PETROLOGY OF THE PLIOCENE PISOLITIC LIMESTONE IN THE GREAT PLAINS

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ABSTRACT

Petrographic study of 34 oriented samples of pisolitic ("algal") limestone from the upper part of the late Tertiary Ogallala Formation in Kansas, Oklahoma, and west Texas indicates that the rock sampled was developed by predominantly soil-forming processes acting upon sands and silts of the uppermost Ogallala. The absence of fossils, replacement of sand grains by calcite, anomalous distribution of detrital grains with respect to oölites and bulbous structures, and the inverted orientation of the bulbous structures themselves, all argue against algal origin of the rock.

The origin of the limestone is similar to that of the well-developed caliche in southeastern New Mexico described by Bretz and Horberg, except that limestone gravels were not required for formation of the Kansas rock. The concretionary structures are analogous to those formed in bauxites. Conditions favoring development of pisolitic limestone were (1) presence of rocks containing easily soluble minerals yielding residues rich in Ca^{2+} ion; (2) effective rock permeability; (3) deficient rainfall and long dry periods; (4) low topographic relief; and (5) time.

INTRODUCTION

An unusual, thin, discontinuous layer of limestone occurs at the stratigraphic top of the Neogene Ogallala Formation in the central High Plains region. This bed is commonly 1 to 3 feet thick, and in the past it generally has been referred to in Kansas and Nebraska as the "Algal limestone". Its presence as the capping bed of a sequence of fluvial deposits and its prominent exposure on scarps and canyon walls, together with its almost unique physical characteristics, have led to much speculation during the last 25 years concerning its origin. Hypotheses of origin include deposition in a large shallow lake, or a series of lakes, and development by subaerial weathering processes.

The name "Algal" comes from the assertion by Elias (1931, p. 138) that the rocks contain an alga (*Chlorellopsis bradleyi* Elias). As this plant was presumed to demand a permanent body of water for its growth, a lacustrine environment was postulated for the rock. It is true that there is a strong similarity between structures observed in this limestone and algal structures observed in some older rocks.

Many objections have arisen to such a lake in the High Plains region in late Pliocene time. Smith (1940, p. 90) discussed the structural implications and pointed out the strong evidence against the concept that a shallow lake of this type covered a significant portion of the High Plains region. Other workers have discussed other objections, and more recently an alternate hypothesis of origin for superficially similar limestones in New Mexico has been proposed (Bretz and Horberg, 1949). In 1957 Frye and Leonard showed that the interval of time at the close of Pliocene deposition was the culmination of a time trending toward aridity in the Great Plains.

As part of a program of petrographic and stratigraphic studies in the central High Plains we undertook a detailed petrographic study of this unusual rock, based on samples (34 of which were of known orientation) from Kansas, Oklahoma, and west Texas (Fig. 1), in an effort to gain new information about its origin.

The main controversy over origin revolves around the question of formation in a lake or lakes versus formation under a weathering surface. The general presence or absence of an alga that requires permanent open water therefore becomes a major consideration. It is our judgment that the many characters of the rock that point toward subaerial origin outweigh those indicating formation in a lacustrine environment. It is our purpose here to review the petrographic data bearing on this problem.

The stratigraphic position of the limestone is as distinctive as its unique petrography. In Kansas, western Oklahoma, and northwestern Texas—the area under consideration here—the limestone is found only at the stratigraphic top of the Ogallala Formation (or Group) and is variously classified as a part of the Kimball formation, member, and floral zone in Nebraska, Kansas, and Texas, respectively. The Ogallala Formation is a complex of stream deposits that accumulated during Neogene time. Deposition started within valleys leading eastward from the Rocky Mountain region, but as deposition proceeded, the alluvial plain spread laterally, eventually engulfing and blanketing the preexisting topography throughout the Great Plains region northward from Howard County, Texas. In the Edwards Plateau of Texas, source of the southernmost samples described here, the Ogallala consists of thin discontinuous patches of medium to coarse clastic material on Cretaceous limestones and occupies an intermediate position in the topography (Frye and Leonard, 1957a). The climax of Ogallala deposition in the High Plains resulted in a coalescent

