BOL. SOC. GEOL. MEXICANA, v. 32, n. 2, p. 117-141, 1969 (1971)

CHARACTERISTICS AND GENESIS OF CALICHE DEPOSITS

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RESUMEN

Se presenta una discusión de las diversas hipótesis propuestas para explicar la formación de los depósitos de caliche. Esas hipótesis son analizadas considerando información de campo y laboratorio. También se presentan y discuten las características regionales y las estructuras y texturas típicas de esos depósitos, en relación con su génesis, en New Mexico, E.U.A.

Se concluye que los depósitos de caliche fueron formados por procesos de suelo en condiciones de deficiencia de humedad durante todas las estaciones. La roca madre en la cual se formaron esos depósitos fueron sedimentos aluvionales con alto contenido de carbonato de calcio clástico. Calcita epigenética se acumuló en la profundidad correspondiente al nivel de penetración de las aguas de lluvia, debido principalmente a que el agua fue extraida por la vegetación y parcialmente debido a variaciones de temperatura.

El contenido de carbonato de calcio autigénico cementó los sedimentos y originó la formación de estructuras terrosas o concrecionales. Con posterioridad, se produjo la erosión de los horizontes superiores y la meteorización de la zona calcárea produciendo un caliche compacto y duro con muy alto contenido de $CaCO_3$. Algunos depósitos no alcanzaron este grado de madurez; en otros casos se produjeron nuevos ciclos de calichificación.

Debido a oue los depósitos tienen una gran extensión de superficie, los valores locales de las variables que controlaron su desarrollo produjeron importantes variaciones estructurales y texturales.

ABSTRACT

The hypotheses proposed to explain the formation of caliche deposits are discussed. These hypotheses are analized in the light of field and laboratory evidence. Typical structures. textures and regional characteristics of the deposits of New Mexico, USA, are presented and evaluated regarding their genesis.

It is concluded that the caliche deposits were formed by soil processes under conditions of moisture deficency during all seasons. Alluvial sediments with a high percentage of clastic $CaCO_3$ constituted the parent rock within which the deposits were formed. Epigenetic calcite accumulated at the level corresponding to the depth of penetration of rain waters, principally because water was removed by vegetation and partly because of temperature variations.

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The authigenic calcium carbonate content cemented the sediments and led to the formation of earthy or concretionary structures. Later, erosion of the upper horizons occurred and weathering of the calcareous zone produced a hard and compact caliche with very high $CaCO_3$ content; some deposits did not reach this degree of maturity, whereas in some cases new cycles of calichification took place.

Because the deposits are of great areal extent, local values of the variables that controlled their development produced significant structural and textural variations.

INTRODUCTION

Large continental deposits of calcium carbonate of Pliocene or post-Pliocene age, named caliche deposits, are found in several areas of the world. Several hypotheses have been proposed to explain the formation of these deposits. With minor variations they can be designated as the: (1) fluvial, (2) lacustrine, (3) water table, and (4) soil hypotheses. Some authors have proposed combinations of these hypotheses to explain the origin of a single deposit. Others have suggested different hypotheses for deposits located in separate regions. Summaries and discussion of these ideas have been presented by Price (1933), Smith (1940), Bretz and Horberg (1949) and others.

The word caliche has been used with many different meanings in the geological literature. In this paper the term caliche deposit is used exclusively for $CaCO_3$ deposits, as defined in former reports (Aristarain, 1962; 1970). In order to understand why there are so many proposals on the definition and genesis of caliche deposits, it is appropiate to note that such bodies are the result of a special process operating under specific conditions in unconsolidated sediments over large areas. Variations in the chemical composition and the size distribution of the clastic fractions of the sediments affected the calichification processes. As a result structures and textures change accordingly from place to place.

Because $CaCO_3$ was being deposited contemporaneously in such large regions, it is obvious that in local areas the accumulation may be representative of some very local environment, as in the case of playa lakes, spring or fluvial deposits.

The origin of caliche deposits is not only of importance in its own right but the solution of other geological problems depend upon it. Stratigraphic, paleoclimatic and mining problems, among others, rely heavily upon the inferred genesis of caliche.

GENERAL CHARACTERISTICS OF THE DEPOSITS

RELATIONSHIP WITH CLIMATE.—The distribution of the caliche deposits is approximately coincident with that of the arid and semiarid regions of the world (Meigs, 1952) but relicts are found in semihumid regions. In the Southern Hemisphere they are restricted within the area limited by the parallel of 20° and 40° occupying the south central part of Australia, the south end of Africa and the east central part of Argentina in South America.

