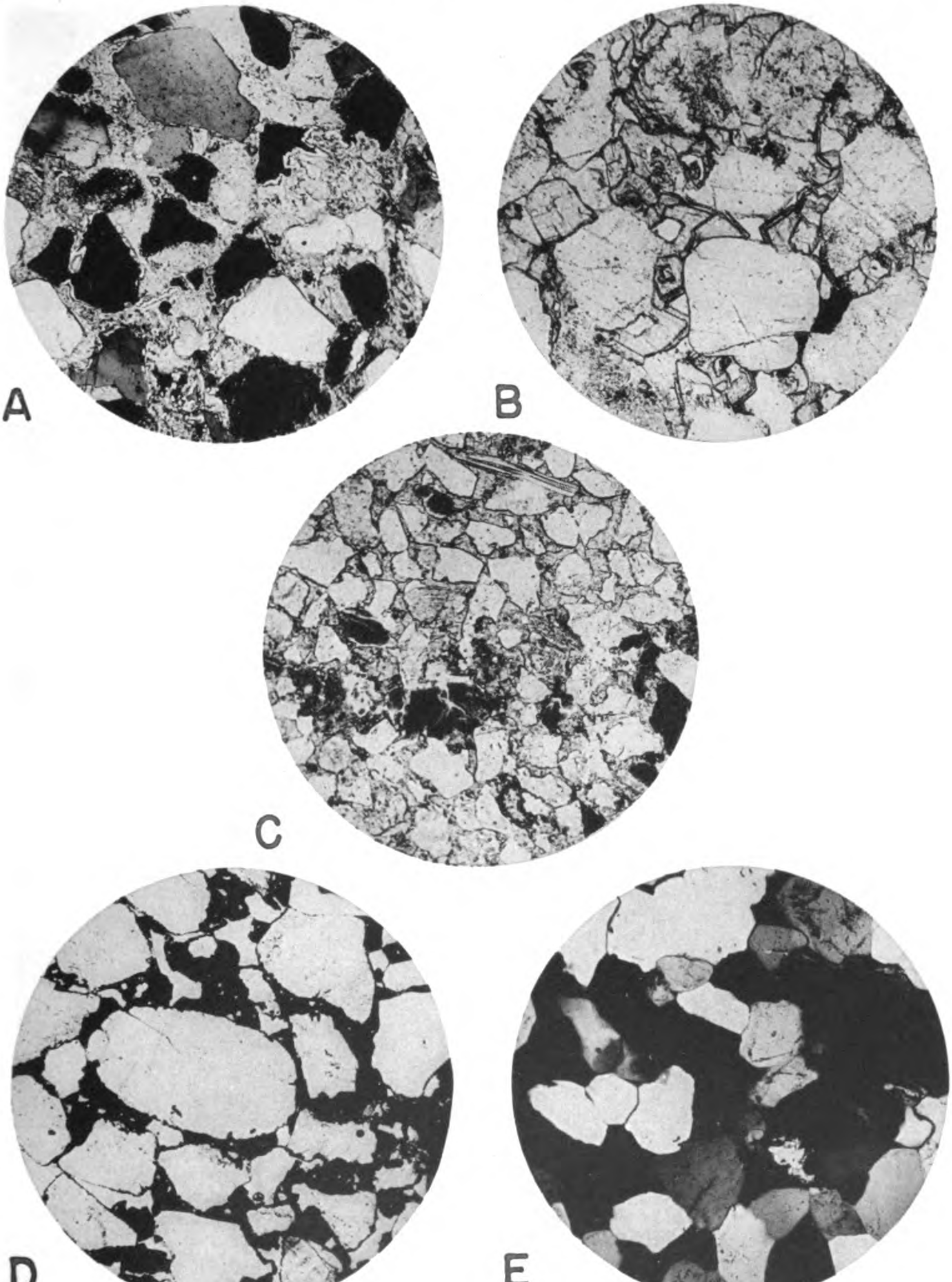
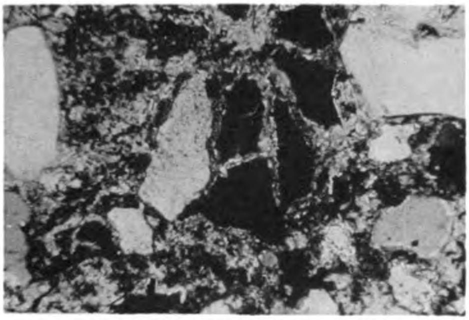
Plate 5.—Thin sections from sandstone in the Kiowa and Dakota formations of Kansas. (Plate erroneously labeled "6".)

A. Etched grains of quartz and feldspar, partly replaced by crystalline calcite cement. Dakota formation, Lincoln quarry, sec. 7, T. 12 S., R. 7 W., Lincoln County. Crossed nicols, X 53.
B. Sandstone cemented with dolomite rhombs. Kiowa shale, sec. 19, T. 17 S., R. 2 W., McPherson County. Plane polarized light, X 53.
C. Calcite-cemented micaceous sandstone with glauconite grains. Kiowa shale, sec. 27, T. 15 S., R. 2 W., Saline County. Plane polarized light, X 53.
D. Limonite-cemented sandstone, Dakota formation, NE¼ sec. 2, T. 3 S., R. 4 E., Washington County. Plane polarized light, X 53.
E. Quartzite, Dakota formation, sec. 17, T. 25 S., R. 37 W., Kearny County. Note original outlines of grains, and ragged staurolite. Crossed nicols, X 53.



Swineford, Cemented Sandstones in Kansas



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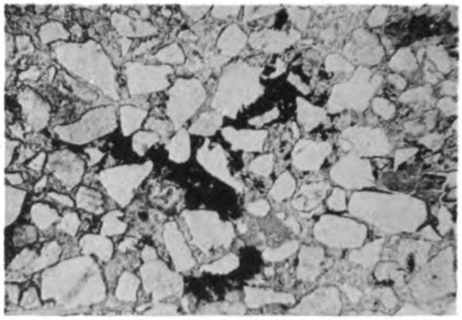

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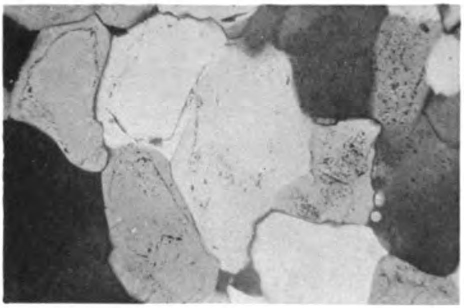

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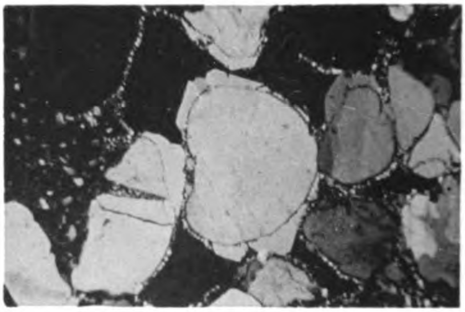

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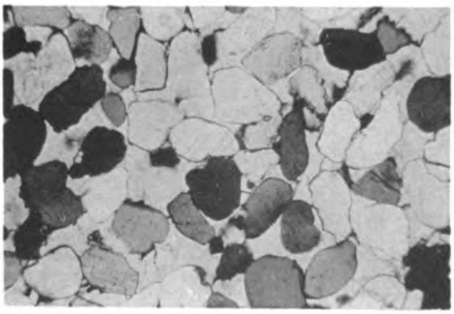

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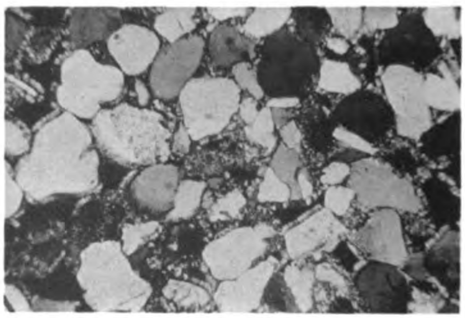

F

Swineford, Cemented Sandstones in Kansas each crystal differs only slightly from that of the adjacent crystal, giving the appearance of curved faces in the hand specimen. The grains of quartz and feldspar are characteristically etched (Pl. 5A). Glauconite is commonly present as irregular grains: The fact that some of the glauconite grains exhibit shrinkage cracks (Pl. 5C) suggests that they were transported only a short distance before deposition. Uncorroded fragments of shells also occur commonly. In some samples uncorroded oyster shells are associated with *Turritella* casts.