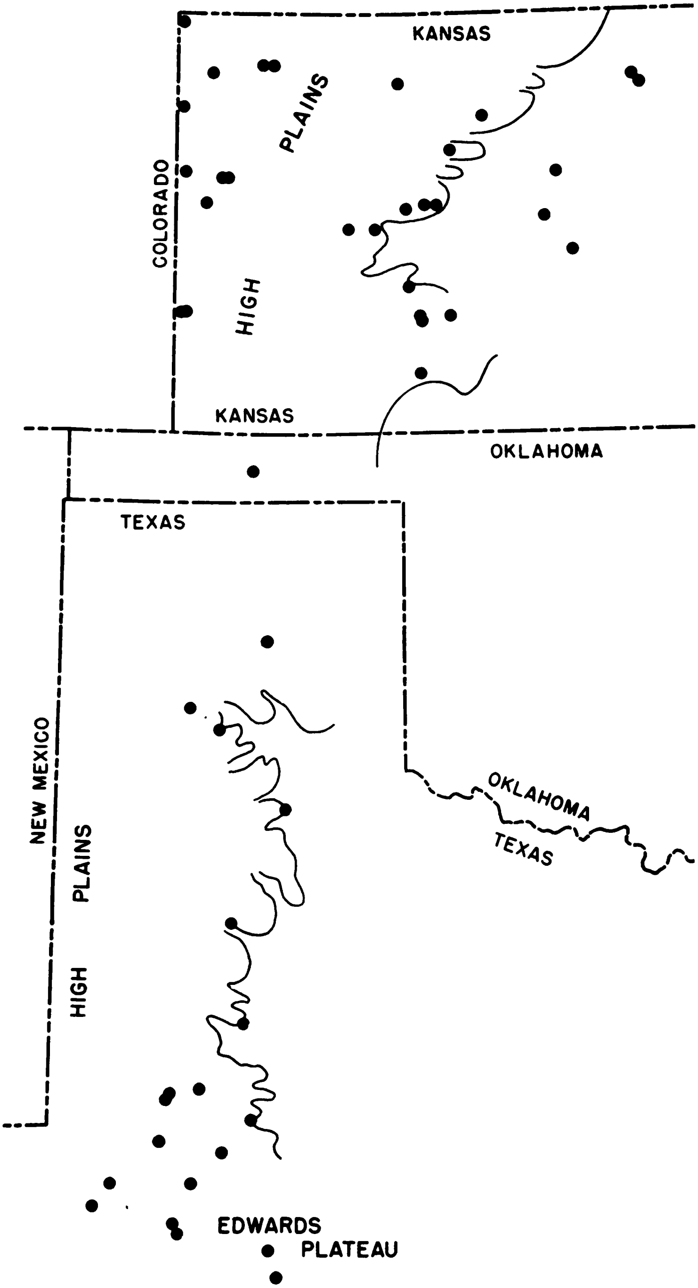


FIG. 1.—Location map, each dot representing a locality from which samples of pisolitic limestone were collected for study.

plain of alluviation, sloping generally eastward, and presenting only the constructional relief features typified by channels, natural levees, and interstream depressions (Frye, Leonard, and Swineford, 1956). Prior to Pleistocene dissection this surface remained at equilibrium for an unknown period of time (middle or late Pliocene to Nebraskan), and it was on this constructional surface that the limestone formed as the topmost layer of a prominent zone strongly infiltrated with calcium carbonate. Its consistent stratigraphic position is confirmed by paleontologic, paleobotanic, physiographic, and regional stratigraphic evidence. Although rocks of superficially similar lithology may occur at other stratigraphic positions in southwestern Texas and adjacent New Mexico, in western Kansas it has been established that lithologically similar limestone does not occur at other stratigraphic positions in the underlying parts of the Ogallala Formation or in the younger, Pleistocene units.

PETROGRAPHY OF THE PISOLITIC LIMESTONE

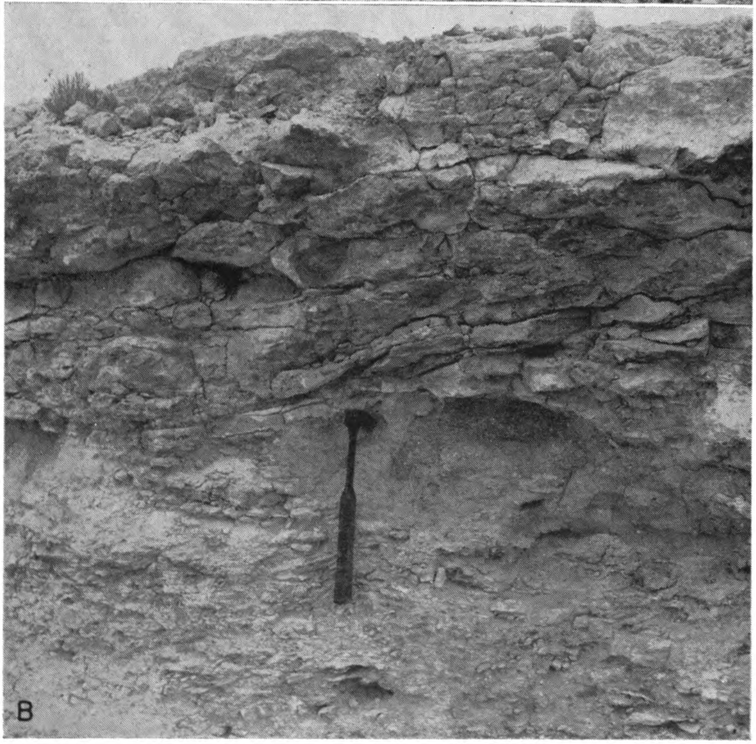
Field Expression

The pisolitic (or so-called "algal") limestone characteristically occurs as a discontinuous zone of white to pink, large nodules of hard dense limestone (Pl. 1A). The zone is about 1 foot thick or less and is the topmost layer of the calcareous upper part of the Kimball Member. Where best developed it forms a continuous layer 2 or 3 feet thick but without bedding planes (Pl. 1B). It occurs at the surface or is overlain by a thin mantle of Pleistocene loess or eolian sand. Secondary encrustations of white calcium carbonate coat the bottom and sides of the nodules.

The greatest density and the deepest pink color generally are near the top of the pisolitic limestone, which grades downward into white, flaky, platy to massive calcareous silt and sand of the Kimball Member of the Ogallala Formation. In some localities the underlying silt and sand is crisscrossed by anastomosing veinlets of fine-grained calcite. Opaline material as nodules, root tubules, and lentils is common below the limestone at some localities.

The surface of the limestone is not everywhere level; at a few localities it has a gentle slope of as much as 15 feet in a distance of 100 feet. The pisolitic limestone has also been observed to follow the microtopography; at several localities (e. g., near Muleshoe,


A


B

Texas, and in the SE¼ SE¼ sec. 24, T. 18 S., R. 29 W., Lane County, Kansas) it dips sharply into steep-walled depressions as much as 4 feet deep and 5 feet in diameter.