In the Northern Hemisphere the caliche deposits are confined to an area also limited by parallels of 20° and 40°. They occupy the south central and southwestern parts of U.S.A., northern part of Mexico, northern Africa, southern Spain, the northern part of the Arabian Peninsula, the east central part of India and possibly part of East China. In North America they extend over more than two thousand miles in north-south direction and several hundred miles in an east-west direction.

Because of coincidence between soil belts and climatic belts, Shantz and Marbut (1923) stated that climatic forces are the predominant soil forming agencies. Marbut (1927) had pointed out the relationship between climate and soil east of the Rocky Mountains, establishing the limits of pedocals and pedalfers.

This relation was further developed by Thornthwaite (1931) who stated that the soils of that region seem to be related to precipitation effectiveness and temperature efficiency. Where the temperature is adequate, the limit of these two great groups of soils depen upon precipitation effectiveness. Where the P/E (precipitation/evaporation) index is low, calcium carbonate accumulates in the soil profile; where the index is high it is leached away. The P/E line separating the regions in which moisture is deficient during all seasons from the region in which moisture is abundant during all seasons (P/E index 48, Thornthwaite, 1931), corresponds to the line separating pedocals from pedalfers. This line separates the deficient moisture subzone from the abundant moisture subzone of the climatic Subhumid Province in the Thornthwaite (1931) classification. The caliche deposits of the United States are stable west of the same line, that is under moisture deficient conditions during all season (see Aristarain, 1971b, fig. 1).

There is evidence that caliche was more extensive than it is at present and that the last great climatic pulsation has reduced its limits.

The mean annual precipitation in the areas of the United States that contain caliche deposits near the surface ranges from 10 to 35 in. The greater part of this precipitation occurs in summer; precipitation during the winter is very low.

Concluding, the distribution of caliche deposits in the United States at present is restricted to areas in which the arid, semiarid and subhumid (moisture deficient) climates of the Thornthwaite's classification prevail, and they must have been formed under conditions of moisture deficiency during all seasons, although the climate was not as arid and warm as that of the area where caliche is found today.

This relationship is not limited only to the present. It seems to have existed a correlation between $CaCO_3$ accumulation in soils and Pleistocene interglacial stages.

Some authors have proposed the use of the upper caliche deposit of the High Plains as a stratigraphic marker. The use of caliche as a key horizon was proposed because of the difficulties in establishing a limit between Pliocene and Pleistocene in areas not affected directly by glacial processes. This limit has been suggested by Flint (1949) and others as a climatic one and caliche deposits are considered the expresion of changing climatic conditions. However, considering the example of Profile 1 (Figure 1) where 3 caliche layers are found, as well as the numerous caliche (?) layers cited in drilling reports from the High Plains, one must conclude that these deposits should not be used as a stratigraphic key horizon, except in very limited areas where very detailed studies were performed.

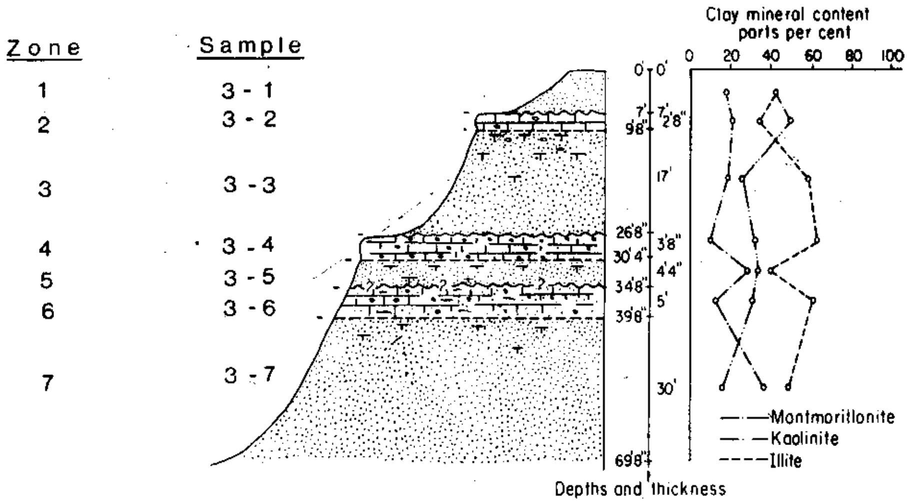

FIG. 1.—Profile 1 from the Rio Grande Depression, at Bernalillo Co., New Mexico. Zone 1: Very fine sand, minor $CaCO_3$, resting unconformably upon Zone 2. Zone 2: Sandy caliche, friable, a few pebbles of igneous rocks, upper boundary sharp, the lower gradational. Zone 3: Medium sand, slightly cemented and containing a few pebbles in the upper part, resting unconformably upon Zone 4. Zone 4: Concretionary caliche, friable, clastic fraction is fine sand. Zone 5: Fine sand, minor $CaCO_3$. Zone 6: Earthy caliche, some $CaCO_3$, very friable. Zone 7: Fine sand, $CaCO_3$ is rare to absent.