Pyrite.—Much of the calcite-cemented sandstone contains small cubes of pyrite disseminated throughout the cement, and also nodules of pyrite cement up to 4 cm or more in diameter. Some pyrite nodules surround fragments of wood. Upon weathering, the pyrite alters to limonite which gives a yellowish-brown color to the rock. Hemispherical pits are formed in the exposed surface of the rock by the action of sulfuric acid, developed by the weathering of the pyrite nodules, on the calcite.

Sand-siderite pellets. — At a few localities calcite-cemented sandstone peppered with small siderite or ankerite pellets occurs. Sand grains are included within the pellets. This feature is well developed in sandstone concretions in the W½ NW¼ sec. 3, T. 14 S,. R. 6 W., Ellsworth County, and sec. 22, T. 9 S., R. 1 E., Clay County; and it seems to be restricted to the Dakota formation. As the pellets weather readily to limonite, they are not found in surface exposures unless protected as in the calcite-sandstone concretions.

Asphalt. — Bituminous or asphaltic material is another im-

Plate 6.—Thin sections from sandstone in the Kiowa and Dakota formations of Kansas. (Plate erroneously labeled "7".)

A. Etched, displaced quartz grain in calcite-ankerite-cemented sandstone, Dakota formation. NE¼ NW¼ sec. 9, T. 1 S., R. 3 E., Washington County. Crossed nicols, X 120.
B. Asphalt in calcite-cemented sandstone, Kiowa shale. SW¼ sec. 24, T. 18 S., R. 2 W., McPherson County. Plane polarized light, X 34.
C. Quartzite, Dakota formation, sec. 17, T. 25 S., R. 37 W., Kearny County, showing original grain outlines. Crossed nicols, X 120.
D. Silica-cemented sandstone, Kiowa shale (?), Twin Mounds. Sec. 1, T. 18 S., R. 2 W., McPherson County. Note chert in fractured grain, and secondary quartz projecting into pore spaces. Crossed nicols, X 120.
E. Celestite-cemented sandstone at base of Cretaceous in SW cor. sec. 2, T. 17 S., R. 5 W., McPherson County. Crossed nicols, X 29.
F. Silica-cemented sandstone from NW¼ SW¼ sec. 15, T. 18 S., R. 1 W., McPherson County. Crossed nicols, X 29.

purity observed in some of the calcite-cemented sandstones. It is well developed in spherical concretions in the SE¼ sec. 16, T. 18 S., R. 1 W., McPherson County, where it gives the rock a dark-gray or dark grayish-brown color. The asphalt occurs as small areas of cementing material admixed with calcite. Plate 6B shows this type of sandstone from the Kiowa shale (?) in the SW¼ sec. 24, T. 18 S., R. 2 W., McPherson County.

Sand-barite. — Sand barite crystals and rosettes characterize many outcrops of calcite-cemented sandstone in the Kiowa shale, but they have not been noted in the Dakota formation in Kansas. Barite crystals, however, have been described by Schramm (1943) in septaria-like concretions in the Dakota formation near Lincoln, Nebraska. The barite crystals are tabular and range in long diameter from 5 mm to more than 20 mm. The rosettes range from about 12 mm to the size of large walnuts, which many of them closely resemble in external appearance. Crystals and rosettes are not scattered uniformly throughout a bed, but are arranged in clusters or groups. Their relative insolubility causes them to protrude above the weathered surfaces of the sandstone outcrops. Localities where the barite sand crystals are well developed include: NE¼ sec. 25, T. 17 S., R. 1 W., McPherson County; NW¼ sec. 36, T. 14 S., R 4 W., Saline County; and the SW¼ NW¼ sec. 15, T. 20 S., R. 6 W., Rice County. Two types of barite rosettes are observed at the Saline County locality. Both types consist of aggregates of tabular barite crystals, but in one type all the crystals radiate about one of their axes (probably *b*), which they have in common; the other is the more usual rosette type, with two tabular crystals at right angles crossing a central depression. Similar forms from Permian rocks are described and illustrated by Tarr (1933), and others are illustrated by Walther (1924, p. 75). Tarr notes that these forms serve as horizon markers in the Garber formation and to a less extent in the Wellington formation in central Oklahoma. He believes that the barium was derived from barium silicates, from barium adsorbed in colloids, or from detrital grains of barite. He concludes that it was leached out by chloride waters (original brines, carried a short distance, and deposited as a cementing material through reaction with a soluble sulfate; and that the time of deposition was probably not long after the formation of the sandstone. The barite in the Kiowa shale probably had its source in the underlying Permian rocks, and, in accordance with the hypothesis of Tarr, may have been dissolved from the Permian deposits by the marine chloride waters of the Kiowa sea. The absence of barite in the Dakota formation may be ascribed in part to the quality of water associated with Dakota deposition and in part to the previous burial of the Permian rocks by Kiowa sediments.

In thin section the barite is seen to have slightly irregular contacts with the calcite cement in some areas and to be bounded by plane faces in others. The orientation of the tabular crystals is random. The sand grains surrounded by calcite are etched to a greater extent than those within the barite crystals. Some individual grains which penetrate a barite-calcite contact are etched on the calcite side and relatively unaffected on the barite side.

Dolomite-Cemented Sandstone

Dolmite-cemented sandstone is known to occur in western Lincoln County (sec. 7, T. 12 S., R. 10 W.), at or near the top of the Dakota formation. It is also observed in the Kiowa shale in McPherson County in sec. 19, T. 17 S., R. 2 W., where it occurs as isolated concretionary masses on a hill side, and in large flattened spheroidal concretions a few feet above the base of Twin Mounds, near the NW cor. sec. 1, T. 18 S., R. 2 W. The appearance of this sandstone in the field is similar to that of much of the calcite-cemented sandstone, and in some localities it may easily have been mistaken for the latter. The clastic grains are well sorted, as in the calcite-cemented sandstone (Table 1).

The dolomite cement occurs as small crystals about the size of the sand grains; the individual crystals seldom enclose quartz grains, and no sample was observed in which one crystal enclosed more than 3 or 4 sand grains. The dolomite may generally be distinguished from calcite in thin section by its occurrence as small rhombohedra (Pl. 5B). Staining tests (silver nitrate-potassium chromate) show that calcite in this sandstone occurs as isolated patches and as small veins less than 1 mm in diameter. The occurrence of pyrite is similar to that in the calcite-cemented sandstones. Chemical analyses (Tables 2 and 4) show that the sandstone contains from 5 to 7 percent magnesium oxide and from 11 to 16 percent calcium oxide. Dolomite-cemented sandstone and typical calcite-cemented sandstone have not been found together or in the same section in any area.

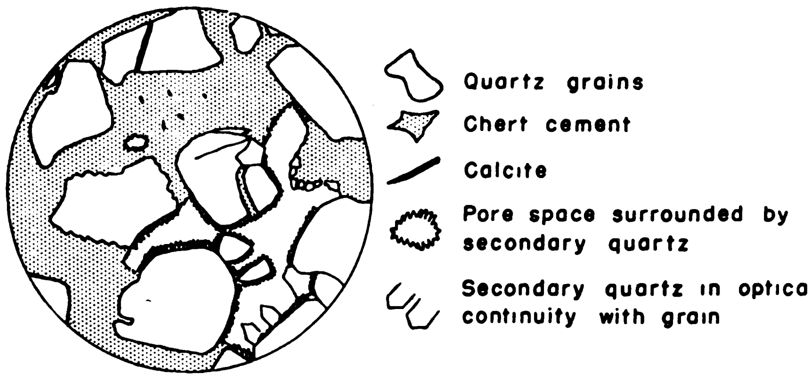

FIG. 2.—Drawing from thin section of silica-cemented sandstone from Twin Mounds, McPherson County, showing evidence of replacement of calcite.