Structure and Petrography

The structure and petrography of the pisolitic limestone were studied by means of oriented vertical polished sections and thin sections. Acid-insoluble residues were made from 13 samples, and a few of the mineral constitutents were checked by x-ray diffraction. A few thin sections are shown on Plate 2, and polished sections are illustrated on Plates 3 and 4.

Laminar and concentric structures.—Both laminar and concentric structures are observed on the polished sections. Continuous laminar structures are particularly well developed in the lower parts of many specimens. Some samples show remnants of laminar structures that were once continuous and have been partly destroyed and rotated within the rock (Pl. 4 A,B).

Concentric structures range in diameter from a fraction of a millimeter to slightly more than a centimeter. Some of these structures contain detrital quartz or feldspar grains as nuclei (Pl. 2E), but in others detrital grains are not observed or are in noncentral positions. In general, there is no consistent relationship between grains and concentric structures. In some specimens the pisolites are essentially equidimensional, but in other specimens they are lopsided in one or more directions. The direction of growth of the outer layers of most asymmetric pisolites, however, is downward. In all samples in which growth is predominantly in one direction, it is downward (as in Pl. 3A).

At localities in which the pisolitic limestone is separated from Cretaceous bedrock by only a few feet, pebbles of Cretaceous limestone are incorporated in the pisolitic limestone (Pl. 3F). These pebbles serve as nuclei for the larger growth units of the limestone, and as such they are somewhat similar to the cupped limestone pebbles of Bretz and Horberg (1949). Although few of the pebbles have a notably cupped shape, they show abundant

Plate 1.—Field views of pisolitic limestone. **A.** Nodular pisolitic limestone overlying Ogallala sand and silt above Kiowa formation in road cut at cen. N½ sec. 27, T. 19 S., R. 10 W., ½ mile north of Raymond, Rice County, Kansas. One of easternmost occurrences of the limestone. **B.** Thick, dense pisolitic limestone grading downward into platy calcareous silt and sand that contain opaline nodules. Road ditch in NW¼ sec. 27, T. 1 S., R. 42 W., Cheyenne County, Kansas.

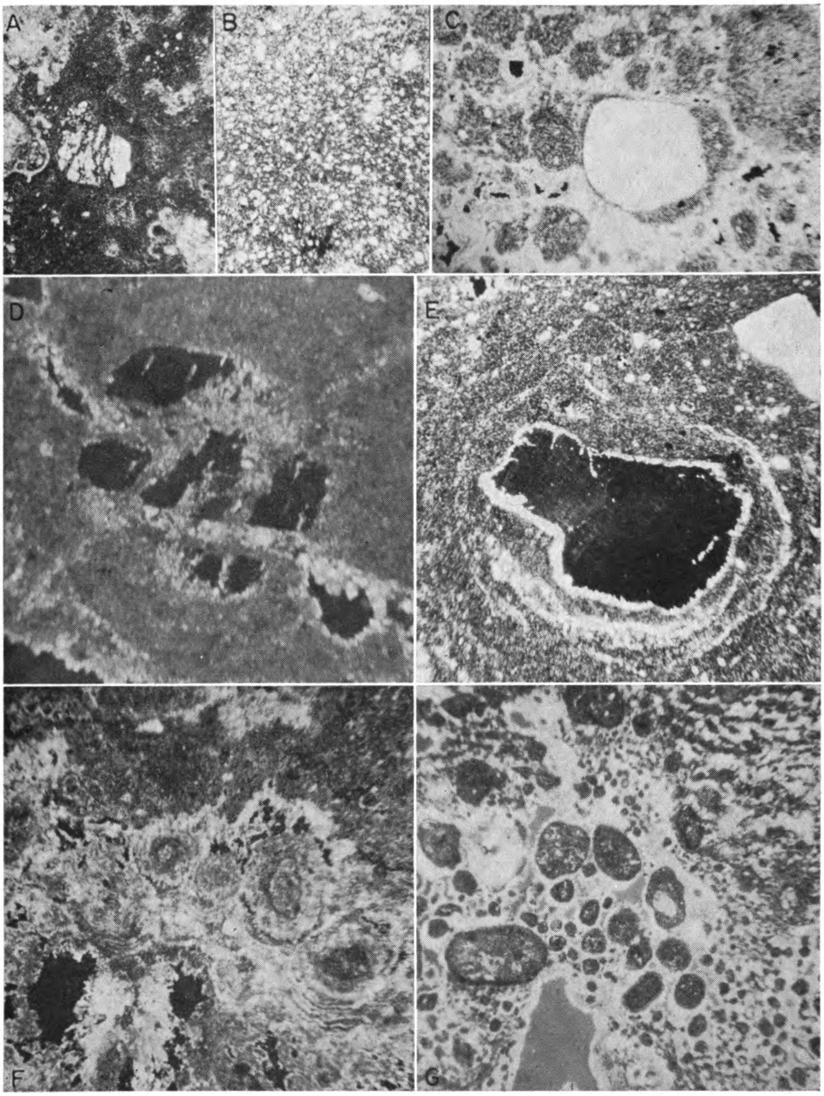


PLATE 2.—Photomicrographs from thin sections of caliche, pisolitic limestone, and travertine (dripstone). **A.** Microcline grain traversed by secondary calcite; pisolitic limestone in sec. 28, T. 1 S., R. 42 W., Cheyenne County, Kansas. ×15. **B.** Late Pleistocene caliche from Brady soil developed in Peoria loess; plane polarized light, ×15. Note large quantity of cement with respect to grains. **C.** Oölitic and pisolitic structure in limestone from sec. 3, T. 14 S., R. 11 W., Russell County, Kansas. Quartz grain forms large nucleus. Plane polarized light, ×15. **D.** Calcite veins traversing plagioclase grain in same sample as C. Crossed nicols, ×285. **E.** Strained

evidence of destruction on top and deposition below, as well as evidence of repeated rotation.