FIELD OBSERVATIONS.—The caliche deposits are epignetic accumulations of calcite in unconsolidated sediments; they are found in flat, "stable" and relatively low areas near the surface of the ground. They form sheetlike bodies that cover large areas conforming roughly with the general surface of the land. Repetition of deposits occurs within the same area.

Deposits on older surfaces generally present characteristics of maturity. Figure 2 presents the case of Profile 2 from the High Plains, New Mexico, which exhibits features that are common to many of the profiles of deposits developed at the top of the Ogallala Formation (Miocene and Pliocene). This profile is located in Roosevelt County; New Mexico (NE 1/4, Sec 18, T 5 S, R 31 E) at an open pit on the north side of U.S. Route 70, at a point 3,5 mi northeast of Kenna. For other profiles from the same physiographic surface see Aristarain (1971a).

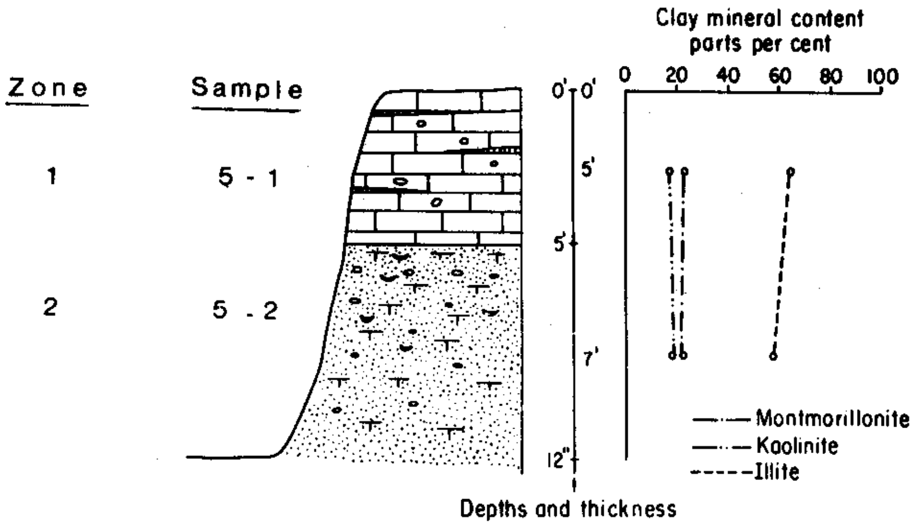

FIG. 2.—Profile 2 from the Rio Grande Depression, at Roosevelt Co., New Mexico. Zone 1: Layered caliche, very hard and compact, conglomeratic, brecciated, with oolitic and banded textures, some sand between layers. Zone 2: Pebbly sand, partially cemented with calcite, pebbles are siliceous and calcareous, some cupped limestone pebbles.

These mature deposits occur within sediments that are considered to be part of that formation; the observable differences result from changes in the size distribution of the sediments before calichification, or in the amount of deposited $CaCO_3$.

A hard and compact layered caliche with a very high $CaCO_3$ content is found at the top. The thickness of this upper limestone ranges from 2 to 5 ft and the total thickness of the deposits ranges from 5 to 9 ft. These values are in part arbitrary because the zone boundaries are gradational.

This zone is followed by sands in which calcite concretions are generally abundant in the upper part, decreasing downward both in size and number, as does the $CaCO_3$ content. The concretionary caliche passes into slightly cemented and then entirely unconsolidated sands. The caliche profiles are commonly overlain by a thin layer of sand in an unconformable relationship.

Diagenetic changes are intense in this type of profile. For example, original limestone pebbles, in some instances, have been altered to cupped pebbles (see structures). Even these modifications are more intense at the top of the profiles, they could be quite marked in the intermediate zone; where the epigenetic carbonate is abundant the concretionary caliche evolved to friable sandy caliche or hard sand limestone.

The caliche deposits formed on younger surfaces, such as those of the Rio Grande Depression, have characteristics not so well marked. Profiles

1, 3, 4, and 5 (Figures 1, 3, 4, and 5) present examples of very low-to medium-degree of calichification.