SILICA-CEMENTED SANDSTONE

Silica cement is observed in sandstones of the Kiowa shale in McPherson and Rice Counties and in the Dakota formation in Kearny County. Hand specimens range in color from white to pink and buff, and several colors occur in one exposure. The sandstone is fine-to coarse-grained and dense to porous. Some of the white sandstone in Kearny County (sec. 17, T. 25 S., R. 37 W.) has a sugary texture. The silica cement is of several types, some of which occur together in the same exposure and even in the same thin section. Quartz cement optically continuous with the grains is noted in two thin sections from the Kearny County locality (Pls. 5E and 6C). The original outlines of many of the grains are made visible by an iron oxide coating, and the grains do not show the etching which is characteristic of the calcite-cemented sandstones. The space occupied by cement is also less than in the carbonate-cemented samples. A thin layer of quartzite containing similar cement and overlying calcite-cemented sandstone occurs in sec. 13, T. 19 S., R. 6 W., Rice County. A thin section from this locality shows relatively unetched sand grains surrounded by optically continuous quartz, although some pore spaces are left. In some areas of the thin section the cement is a coarse-grained chert.

A mixture of chert and quartz cement, with a trace of calcite, is well shown in a thin section of partly cemented sandstone from Twin Mounds, McPherson County (Pl. 6D, Fig. 2). Calcite is observed in a small crack traversing a quartz grain which is surrounded by chert, and also as minute specks in part of the chert cement. Most of the quartz cement occurs outside of a thin layer of chert cement which surrounds the grains, and projects as euhedral crystals into the pore spaces of the sandstone. The chert not only surrounds the grains, but also projects into wedge-shaped cracks and fractures, and cuts entirely across grains which have been fractured along planes of weakness and rotated, or displaced.

Uniformly medium-grained, granular chalcedonic chert is the cementing material in a thin section of pinkish-brown quartzite from the Kearny County locality. The quartz grains are closely packed, and the color results from large quantities of iron oxide coating the grains. A few of the grains show some indication of etching.

Chalcedonic chert cements the quartz grains in a thin section of sandstone from the NW¼ SW¼ sec. 15, T. 18 S., R. 1 W., McPherson County. It consists of thin bands of fibrous silica coating the grains, with the long dimensions of the fibers normal to the surfaces of the grains (Pl. 6F).

Most of the thin sections of silica-cemented sandstone are characterized by the extreme scarcity or absence of feldspars and by the absence or relative unimportance of etched surfaces of quartz grains. One thin section from Kearny County shows delicately etched staurolite, but other minerals are unaffected (Pl. 5E). The preservation of quartz grains in secondary silica is noted by Hatch, Rastall, and Black, (1938, p. 90).

Relation to other cements. — In a description of cementing materials in sandstones of Mississippian to Cretaceous age in the Rocky Mountain region, Waldschmidt (1941, p. 1,858) indicates the following sequence of deposition of cements: quartz, dolomite, calcite, anhydrite. This type of sequence was not recognized in any of the sandstones examined by me. No beds or concretionary bodies in which both calcite and secondary silica were observable were noted in the field, and only one thin section (Twin Mounds, McPherson County) displayed this combination. The only other cementing material commonly found in association with silica is ferric oxide, some of which may be in the form of hematite.

The type of silica cement observed in a sandstone seemingly is related to the presence or absence of impurities in the sand. Chert cement or finely divided silica is associated with sandstone containing clay (as in the upper siltstone of the Dakota formation in Ford and Hodgeman Counties) or iron oxide (as in some samples from McPherson and Kearny Counties). Quartz cement occurs in the pure, well-sorted sandstones. This association is observed in other sands (Hadding, 1929, pp. 19-20).

Ankerite- and Celestite-cemented Sandstones

Ankerite cement occurs in a few concretionary sandstones in northern Washington County (Pl. 6A). Celestite cement occurs as very large crystals in a small lens of sandstone 6 inches thick and a few feet in lateral extent at the base of the Kiowa in northwestern McPherson County (SW¼ sec. 2, T. 17 S., R. 5 W.), where it is associated with the basal Cretaceous pebble zone (Plummer and Romary, 1942, p. 320). A thin section of this sandstone is shown in Plate 6E, which illustrates the close packing of the quartz grains and the absence of etching.

ORIGIN

Early theories of origin of the spheroidal, calcite-cemented sandstone concretions in the Dakota formation have been reviewed by Bell (1901) and Schoewe (Schoewe *et al.*, 1937, pp. 183-184). The concretions have been described as corals, as bunches of calcium carbonate-depositing algae, and as erratic boulders brought down to their present location by a continental ice sheet. Landes (1935), Schoewe (in Schoewe, *et al.*, 1937, p. 184), and Williams and Lohman (In press) have attributed the concretions and other carbonate- and silica-cemented sandstones in the Dakota and Kiowa formations simply to deposition by percolating ground water rich in those minerals subsequent to the deposition of the sandstone. Plummer and Romary (1942, p. 336) studied the stratigraphic occurrence of the calcite-cemented sandstones in greater detail and concluded that "the presence of the 'quartzite' is due to the fact that the conditions favorable to cementation are distributed at definite horizons and that, whenever a sufficiently permeable bed occurs, a 'quartzite' is formed at this horizon." Many of the sandstones attributed by Tester (1931, p. 279) to a marine embayment in northeastern Nebraska are cemented with calcium carbonate similar to that in the Dakota formation of Kansas.

Scattered areas of coarsely crystalline carbonate cement are not uncommon in sandstones of other ages and other localities. Walther (1924, pp. 74-75) believes that calcite sand-crystals, such as those of Fountainebleau, and barite sand-crystals are products of insolation and evaporation in desert areas. Jukes (1872; quoted by Rogers and Reed, 1926) relates the Fountainebleau sand-crystals to overlying beds of freshwater limestone, from which water percolated downward. Graham (1930, p. 704) describes sand-calcite crystals in the Upper Cambrian Jordan sandstone of Minnesota, and notes that they occur for some distance below the Oneota dolomite.

Mathias (1931) describes calcareous sandstone concretions (similar in general appearance to those of "Rock City") in the Upper Cretaceous Fox Hills sandstone in Colorado. He believes that they were penecontemporaneous with deposition of the Fox Hills sandstone because delicate algal structures are preserved, and he suggests that the source of the calcium carbonate would have been the overlying Fox Hills sea. Ross, Miser, and Stephenson (1929, pp. 184-185) describe coarsely crystalline calcite-cemented concretions in tuffaceous Woodbine sand of Arkansas and note that they must have formed soon after deposition of the tuff, because the volcanic glass within the concretions was prevented from being altered to bentonite. Similar deductions concerning concretions in the Hambre sand (Miocene) of California were made by Bramlette (1941).

A discussion of the origin of carbonate- (and silica-) cemented sandstones in the Dakota and Kiowa formations involves consideration of the following features: the degree of etching of the grains, the percentage of space occupied by cement, the common association with cone-in-cone, the restriction of carbonate cement to certain zones in the Dakota and its prevalence in the Kiowa shale, and its common association with marine shells and glauconite. The time of deposition of the cementing material must be established, and also the sequence of cements, if more than one type occurs. The ferruginous cement, which was not examined in detail, is not unusual and hypotheses of its origin will not be discussed to any great extent in the present report. Precipitation of iron, transported as the bicarbonate, may take place anywhere if oxygen enters the waters and carbon dioxide can escape (Twenhofel, 1939, pp. 383-384). This precipitation in some instances may be related to the position of the water table.