Thin sections and polished sections of the basal secondary encrustation invariably show oölitic and pisolitic structures similar to those in the main part of the rock, except that evidence of solution and rotation is not present. Examples of the structure of the secondary encrustations are shown in Plates 3D, 4E, and 2G. An identical structure was observed on the base of a block of upper Ogallala snail-bearing lacustrine limestone (Pl. 2F).

Veins.—Veins of calcite are common in most specimens. They intersect matrix, pisolites, laminar structures, and sand grains almost indiscriminately, and are generally but not everywhere more coarsely crystalline than the rest of the calcite. Plate 4G shows a white calcite vein intersecting two pisolites in the lower right-hand corner of the specimen. Plate 4A shows veins intersecting laminar structures; some of the broadest veins contain oölites. Plate 2D shows two or more calcite veins cutting through a grain of plagioclase feldspar.

Extremely thin veins of white, fine-grained barite are observed in specimens that have been dissolved slowly in dilute hydrochloric acid without agitation. These thin fragile structures, identified as barite by x-ray diffraction, cut across all other structures except the basal encrustation (dripstone). In a sample of pink pisolitic limestone from Hamilton County, Kansas, 17 percent of the insoluble residue (2 percent of the limestone sample) consists of barium sulfate.

Open cracks.—Open cracks are common in most specimens. They are of two types, one cutting across other structures, the other as concentric shrinkage cracks in pisolites. The cracks are believed to represent an initial stage of calcite venation, for some thin sections reveal cracks that are partly lined with small calcite crystals.

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quartz grain forming nucleus of pisolite in pink pisolitic limestone from sec. 7, T. 25 S., R. 42 W., Hamilton County, Kansas. Concentric rings of coarse calcite in pisolite represent filled shrinkage cracks. Note partial corrosion of grain and replacement by coarsely crystalline calcite. Crossed nicols, ×15. **F.** Vertically oriented section of travertine (dripstone) from lower side of slab of lacustrine gastropod limestone from upper Ogallala Formation. Note oölitic structures and concentric layers on lower sides of nuclei. Plane polarized light, ×15. **G.** Travertine (dripstone) from lower side of pisolitic limestone from sec. 19, T. 23 S., R. 23 W., Hodgeman County, Kansas. Note silty oölites. Plane polarized light, ×15.

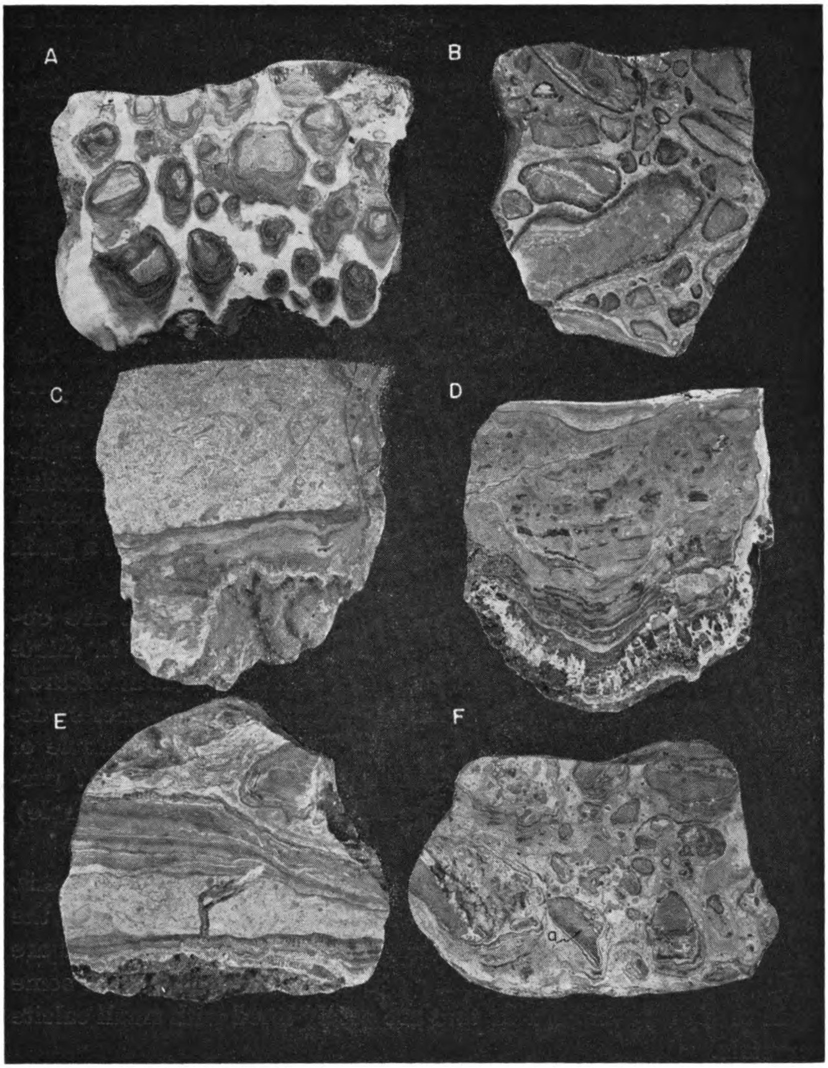

PLATE 3.—Vertically oriented polished sections of pisolitic limestone. **A.** Pisolitic limestone from top of 2-foot bed on W. line NW¼ sec. 30, T. 18 S., R. 26 W., Ness County, Kansas. Note downward growth of pisolites, general absence of rotation and brecciation. ×0.65. **B.** Pisolitic limestone from top of caliche pit under general upland surface 8 miles east of Odessa on U.S. Highway 80, Ector County, Texas. Sample is characterized by manganese oxide banding and scattered well-rounded pebbles (av. diam. 8 mm) of quartz and potash feldspar. Quartz pebbles are partly replaced by calcite. Internal structure of pisolites suggests several periods of growth followed by rotation. ×0.53. **C.** Block of Cretaceous limestone bedrock heavily coated on side and base with pisolitic limestone. Sample collected

Insoluble residues.—Hydrochloric acid-insoluble residues were obtained from 12 samples of pisolitic limestone from Kansas and Texas. The insoluble residue ranged from 3 percent in a sample from Russell County, Kansas, to 18 percent in a sample collected 3 feet below the top of a 4-foot bed of pisolitic limestone in Ward County, Texas. Where consecutive samples were taken at various depths at a single locality, the higher samples generally yielded smaller residues.

For comparison, the percent of insoluble residue was determined in a sample of late Pleistocene caliche from the Brady soil (Peoria loess) in Doniphan County, Kansas (Pl. 2B). This sample, although much younger than the Ogallala pisolitic limestone, contained only 26 percent acid-insoluble material. Evidently even the calichification that forms late Pleistocene calcareous silt nodules can produce a much larger proportion of calcium carbonate than that found in normal calcite cements.

Residues from the pisolitic limestone samples consist of grains of silt and sand and occasional pebbles, thin films of barite, and red-brown colloidal material. The last is nearly amorphous to x-rays but shows indication of the presence of montmorillonite. Organic matter in all residues imparted a brown color to acetone that was used to rinse them.

Distribution of detrital grains.—The distribution of grains of quartz and feldspar bears little or no relation to the lamination of the pisolitic limestone. This fact is in direct contradistinction to the distribution of detrital grains in algal limestone described by Bradley. According to Bradley (1929, p. 210, 217), sand grains commonly occur as pockets and stringers, particularly between the lobes of the algal reefs. Furthermore, within a true lacustrine

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0.7 mile from junction of Ranch Road 33 and Texas Highway 163, about 15 miles north of Ozona, Crockett County, Texas. Down long gentle slope from upland to south. ×0.51. **D.** Thin dense caliche overlying Niobrara chalk on N. line NE¼ sec. 28, T. 16 S., R. 21 W., Ness County, Kansas. Note pronounced pisolitic structure of dripstone at base of specimen, and truncated lamination at top. ×0.49. **E.** Caliche exposed in road ditch on long gentle slope from High Plains surface to Beals Branch, Colorado River; 5 miles east of junction of Texas Highways 349 and 176, Martin County, Texas. Note vein cutting through earlier generation of pisolitic limestone. ×0.74. **F.** Pisolitic limestone overlying Upper Cretaceous Greenhorn Limestone on S. line SE¼ SE¼ sec. 34, T. 6 S., R. 4 W., Cloud County, Kansas. Gray granular areas in photo (as at *a*) are remnants of partly dissolved Greenhorn Limestone pebbles. Shows multiple generations of rotation and depositional growth; downward orientation of deposits is especially conspicuous in latest phase of growth. ×0.42.