Origin of etched grains. — The etching of sand grains by carbonate-bearing waters, by calcite replacement, or by other causes, has been described by several writers. Ross, Miser, and Stephenson (1929, pp. 184-185) describe etched and corroded augite and orthoclase grains which have been partly replaced by calcite in the concretions of the Woodbine sand. They note that corroded augite also occurs outside the concretions and conclude that carbonate-bearing waters were also capable of corroding and etching augite. They observed that no minerals of igneous rocks except augite and orthoclase had been affected. Krynine (1940, p. 24) noted that calcite, dolomite, and ankerite-siderite had corroded and partly replaced quartz grains in the Third Bradford sand. Hatch, Rastall, and Black (1938, pp. 299-300) report that the quartz grains of many sandy limestones and dolomites are etched, and that sometimes the carbonate crystals have replaced the quartz along cracks passing through the grains, which then are reduced to corroded remnants. They indicate (p. 90) that alkaline solutions released from decaying feldspars are probably to some extent responsible for corrosion of detrital quartz. Storz (1928, pp. 67-78) also observes that the decomposition of feldspars causes etching of quartz grains. Quartz grains partly replaced by kaolinite have been described by several writers (Ries, *et al.*, 1922, pp. 161-162; Ross and Kerr, 1931) and this feature has been attributed to the action of sulfates derived from pyrite.

The mechanism of replacement of quartz and feldspar by calcite is a common one and, in the case of quartz, apparently reversible. No further light can be shed on it in this study. The thin sections show that the sand grains were etched *in situ* (Fig. 3) and one concludes, when aided also by microscopic examination of loose grains, that the sand when originally deposited was fairly well rounded, or at least not sharply angular. Loose sand collected from below the Kearny County quartzite shows a degree of etching similar to that in the calcite-cemented sands. Sand separated from clays in the Dakota and Kiowa formations is also etched. The only Dakota and Kiowa sands observed by me which were not affected by solvent action or replacement are cemented with silica, barite, or celestite; the sand in some quartzites, however, has been etched.

Space between grains. — The packing of the grains in the carbonate-cemented sandstones and in some of the silica-cemented

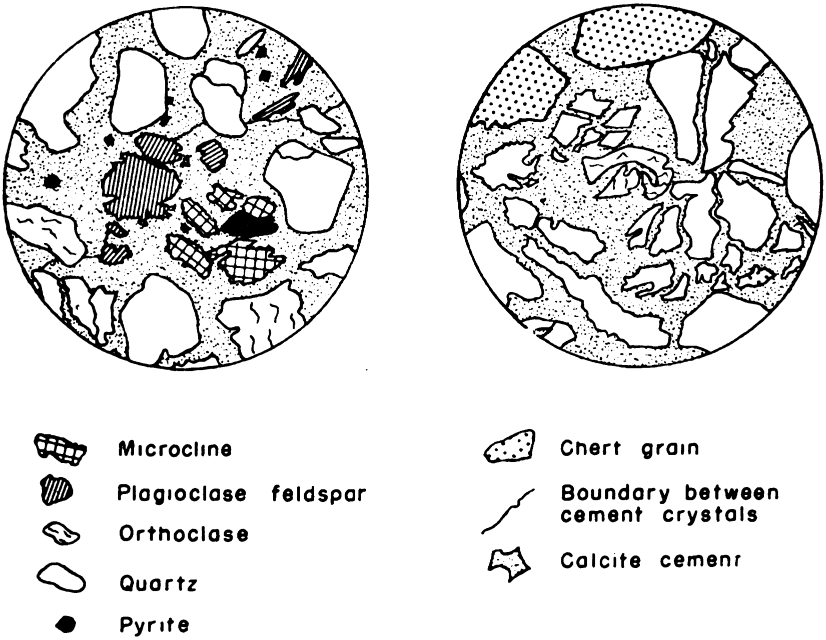

FIG. 3.—Drawings from thin section of calcite-cemented sandstone from Lincoln quarry, showing etched and displaced grains.

sandstones is extremely poor, and very few of the grains are in contact with each other. Hadding (1929, pp. 19-20, 204) writes that this condition in calcareous sandstones is due to the deposition of calcareous mud along with the sand grains, followed by recrystallization of the matrix. Two other causes for the wide spacing of the grains are apparent in thin sections from the Kiowa and Dakota formations, and it is therefore not necessary to postulate the deposition of a pure calcareous mud. The most obvious of these factors is the replacement of the outer parts of the grains by calcite. In some large areas of cement, outlines or "ghosts" of grains which have been completely replaced may be observed, and it is conceivable that the process of replacement might continue until calcite alone remains. The second factor, a quantitatively minor one, is the tendency of calcite to force particles apart during the course of crystallization. This is shown in thin sections of sandstone where the grains have been forced apart along incipient fractures and the fragments scattered and rotated so that they are no longer in optical continuity with each other (Fig. 3).

Sequence of cements. — As has been previously noted, quartz and calcite cement are not observed together in many thin sections of sandstones in the Kiowa and Dakota formations. The thin section (Fig. 2) from Twin Mounds, described above, perhaps sheds more light on the sequence of cementation than do the other thin sections, but it is by no means certain that the same conditions prevailed in all the areas of silica-cemented sandstone in the two formations. Study of this thin section suggests the following events after deposition of the sand. (1) Introduction of calcite cement. This is indicated by the presence of calcite in a fracture across one quartz grain, the replacement of part of a feldspar grain, and the occurrence of minute particles of calcite in the chert; by the etched appearance of many of the grains; and by the presence of grains which have been parted and rotated since deposition. The last two features are typical of the calcite-cemented sands and are not observed in most of the other sandstones, and are therefore thought to be fair evidence of the former presence of carbonate cement. (2) Introduction of silica cement replacing calcite. The chert is the earlier of the two types of silica cement present in this rock, for it occurs adjacent to the grains and in the fractured displaced grains. The quartz cement is later than the chert, for although it is optically continuous with the grains, there is in most parts of the thin section a thin layer of chert between the grain and the secondary quartz (Pl. 6D). The position of ferruginous material in the sequence is not clear. Some of it may be primary. Other parts, which occur in the chert as faint stains with rounded outlines, may be the remnants of decomposed or replaced feldspars.

In those thin sections of quartzite in which the sand grains are not etched, the evidence of replacement of carbonate is not clear, and the quartz or chert may be the primary cement. The only characteristic of these rocks which suggests that the latter is not the case is the relatively large amount of space between the grains. Chert and quartz seem to have been deposited simultaneously in several of the thin sections studied. Cayeux (1920) and Krynine (1941) describe primary quartz deposited on the sea floor during deposition of the sediment.

The position of barite in the sequence is in doubt. No grains embedded in the barite crystals (in the thin section from sec. 36, T. 14 S., R. 4 W., McPherson County) which had been fractured and rotated were noted. On the other hand, etching is present, but not to the degree that it is in the grains occurring in the adjacent calcite. The etching of the grains in the barite may have been effected (1) by ground-water solutions before cementation; (2) by incipient replacement of quartz and feldspar by calcite, followed shortly thereafter by replacement of the calcite by barite; or (3) by direct replacement of quartz and feldspar by barite.

The history of the dolomite cement is also unknown. It may be primary, but is generally considered to be a replacement of calcite. As the sand grains in the dolomite-cemented sandstones are less strikingly etched than those in calcite-cemented sandstones, the dolomite is judged to be either primary or to have replaced calcite shortly after the original cementation.

Time of cementation.—Two lines of evidence point to the hypothesis that cementation with calcite was penecontemporaneous (Richardson, 1921) with deposition of the sand. The first of these is the apparent restriction of the calcite-cemented sandstone to certain horizons, particularly in the Dakota formation. If it were due merely to circulating ground waters long after deposition, its distribution would be more haphazard, and it would not be so commonly associated with glauconite. The second evidence is more direct, and consists of a thickening of the sand bodies at the local areas where they are cemented from top to bottom with calcium carbonate. At one place in the Kanopolis quarry (sec. 19, T. 16 S., R. 6 W., Ellsworth County) calcite-cemented sandstone forms a sag or bulge in a sandstone bed overlying dark-gray shale, and a thin bed of cone-in-cone curves around the base of the cemented sandstone at the contact. This suggests that consolidation of the sediments took place after cementation, as has been suggested by Shaub (1937, p. 344) for other localities.