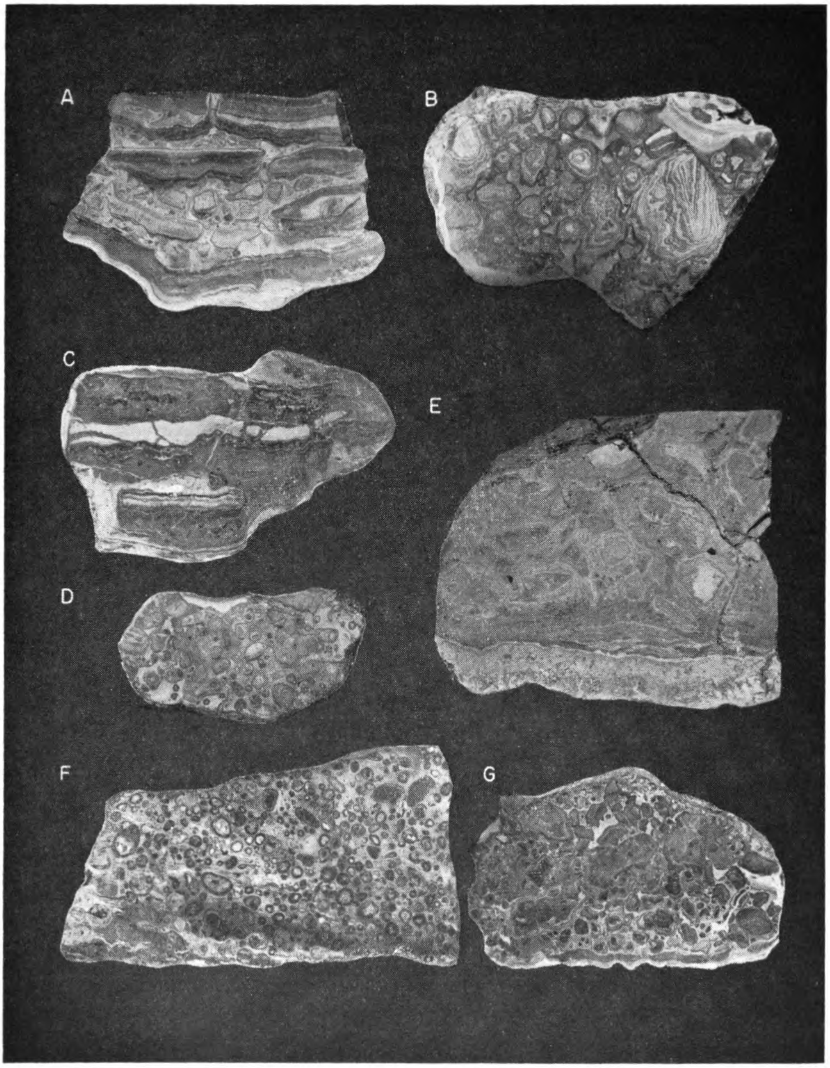

PLATE 4.—Vertically oriented polished sections of pisolitic limestone and polished section of Arkansas bauxite. **A.** Brownish-pink laminar pisolitic limestone from thin bed (less than 1 foot) in NE¼ SE¼ sec. 12, T. 14 S., R. 39 W., Wallace County, Kansas. Discontinuous laminar structures represent earlier generations of calichification. Most sand grains are concentrated in nonlaminar parts. ×0.53. **B.** Complexly layered pink pisolitic limestone from E. line NE¼ sec. 8, T. 25 S., R. 42 W., Hamilton County, Kansas. Shows truncation of upper parts of nodular units, deposition on lower parts. ×0.40. **C.** Basal part of 3-foot bed of dense pisolitic limestone from NW¼ sec. 27, T. 1 S., R. 42 W., Cheyenne County, Kansas. Note successive deposits, all cut by unfilled shrinkage cracks. ×0.46. **D.** Dense, pink pisolitic lime-

deposit one would expect to find local areas of bedded, well-sorted sand. Such areas are not observed in the Ogallala pisolitic limestone.

Evidence for destruction of quartz and feldspar grains.—Many samples of well-developed pisolitic limestone contain 10 percent acid-insoluble material, or less. If, then, the caliche developed in Kimball sand and silt, there must have been wholesale destruction of the detrital grains. Direct evidence for replacement of quartz and feldspar is shown in Plate 2A, 2D, and 2E. Plate 2D shows calcite veins traversing a feldspar grain. The rim of relatively coarse calcite surrounding the quartz grains in Plate 2E is typical of the calcite that has replaced grains, and it seems probable that small, sand-sized areas of coarse calcite observed in many thin sections represent the former positions of detrital grains.

More recent caliche (*loess kindchen* in Brady soil, Pl. 2B) also shows large quantities of calcite in comparison with the volume of detrital grains, but evidence for replacement of detrital grains by calcite is less clear. It is possible that in the *loess kindchen* the grains have been pushed apart by crystal growth of the calcite, but an appearance of mottling (in the thin section) caused by silt-sized areas of coarser calcite strongly suggests replacement.

Organic Remains

The only fossils found in thin sections of the pisolitic limestone were foraminifera and fragments of mollusk shells reworked from Cretaceous rocks. These fossils are restricted to localities in which the pisolitic limestone is only a few feet above the Cretaceous bedrock surface. No fossils of Pliocene age were observed. Particularly notable is the absence of diatoms, which are invariably present (usually associated with an assemblage of mollusks characteristic of stagnant waters) in Ogallala limestones formed under obvious lacustrine conditions.

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stone from cen. sec. 7, T. 25 S., R. 42 W., Hamilton County, Kansas. Note structural similarity of bauxite (F). ×0.42. **E.** Sample from top of 3-foot bed of pale-buff pisolitic limestone, NW¼ sec. 19, T. 23 S., R. 23 W., Hodgeman County, Kansas. Note fitted polygonal concentric structures. Dripstone at base is finely nodular and paler than rest of rock. ×0.84. **F.** Pisolitic bauxite from Alcoa mine, Bauxite, Arkansas. ×0.42. **G.** Complex pink pisolitic limestone from E. line NE¼ sec. 8, T. 25 S., R. 42 W., Hamilton County, Kansas. Shows multiple generations of brecciation, solution, rotation, and recementation. Note white calcite vein traversing pisolites in lower right part of slab. ×0.35.

Elias (1931, p. 137) noted in the pisolitic limestone "a few small spherical bodies" ranging in diameter from 62 to 97 microns. He described the structures as follows:

> In the broader bands [of calcium carbonate] may be noticed a few small spherical bodies with comparatively thin outer zone made of a mosaic of comparatively coarse-grained colorless calcite, much like the walls of the hollow spheres representing the individual cells of *Chlorellopsis coloniata* Reis, the microscopic alga of the Green River formation reefs. Some of the spherical bodies from the Ogallala rock are hollow also. The more important difference between the spheres from the limestone of the two formations is the smaller diameter of the spheres from Ogallala. . . . It appears as if the spherical bodies from the concentrically banded limestone of the Wallace county Ogallala, which is of Lower Pliocene age, if correctly interpreted as individual cells of an alga, belong to a different species of *Chlorellopsis*.

W. H. Bradley, who examined two of Elias' samples, made the following comments (Elias, 1931, p. 138):

> In general all parts of these reefs appear to have been more extensively recrystallized than many others that I had available for study from the Green River formation. Nevertheless, I agree with you that a large part of these deposits was apparently formed by an organism much like *Chlorellopsis*. The cells are indeed smaller than the species which I described and probably should be referred to a different species. They show a similar habit of growth in roughly concentric layers much the same as those that I described. Many of them, however, especially those detached from the areas showing systematic growth layers are enlarged by external coatings. I think your interpretation of these enlarged cells is probably right, namely, that it is an inorganic incrustation perhaps quite independent of the original algal cell. This seems the more probable because associated with the parts of the reef showing definite algal structure are undoubted oölites. . . . In addition to the layered *Chlorellopsis* structure there is apparently some algal deposit like that which I called, for the want of a better name, the spongy structure.