Supporting evidence of penecontemporaneous origin of similar calcareous sandstone bodies has already been noted in the literature (Mathias, 1931; Ross, Miser, and Stephenson, 1929, pp. 184-185, Bramlette, 1941.)

Some of the silica cement seems to have replaced calcite cement at an early stage, but some may have been introduced at a much later time, as indicated by the advanced stage of etching of the sand grains in some samples. Barite and celestite cement were probably formed fairly soon after deposition of the sand.

Causes of localization of cement.—The available evidence suggests that the calcite-cemented sandstone is related to a marine or near-marine environment. This evidence has been described earlier in the section on petrography. An immediate cause of deposition of the cement possibly is the mixing of fresh and marine waters, in sands at or immediately below the sea floor which are well sorted and permeable enough to allow the mixing to take place.

USES

The usefulness of the various sandstones in the Dakota formation and Kiowa shale depends upon the type of mineral with which they are cemented, and also upon their availability in deposits large enough to be exploited commercially. Several samples of carbonate-cemented sandstone were subjected to standard physical tests and chemical analyses by the Corps of Engineers, War Department. The results of these tests, which supplement the petrographic descriptions, have been furnished to us and are presented in Tables 3 and 4.

Although the ferruginous sandstone is the most prevalent type, and has been used extensively as a building stone in small structures, it is not high-quality building matrial, and its usefulness at present is restricted to riprap for a few stock ponds and to surfacing material for some county roads. The deposits of quartzite are scattered and most of them are too small to be of economic importance. The carbonate-cemented sandstones have the greatest present and potential usefulness and many of the following data are concerned with this type of rock.

Test Data

The data, furnished to us by the Corps of Engineers, War Department, Kansas City, Missouri, and reported in Tables 3 and 4, describe the results of physical tests on 30 samples from four localities in Lincoln and Ellsworth Counties and are restricted to carbonate-cemented sandstones—calcitic and dolomitic. Specific gravity was determined in accordance with A.S.T.M. Standard C127-42. The apparent specific gravity ranges from 2.65 to 2.70. The lowest observed gravities are those of calcite-cemented sandstone from sec. 12, T. 12 S., R. 8 W., and dolomite-cemented sandstone from sec. 7, T. 12 S., R. 10 W., Lincoln

County, and the highest represents calcite-cemented sandstone from the Kanopolis quarry in Ellsworth County. The bulk specific gravities, which are slightly lower, range from 2.55 to 2.66.

The percentage of absorption is fairly constant, and ranges from 0.3 to 1.3, the highest absorption being shown by a sample of dolomite-cemented sandstone from the Sylvan Grove quarry, Lincoln County. In determining absorption the test procedure was in accord with the A.S.T.M. standard test C-127-90, as modified by the Central Concrete Laboratory of the Corps of Engineers, (War Department, 1942, pp. 49-50). Specimens are prepared by quartering the field sample to a size of approximately 5 kg, rejecting all material passing a particular sieve. After drying to constant weight the sample is immersed in water at 15 to 25 degrees Centrigrade, thoroughly agitated to remove dust or other coatings from the particles, and allowed to absorb water for 24 hours. The material is then removed from the water, surface dried, and weighed. The percent absorption is calculated from the weight before and after immersion.

The freezing and thawing tests were made according to the A.S.T.M. standard test procedure C-137-38T, as modified by the Central Concrete Laboratory (War Department, 1942, pp. 69-73). Seven of the samples tested were subjected to five cycles of alternate freezing and thawing, and six to 25 cycles. The percentage of loss was computed by subtracting from the original weight of the sample the final weight of all particles which had not broken into three or more pieces during testing. Two of the seven samples subjected to the five-cycle test showed no loss whatever; and the highest loss, in a sample from the Lincoln quarry, was 1.2 percent. All these values are low. Magnesium sulfate tests (five cycles), which are designed to simulate the effects of a much larger number of freezing-thawing cycles as a measure of soundness, (A.S. T.M. standard C88-44T) were made on six samples; the loss ranged from 0.0 to 11.1 percent.

Abrasion tests were made in Deval and Los Angeles machines. In the Deval method, the crushed aggregate is placed in iron cylinders that are rotated on a shaft for 10,000 revolutions at a rate of 30 to 33 r.p.m. This test is designed to simulate resistance to wear under traffic conditions. At completion of the test the material is removed from the cylinders and sieved on a No. 12 (1,680 micron) sieve, the part passing the sieve being considered

TABLE 3.—*Data from standard physical tests of samples from calcareous sandstone in central Kansas*
(Data furnished by the Corps of Engineers, War Department, Kansas City, Missouri)

Lab. serial No.	County	Location	Type of sample	Specific Gravity			Absorption, percent	Freeze & thaw, 5 cycles, percent loss	$MgSO_4$ 5 cycles, percent loss	Abrasion		
				Apparent	Bulk	Bulk S.S.D.				Los Angeles, percent loss	Deval percent loss	Deval French coefficient
6128	Lincoln	6-12-7W	Ledge rock	2.68	2.64	2.65	0.67	0.00			2.54[1]	15.8[1]
9819[2]	do	do	Crushed rock	2.67	2.62	2.64	0.62				2.54[1]	15.7[1]
9820[3]	do	do	do	2.66	2.61	2.63	0.56				3.18[1]	12.5[1]
9819-9820[4]	do			2.67	2.61	2.63	0.73	1.2	11.1	45.0		
247709	do	do						0.0[1,5]				
247710	do	do									2.72[1]	14.7[1]
247711	do	do		2.65[1]			0.80[1]					
247715	Lincoln	NE¼ 12-12-8W	Ledge rock					0.0[6]				
247717	do	do	do	2.65			0.40					
247716	do	do	do								5.09	7.8
23934	do	do	do	2.66	2.63	2.64	0.3	0.23	0.61	46.2		
11562	Lincoln	NE¼ 7-12-10W	Ledge rock	2.67	2.61	2.63	0.76	0.0	0.0		1.72	23.2
21679	do	do	Crushed rock	2.68	2.62	2.65	0.8	0.3	2.0	37.8		
23997	do	do		2.65	2.60	2.62	0.68	0.04	0.26	37.7	2.27	17.6
27423	do	do	Crushed rock	2.65	2.56	2.60	1.3	0.32	2.45	46.3		
48681[16,7]	do	do	Ledge rock		2.55[8]	2.58[9]	1.2	1.5[10]		60.0		
48682[16,11]	do	do	do		2.56[8]	2.59[9]	1.3	0.6[10]		63.5		
48683[16,12]	do	do	do		2.62[8]	2.64[9]	0.8	0.3[10]		38.7		
48684[16,13]	do	do	do		2.61[8]	2.59[9]	0.9	0.5[10]		35.7		
54467[16]	do	do	Crushed rock							41.5		
54486[16]	do	do	do							43.0		
54564[16]	do	do	do							27.2[14]		
54562[16]	do	do	do							27.1[14]	4.44	9.0
8973	Ellsworth	E½ 19-16-6W	Ledge rock	2.69	2.65	2.66	0.57	0.06			2.27[1]	17.6
12018	do	do	Crushed rock	2.70	2.66	2.68	0.44		1.7	47.4		
18428	do	do	Ledge rock	2.69	2.67	2.68	0.3	0.2	0.4	55.96	18.81[1,14]	
18426	do	do	Crushed rock	2.69	2.67	2.68	0.3	0.27	1.56	60.4	13.62[1,14]	
50211	do	do								48.5[16]		
54494										32.8[16]		
15220 (K-1)	do	do		2.67	2.61	2.63	0.81	0.9	3.81	76.1		
12709[15]						2.66	0.83	3.5	33.6			

1. By Kansas City Testing Lab., Inc.
2. Sizes No. 4 to 1½ inches.
3. Sizes 1½ to 3 inches.
4. Samples 9819 and 9820 combined.
5. 25 cycles, loss 1.67 percent.
6. No spalling or disintegration in 25 cycles but 20 percent of pieces split in two.
7. Sample from 40-foot face at SW edge of proposed quarry.
8. Reported as "dry."
9. Reported as "saturated."
10. 25 cycles.
11. Sample from top 12 feet in NW corner of proposed quarry.
12. Sample from top 16 feet in SE corner of proposed quarry.
13. Sample from top 20 feet in NE corner of proposed quarry.
14. A.S.T.M. method D-289-42T, with abrasive charge.
15. Crushed to sand size.
16. By Kansas State Highway Commission Laboratory.