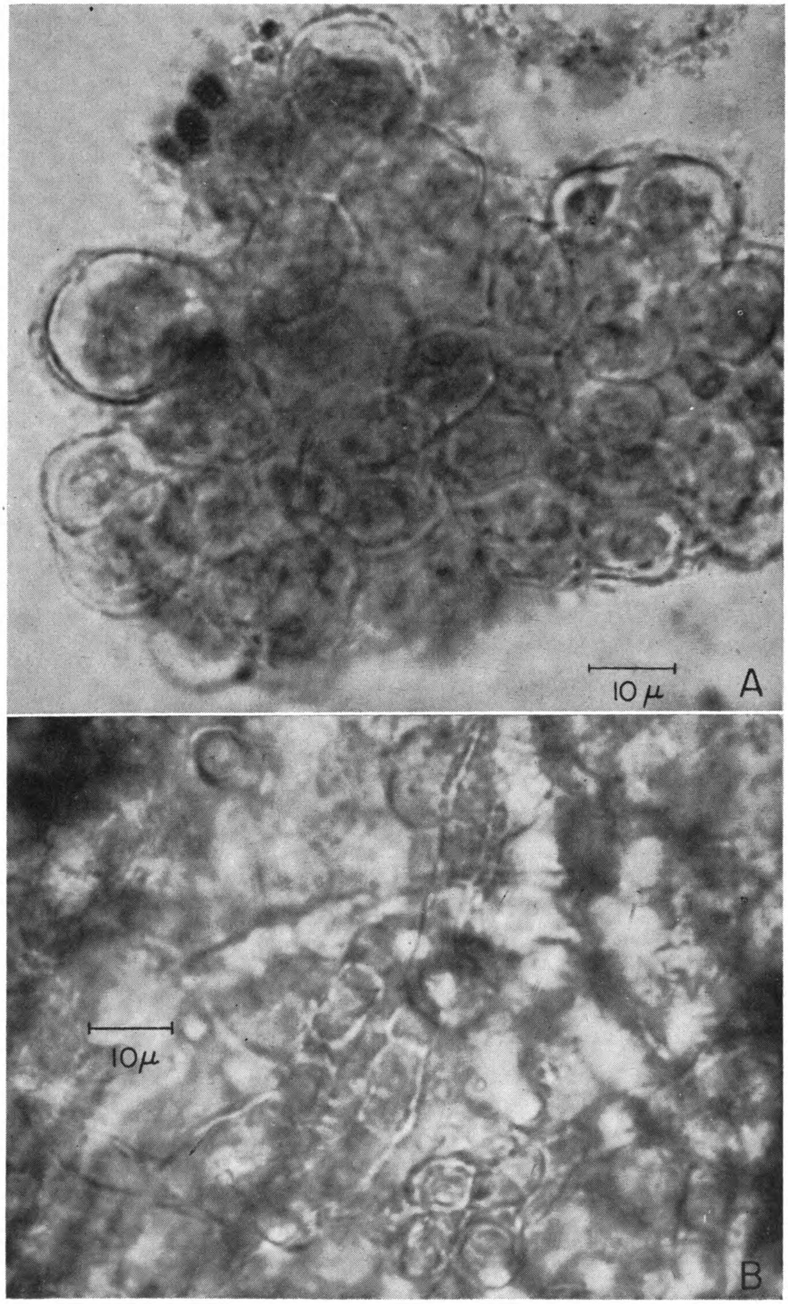
> The oölites associated with the algal deposits in these reefs are of quite various sizes. Their nuclei are of irregular particles of clay or marl. These oölites usually show concentric growth, but a few consist of radial fibrous crystals. Areas of these oölites, however, are usually mixed with more or less clastic material and are rather easily distinguished from areas *built up* by systematic growth of algae. [Italics ours]

Although the algae described by Elias and Bradley were not recognized by us in any of the thin sections, this fact obviously does not preclude their presence elsewhere in the pisolitic limestone. Other characteristics of the rock, however, indicate that it was not formed in bodies of water. No gross structures indicative of algal reefs or algal heads were observed, either in thin section or in hand specimens. Lamellar structure similar to that described by Bradley (1929), where present, clearly developed in a downward direction rather than upward. The only spherical cells of organic origin and of the size range of *Chlorellopsis bradleyi,* observed in thin section, were isolated chambers of reworked Cretaceous foraminifera. These chambers have thin calcite rims and coarsely crystalline calcite interiors. A few are hollow.

Robert M. Kosanke[1] has examined 13 thin sections and macerated samples of pisolitic limestone from Russell, Ellsworth, and Hamilton Counties, Kansas. He reports (personal communication) that all the samples contain organic matter, and that the samples from Russell and Hamilton Counties contain algae of the type recorded on Plate 5. He describes these as follows:

> The algae observed, both spheres and filamentous types, are members of the Chlorophyta (green algae). The spheres are usually found in clusters or colony habitat such as found in the Palmella stages of *Chlamydomonas* or certain genera of the Tetrasporales. Individual algal cells measured up to 17 microns in diameter and the largest colony measured was 90 microns in diameter. Many of the individual cells have a very faint yellowish-green color and a few appear to contain some cell substance of a slightly darker color. The filamentous forms occur scattered throughout pieces of

[1]We are grateful to Dr. Kosanke, of the Illinois State Geological Survey, for the assistance he gave us and for his critical review of the manuscript.


10 μ
A
10μ
B

matrix forming a network. Individual cells of the filaments are about 6 microns wide and somewhat irregular in length. This filamentous form is probably a member of the Chlorophyta.