TABLE 4.—*Report of chemical analyses of samples from calcareous sandstone in central Kansas*
(Data furnished by the Corps of Engineers, War Department, Kansas City, Missouri)

Lab. serial No.	County	Location	Chemical analysis (percent)										
			Ignition loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Undeter-mined	Soluble in HCl
9820	Lincoln	6-12-7W	16.00	62.70	1.84	0.42	18.22	0.37	0.00	......	......	0.45	37.28
9819	do	do	15.20	63.50	1.86	0.64	18.08	0.37	0.00	......	......	0.35	36.08
247711[1]	do	do	16.31	60.62	0.03	1.48	21.24	0.00	0.00	......	......	0.28	40.50
6128	do	do	15.68	61.10	1.32	0.50	19.92	0.87	0.09	......	......	0.52	34.78
23934	Lincoln	NE¼ 12-12-8W	14.95	63.11	1.75	0.00	19.82	0.37	0.00	[2]	[2]		34.91
23934[3]	do	do	15.24	62.26	0.95	0.21	20.60	0.55	0.00		......	0.19	35.00
9819	do	do	14.55	64.02	1.07	0.83	19.12	0.38	0.00	[4]	......	......	35.27
247717[5]	do	do	15.74	64.42	0.08	0.92	18.46	0.00	0.00	......	......	0.34	37.54
11562[6]	Lincoln	NE¼ 7-12-10W	16.16	64.38	1.98	0.18	11.58	5.64	0.00	[7]	[7]	0.08	35.22
[8]	do	do	15.70	63.30	1.08	1.52	12.22	5.61	0.00	[9]	[9]	0.45	35.01
23997[8]	do	do	16.92	60.86	2.40	1.62	12.93	5.07	0.00	[10]	[10]	0.10	37.97
27423[8]	do	do	15.04	63.32	0.98	2.66	14.14	3.68	0.01				34.04[11]
8973[6]	Ellsworth	E¼ 19-16-6W	16.20	62.42	1.12	0.16	19.18	0.60	......	......	......	0.32	37.00
21092[6]	do	do								0.34[12]			
12709[13]	do	do	12.65	65.12	1.34	1.34	17.06	1.05	0.07	......	......	1.37	32.00

1. Moisture, 0.04 percent.
2. Na_2O+K_2O, 0.09 percent; alkali as Na_2O equivalent, 0.06 percent.
3. Sample represents material lost in L.A. abrasion test.
4. Na_2O+K_2O, 0.03 percent, average of two tests.
5. Moisture, 0.04 percent.
6. Ledge rock.
7. Na_2O and K_2O not determined.
8. Crushed rock.
9. Na_2O+K_2O, 0.12 percent.
10. Total alkali as Na_2O, 0.09 percent; Na_2O+K_2O, 0.10 percent.
11. Insoluble residue, 65.96.
12. Na_2O+K_2O, 0.51 percent; alkali as Na_2O equivalent, 0.34 percent.
13. Rock dust from crusher.

as a measure of the wear. Wear is expressed either as percent of loss of original sample, or as the French coefficient of wear calculated by dividing the weight in grams of the detritus under 0.168 cm in size, per kilogram of rock used, into 400. The test procedure was according to A.S.T.M. standard method D-289-42T (A.S.T.M., 1944, pp. 1,369-1,371). Of the nine samples tested by the Deval method, the range in French coefficient is from 7.8 to 23.2; the highest represents dolomite-cemented sandstone from the Sylvan Grove quarry, and the lowest, calcite-cemented sandstone from sec. 12, T. 12 S., R. 8 W., Lincoln County. Six of the samples have a French coefficient of more than 14. According to Nash (1918, p. 148), "The best wearing rocks have a percent of wear of 2 or coefficient of 20. If this coefficient of wear is below 8, it is considered as low; from 8 to 13 medium; from 14 to 20 high; and above 20, very high."

In the Los Angeles test (War Department, 1942, pp. 91-93), the crushed sample is placed in a steel cylinder with cast-iron spheres, and the machine is rotated for 500 revolutions at a speed of from 30 to 33 r.p.m. At the completion of the test the material is sieved on a No. 12 sieve, as in the Deval test. The difference between the original weight and the final weight of the sample retained on the sieve is expressed as a percentage of the original weight of the test sample, and this value is reported as the percentage of wear. Seventeen samples were subjected to this test, and the percentage of wear ranged from 32.8 to 76.1. All but one lost more than 35 percent, and only four others lost less than 40 percent. These figures indicate rather low resistance to abrasion. The discrepancy between the two types of abrasion tests reflects a difference in the type of abrasion that takes place. The Deval machine produces a loss of material primarily by wear, and the Los Angeles machine chiefly by impact.

Solubility of the sandstone in hydrochloric acid (Table 4) ranges from 32 to 40 percent, and chemical and petrographic analyses show that most of the acid-soluble fraction consists of carbonate cement. The sample with the lowest solubility is rock dust from the crusher in the Kanopolis quarry, and a slightly lower content of carbonate cement is to be expected. Chemical analyses show the silica content to range from 61 to 65 percent in all samples. Magnesium oxide is 1 percent or less except in the samples from the Sylvan Grove quarry, where it is nearly 6 percent. The percent of iron oxide is 2.7 or less, and aluminum oxide less than 2.5.

Conclusions

The data presented in this report, together with information supplied by the State Highway Commission and other users, indicate that the carbonate-cemented sandstone in the Dakota and Kiowa formations is high-quality rock for concrete aggregate and other uses. Peyton (1946, p. 104), in a study of the effect of coarse aggregate on the condition of concrete pavements in Kansas, gives unqualified approval to the Lincoln sandstone or "quartzite." He writes: "Nearly 7 percent of the pavements examined contain this material. Its record is universally good without regard to age." Concrete pavements in which this material has been used as aggregate and which have been in use for 20 years or longer are located in the towns of Lincoln, Minneapolis, Bennington, Salina, and on U. S. Highway 81 between Minneapolis and Bennington (personal communication, J. R. Carlgren). The rock has also been used successfully as riprap, road metal, secondary railroad ballast, filter stone for sewage disposal plants, and as aggregate for concrete blocks and tile. It is not used as a building stone because it breaks into angular fragments instead of along bedding and joint planes, and because occasional pyrite nodules cause prominent brown stains upon weathering.

Physical test data on the other types of sandstone which occur in the Dakota and Kiowa formations are not available, but Table 5, furnished by the Corps of Engineers, War Department, provides a comparison of the calcite-cemented sandstone with a few other materials in the Kansas City district. The test data on each of 12 materials have been averaged in order to summarize their characteristics. Only one sample—the Tonganoxie quartzitic sandstone—has a lower absorption than has the Dakota carbonate-cemented sandstone. Two samples—Fort Scott limestone and Tonganoxie sandstone—show less loss on the freeze-thaw test (five cycles). The Dakota sandstone shows the least loss of the six samples undergoing the magnesium sulfate test. The average percent loss on the Los Angeles abrasion test is high, and is exceeded only by tests on the Fort Hays chalky limestone and the Fort Riley dolomite, but only six of the rocks were subjected to

TABLE 5.—*Summary of physical test data of construction materials in Kansas*

(Data furnished by the Corps of Engineers, War Department, Kansas City, Missouri)

					Specific gravity				Absorption	
					Apparent		Bulk (S.S.D.)			
Geologic age	Formation	Member	Rock type	Sample location	No. of tests	Average	No. of tests	Average	No. of tests	Average percent
Tertiary	Ogallala		Chert	Rawlins Co., Kansas	1	2.31	1	2.21	1	3.27
Tertiary	Ogallala	"Quartzite" opaline ss.	"Quartzite" opaline ss.	NW Kansas, SW Nebraska	16	2.45	16	2.38	18	1.95
Cretaceous	Niobrara		Silicified chalk	NW Kansas	1	2.45	1	2.35	2	2.06
Cretaceous	Niobrara	Fort Hays	Chalky limestone	Jewell Co., Kansas	1	2.50	1	2.08	1	15.5
Cretaceous	Dakota		"Quartzite" calcareous ss.	Ellsworth & Lincoln Cos., Kans.	10	2.67	10	2.65	10	0.56
Permian	Barneston	Fort Riley	Dolomite	Marshall Co., Kansas	2	2.67	2	2.40	2	7.2
Pennsylvanian	Deer Creek	Ervine Creek	Limestone	Elk Co., Kansas	4	2.69	4	2.62	8	1.52
Pennsylvanian	Oread	Plattsmouth	Limestone	Atchison Co., Kansas	3	2.68	3	2.56	5	2.16
Pennsylvanian	Stranger	Tonganoxie	Quartzitic sandstone	Woodson Co., Kansas	1	2.64	....	....	1	0.43
Pennsylvanian	Plattsburg	Spring Hill	Limestone	Anderson Co., Kansas	1	2.69	1	2.62	1	1.58
Pennsylvanian	Wyandotte	Argentine	Limestone	Johnson Co., Kansas	1	2.71	1	2.65	1	1.30
Pennsylvanian	Fort Scott	Higginsville	Limestone	Bourbon Co., Kansas & Bates Co., Missouri	1	2.63	...	....	1	1.38

					Soundness tests				Abrasion tests				
					Fr-thaw, 5 cycles		$MgSO_4$, 5 cycles		Los Angeles		Deval		
Geologic age	Formation	Member	Rock type	Sample location	No. of tests	Average loss, percent	No. of tests	Average loss, percent	No. of tests	Average loss, percent	No. of tests	Average loss, percent	French coef-ficient
Tertiary	Ogallala		Chert	Rawlins Co., Kansas	1	0.49	..	......	..	......	1	8.54	4.7
Tertiary	Ogallala	"Quartzite" opaline ss.	"Quartzite" opaline ss.	NW Kansas SW Nebraska	18	0.49	7	5.69	7	35.8	9	4.89	8.9
Cretaceous	Niobrara		Silicified chalk	NW Kansas	2	0.50	..	......	..	......	1	3.95	11.1
Cretaceous	Niobrara	Fort Hays	Chalky limestone	Jewell Co., Kansas	1	5.00	1	14.3	1	48.6	..	......	......
Cretaceous	Dakota		"Quartzite" calcareous ss.	Ellsworth & Lincoln Cos., Kans.	11	0.44	8	2.68	8	47.4	7	2.87	15.3
Permian	Barneston	Fort Riley	Dolomite	Marshall Co., Kansas	2	2.30	2	39.2	2	63.5	..	......	......
Pennsylvanian	Deer Creek	Ervine Creek	Limestone	Elk Co., Kansas	2	1.87	2	17.0	6	34.4	..	......	......
Pennsylvanian	Oread	Plattsmouth	Limestone	Atchison Co., Kansas	7	5.54	3	10.5	3	32.0	5	4.67	8.8
Pennsylvanian	Stranger	Tonganoxie	Quartzitic sandstone	Woodson Co., Kansas	1	0	..	......	..	......	1	1.18	33.9
Pennsylvanian	Plattsburg	Spring Hill	Limestone	Anderson Co., Kansas	1	0.62	..	......	..	......	1	4.81	8.3
Pennsylvanian	Wyandotte	Argentine	Limestone	Johnson Co., Kansas	2	4.80	..	......	..	......	1	4.54	8.8
Pennsylvanian	Fort Scott	Higginsville	Limestone	Bourbon Co., Kansas, & Bates Co., Missouri	2	0.01	..	......	..	......	2	4.13	10.0

this test. Of the nine values recorded for the Deval French coefficient, only that for the Tonganoxie quartzitic sandstone exceeds the Dakota average.

OCCURRENCE BY COUNTIES

The following paragraphs present a description of the larger areas of calcite- and dolomite-cemented sandstone and silica-cemented sandstone in the Dakota and Kiowa formations of Kansas. Areas of large numbers of calcite-cemented sandstone concretions are discussed, but are not considered to be of economic importance. Ferruginous sandstone is not included in this section, except in a few instances where quarries have been noted. No core data were available, and estimates of the available tonnage are omitted because of the erratic pattern of cementation and because natural outcrops of the calcareous sandstone do not permit accurate estimation of its thickness. Special note is made of any areas of calcareous sandstone which may prove to be of economic value.

Clay County

Two large concretionary bodies of calcite-cemented sandstone near the Clay-Cloud County line 1½ miles west of Oak Hill are reported by the County Engineer to have been used on State Highway 9. No other large quantities of calcareous sandstone were observed in the county. There are several small county quarries in ferruginous sandstone: in the west side of sec. 25, T. 8 S., R. 1 E., 2 miles south of Idana, a bed of dark-brown sandstone 8 to 10 feet thick capping a prominent hill has been quarried for road material. Some of the hardest ferruginous sandstone in the county occurs in a large hill along the west line of sec. 3, T. 6 S., R. 2 E., 6 to 7 miles north of Morganville. There is a small quarry at the south end of the hill.

Small isolated calcareous sandstone concretions are observed in various parts of the county, as, for example, in a road cut in the NE cor. sec. 17, T. 10 S., R. 1 E., 1 mile north of Longford, and at the SW cor. sec. 7, T. 9 S., R. 1 E., near the Cloud County line. Thin beds of calcite-cemented sandstone occur in the SW cor. sec. 22, T. 9 S., R. 1 E., 1½ miles east of Oak Hill, and in the N½ NE¼ sec. 17, T. 9 S., R. 1 E., 2 miles north of Oak Hill.

Dickinson County

Extensive ledges of calcite-cemented sandstone, some of which contains barite sand-crystals, have been reported in the "Black Hills" southwest of Elmo. Two small areas of calcite-cemented sandstone were observed in the NW¼ sec. 35, T. 16 S., R. 1E., but the sandstone is of poor quality because of the presence of iron, and the deposits are not large enough for exploitation.

Ellsworth County

Large quantities of calcite-cemented sandstone have been quarried in the SE¼ sec. 19, T. 16 S., R. 6 W., for use in the construction of the Kanopolis dam. This quarry is in an extensive area of calcareous sandstone which extends to the west and northwest, and crops out in at least five sections south of the Smoky Hill River, where it attains a thickness of several feet near a group of farm buildings in the NW¼ sec. 30, T. 16 S., R. 6 W. In the N½ sec. 18 of the same township the rock is exposed on both sides of the Smoky Hill River; on the north side of the river it is at least 50 feet thick. In the summer of 1947 a new quarry was opened in this area, in the NE¼ sec. 24, T. 16 S., R. 7 W., where a maximum thickness of about 40 feet was reported from test drilling (personal communication from Stafford C. Happ to John C. Frye).

In the original Kanopolis quarry, at which site there were probably at least 250,000 tons available, the hard sandstone crops out on both sides of a small ravine. At the time the quarry was examined, the calcareous sandstone seemed to occur at two levels, a fairly continuous lower one, attaining a thickness of more than 8 feet, and an upper zone consisting of large concretionary bodies 10 to 12 feet in diameter and 3 or more feet thick. Much of the lower quartzite contains pyrite. Between the two is a bed 6 inches to 3 feet thick of clay or shale containing cone-in-cone.

A discontinuous bed of calcite-cemented sandstone about 5 feet thick may be traced for several hundred feet in sec. 33, T. 15 S., R. 7 W., about 2½ miles east of Kanopolis, on the east side of the Smoky Hill River (Twenhofel and Tester, 1926). The total quantity present is not known. Calcite-cemented sandstone concretions, occurring alone and in small groups, are common in the Dakota in the eastern part of Ellsworth County. They may be observed at several places near Highway U. S. 40 between Carneiro and the Saline County line.