The organic fraction is small, probably less than one percent of the samples, and is most abundant in sample 1451-2 [Russell County, Kansas], which contains both the spherical and filamentous algae. When viewing the thin sections with low magnification, there are color or textural differences some of which are more or less spheroidal, but when these are examined with high magnification, there is no structural organic matter.

Kosanke also reports the presence of poorly preserved or corroded pollen grains.

The spherical algae noted by Kosanke are much smaller than *Chlorellopsis bradleyi*, and they do not require a lacustrine environment for their growth. Furthermore, it is improbable that algal cells of late Pliocene or early Pleistocene age would retain their greenish color. It is believed that these algae were derived from the relatively recent secondary encrustation of dripstone, or travertine, that coats the lower surfaces of most of the blocks and that they grew subaerially or in the soil rather than in ponds.

ORIGIN

The Lacustrine Hypothesis

According to the lacustrine hypothesis the pisolitic limestone was deposited at the bottom or near the shores of a lake or lakes at the close of Ogallala time (Elias, 1931, p. 141; Frye, 1945). The calcite was supposedly deposited by a combination of systematic growth of algae and inorganic precipitation. The only evidence for lacustrine origin of this limestone is the reported presence of the alga, *Chlorellopsis bradleyi*.

Objections to the lacustrine hypothesis are based on (1) the distribution of clastic grains, (2) the evidence of multiple generations of deposition and desiccation, (3) the similarity of the structure to that of pisolitic bauxite, (4) the pisolitic and oölitic struc-

Plate 5.—Green algae from pisolitic limestone from center E. line sec. 3, T. 14 S., R. 11 W., Russell County, Kansas. Preparations, identifications, and photomicrographs by R. M. Kosanke. **A.** Probably Chlorophyta, Order Tetrasporales. ×1150. **B.** Probably Chlorophyta, Order Cladophorales. Possibly the genus *Trentepohlia,* an aerial alga. ×1150.

ture of dripstone that is known to have been formed subaerially, (5) the history of sedimentation and lithologic sequence of the underlying beds, (6) the progressive ecological trends developed during deposition of the Ogallala, and (7) structural considerations. Perhaps the most devastating argument against a lacustrine algal origin, however, is the abundant evidence of downward growth of the rock. In Plate 3A, for example, the predominant downward direction is obvious, for almost no rotation of units has taken place. In the specimen shown in Plate 3F, however, the latest growth of each unit is downward, and it is evident that the apparent earlier growth in other directions is a function of rotation after deposition. In this particular specimen, the nuclei are pebbles of Cretaceous limestone; it is difficult to conceive of lacustrine algae (or lacustrine inorganic precipitates) growing only (or primarily) on the under surfaces of these pebbles.

An Alternate Hypothesis of Origin

The various lines of evidence indicate that the concentration of caliche was initiated just below the late Tertiary surface during the latest phases of Ogallala deposition and was most intensive after the surface of the alluvial plain came to an erosional-depositional equilibrium. Development of caliche is judged to have continued on this surface at least until the beginning of dissection by Pleistocene streams— thus dating the rock as latest Tertiary and earliest Pleistocene, with the possibility that deposits in isolated interfluve positions continued development well into the Pleistocene. The latest generation of dripstone shows pisolitic structure and still-green algae, suggesting that a similar process is going on today.

Effects of successive episodes of desiccation, shrinkage, solution, and reprecipitation are shown in the shrinkage cracks, barite and calcite veins, and rotated blocks.

The absence of pisolitic caliche on Pleistocene deposits in Kansas suggests that the process was not effective in this region during most of Pleistocene time. But on the Ogallala climax surface, conditions were right for such a caliche development, and as the period of surface stability was long and the climatic trend was toward desiccation, a thick caliche zone developed generally. As the climate moved toward aridity the friable A horizon became subject to eolian or other erosion and ultimately the caliche zone was modified, with concentration at or near the surface, and desiccation and fracturing of the formerly soft and porous caliche mass. Such fracturing would permit movement and reorientation of fragments.

The theory of Bretz and Horberg (1949) for the development of similar rock in southeastern New Mexico requires the presence of limestone gravels. Such gravels are of only local importance in the Ogallala of Kansas, but where a few feet of Ogallala sediments overlie Cretaceous limestones, structures similar to those of Bretz and Horberg are developed. The caliche develops equally well, however, where limestone gravels are not available.

The development of a dense limestone, containing only a few percent of acid-insoluble material, from a calcareous feldspathic quartz sand or silt poses the problem of elimination of the sand grains. Much of the silica that was replaced by calcium carbonate, and some other ions (notably aluminum and alkali and alkaline earth metals), are thought to be present as opal at somewhat lower horizons (Eitel, 1957). The barium of the barite films probably was derived from the feldspars and micas.

The similarity of some of the pisolitic limestone to Arkansas pisolitic bauxite is striking (Pl. 4 D, F). In conclusion we wish to suggest, by analogy with Harder's (1952, p. 35) conditions of origin of bauxite, a concretionary origin of the Ogallala pisolitic limestone. The optimum conditions for development of pisolitic bauxite or pisolitic limestone are, then, (1) presence of rocks containing minerals yielding residues rich in alumina (for bauxite) or calcium carbonate (for pisolitic limestone); (2) climatic conditions that make such residues possible—hence warm climate and abundant rainfall alternating with dry periods (for bauxite) and aridity alternating with moderately wet periods (for pisolitic limestone); (3) effective rock permeability; (4) low to moderate topographic relief allowing a minimum of erosion; and (5) sufficient time. We may add to this the requirement of Gordon and Tracey (1952, p. 12), for pisolitic limestone as for pisolitic bauxite, that the rocks be above the level of the permanent water table.

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