Kearny County

A hard, 3- to 5-foot ledge of silica-cemented sandstone extends for nearly a mile in sec. 17, T. 25 S., R. 37 W., on the south side of the Arkansas River 2 miles west of Hartland. The overburden is only a few feet thick, and consists of unconsolidated sand and gravel. J. M. Jewett (personal communication) reports that a test hole shows the presence of the same thickness of quartzite for several yards at least, back under the sand and gravel. Small amounts of opal may occur in some parts of this rock, as in other areas of quartzite in the Dakota and Kiowa formations. No other outcrops of the Dakota formation are known to occur in Kearny County (McLaughlin, 1943).

Lincoln County

Although calcareous sandstone has been quarried in Lincoln County since 1921, the largest reserves are still thought to occur in this area. The rock was first quarried 1 mile southeast of Lincoln by the Lincoln Crushed Stone Company of Concordia. In 1924 the Lincoln quarry was sold into new hands but retained the old name; in 1931 in was sold to J. R. Carlgren and called thereafter the Quartzite Stone Company. The rock has been quarried from a solid ledge of hard sandstone, 500 feet long and from 15 to 40 feet thick, but the location is now abandoned. Mr. Carlgren (personal communication) reports that probably 2 million tons have been removed since 1921; since 1931 at the rate of 100,000 tons per year. Large reserves of calcareous sandstone occur southwest of Lincoln in a lentil or series of lentils in secs. 12, 13, 14, 23, and 24, T. 12 S., R. 8 W. In parts of secs. 12 and 13 it attains a thickness of more than 30 feet.

Dolomite-cemented sandstone is quarried by the Quartzite Stone Company at a new location in the NE¼ sec. 7, T. 12 S., R. 10 W., near State Highway 18, 5 miles west of Sylvan Grove (Pl. 1A). In this area a large lentil of hard sandstone one-half mile in diameter and up to 50 feet or more thick is traversed by Wolf Creek, a tributary to the Saline River (Pl. 7). The total quantity of rock here is estimated at more than 5 million tons.

Small quantities of calcite-cemented sandstone occur in other parts of the county, as, for example, along East Elkhorn Creek in the W½ sec. 10, T. 13 S., R. 7 W., and in the SE¼ sec. 1, T. 11 S., R. 6 W.

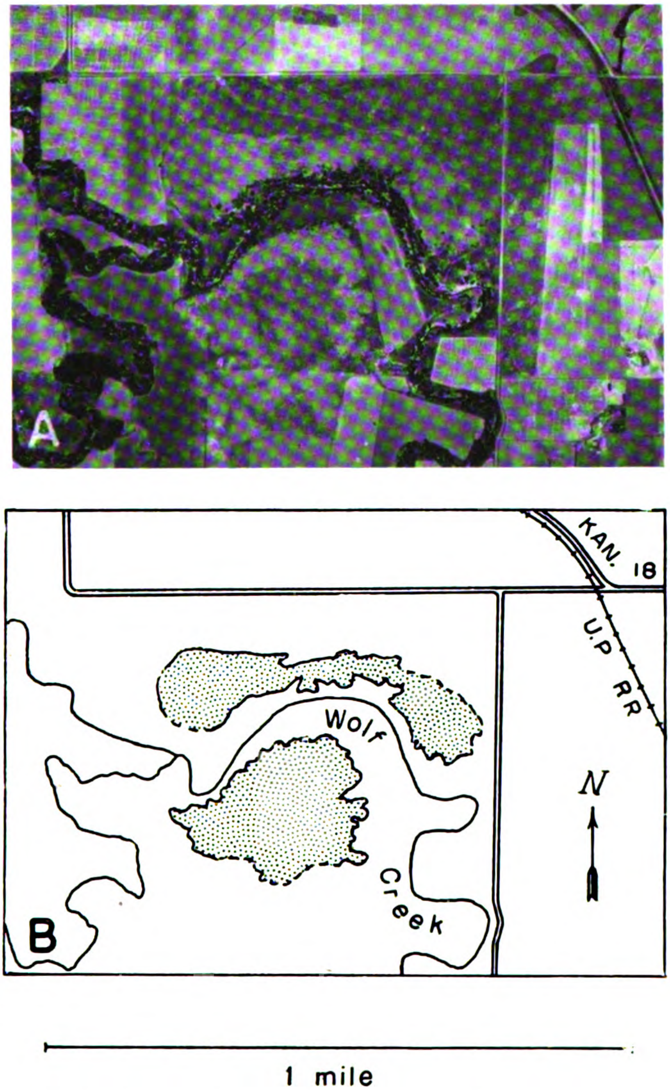

PLATE 7.—*A*, Aerial photograph of lentil of dolomite-cemented sandstone in sec. 7, T. 12 S., R. 10 W., Lincoln County. Site of Sylvan Grove quarry. (U. S. Dept. of Agriculture photograph) *B*, Sketch map of same area, showing outlines of the lentil, roads, railroad, and drainage.

McPherson County

Two large areas of calcite-cemented sandstone occur in McPerson County. One is 3 miles west of Roxbury; the other is a long series of lentils trending south from sec. 2, T. 18 S., R. 2 W., to sec. 6, a distance of about 4 or 5 miles. The deposit west of Roxbury crops out in a long hill or ridge in the NE¼ sec. 25, and the E½ sec. 24, T. 17 S., R. 2 W. (Pl. 4C). The southern part of the ridge is capped with thin silica- and iron-cemented sandstone. The rock, which ranges in thickness from a featheredge to 15 feet or more, locally contains barite sand-crystals and has been quarried by the W.P.A. in the NE¼ sec. 25. Mr. H. F. Gonnerman, Director of Research, Portland Cement Association, reports (personal communication) that small quantities of barite (less than 2 percent) when present in a calcareous sandstone used for aggregate are not believed to have any deleterious effect on concrete.

There are at least two abandoned quarries in the other large area of calcite-cemented sandstone. The county has removed several tons of rock for road material from a quarry (Pl. 2C) in the NE¼ sec. 14, T. 18 S., R. 2 W., east of the North Diamond district school. A small worked-out quarry is located along the south line of the SW¼ sec. 23. The total quantity of sandstone available in the area is judged to be more than 1 million tons.

Small quantities of silica-cemented sandstone cap Twin Mounds (NW¼ sec. 1, T. 18 S., R. 2 W.) and form a low hill in the west side of sec. 15, T. 18 S., R. 1 W., 4½ miles south of Roxbury. In the latter vicinity, three similar hills of quartzite have been removed. Isolated concretions of dolomite-cemented sandstone are observed near the base of the northern Twin Mound, and in the south side of the SE¼ sec. 19, T. 17 S., R. 2 W., 8 miles west of Roxbury.

Ottawa County

The only locality known to me in which calcareous sandstone occurs in quantities large enough to be quarried is in the SE¼ sec. 20, T. 9 S., R. 2 W. The deposit is small, and some of it has been removed for road material.

Rice County

A lenticular area of calcite-cemented sandstone extends from the SE¼ SW¼ sec. 20, T. 20 S., R. 6 W. along the top of a hill northeastward to the SW¼ NW¼ sec. 15, T. 20 S., R. 6 W. The rock is poorly exposed, but its thickness in some places is observed to be at least 10 feet, and may be much more.

Another area of calcite-cemented sandstone of considerable extent occurs near Raymond in the southwestern part of the county. The sandstone crops out along the valley side of the Arkansas River from the SW¼SE¼ sec. 21, T. 20 S., R. 10 W. to the SW¼SE¼ sec. 26. Its thickness is about 5 feet, and it has been quarried to a small extent.

Saline County

A large quarry in a hillside in thick, calcite-cemented sandstone is located in the NW¼ sec. 36, T. 14 S., R. 4 W., 2 miles east of Bavaria. This quarry was first leased by a private contractor, then by the Army for Camp Phillips. It was recently leased by another private contractor. The quartzite is fine- to medium-grained with numerous sand-barite nodules, and several hundred thousand tons seems to be available. No other large quantities have been observed in the county.

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