The Profile 3 (Figure 3) is located in Socorro County, New Mexico (NE 1/4, Sec 12, T 4 S, R 1 W) at a roadcut on west side of U.S. Route 85, at a point 3.7 mi south of Socorro. This profile shows a case where the process is so incipient that hardly it could be named a caliche deposit. The surface of the land at the area of the profile is a small flat erosional remnant. In the upper part of the profile, there is a gravel cemented by $CaCO_3$ which rests on sands with very little calcite content. In this case there are no structural, textural or chemical evidence to show that this is a caliche profile, the only suggestion is being in a region where caliche was developed; therefore, the name caliche is avoided.

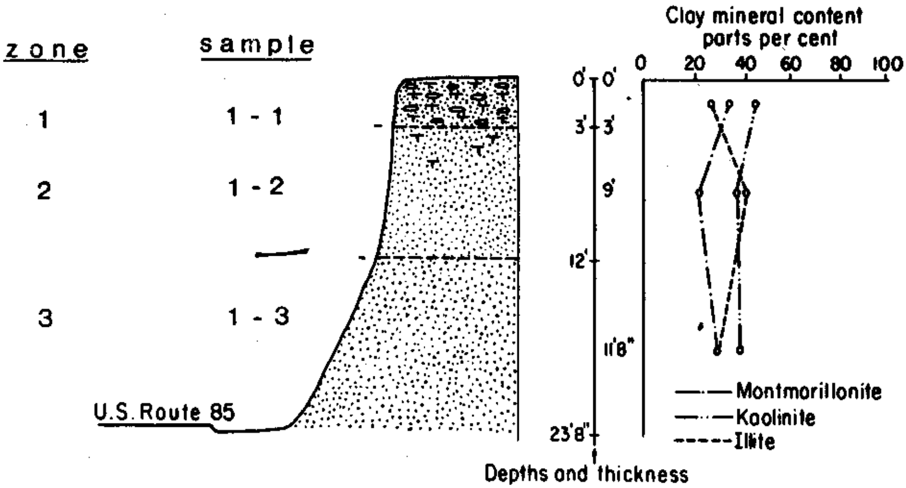

FIG. 3.—Profile 3. from the Rio Grande Depression, at Socorro Co., New Mexico. Zone 1: Sandy gravel, partially cemented with $CaCO_3$. Zone 2: Very fine sand, minor $CaCO_3$ in the upper part. Zone 3: Medium sand, no $CaCO_3$.

Profile 4 (Figure 4) is located in Bernalillo County, New Mexico, 11 mi west of Rio Grande, along U.S. Route 66, and 1/4 mi south of this route following a secondary road; it is at the west escarpment of the Llano de Albuquerque known as the Ceja del Río Puerco.

Profile 1 (Figure 1) is also located in Bernalillo County, New Mexico, 4.7 mi west of Rio Grande along U.S. Route 66 and one mile north of this highway following a secondary road; it is at the east escarpment of the Llano de Albuquerque, known as the Cejita Blanca.

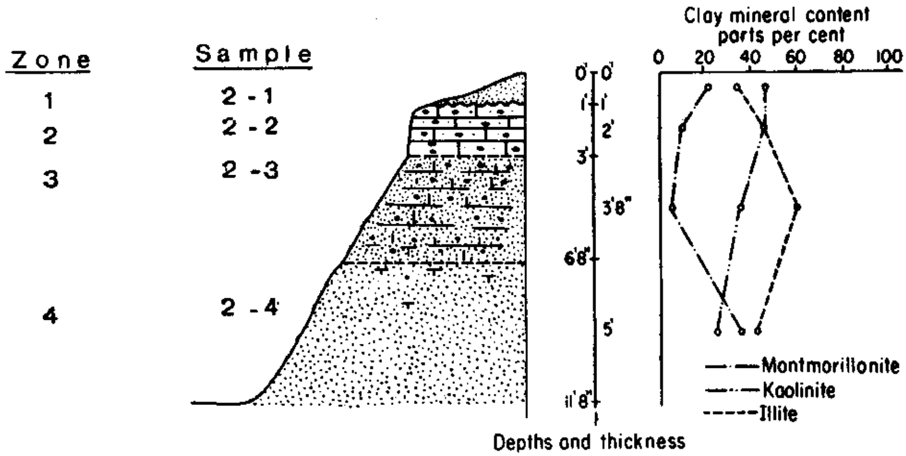

FIG. 4.—Profile 4 from the Rio Grande Depression, at Bernalillo Co., New Mexico. Zone 1: Fine sand, windblown, resting unconformably upon Zone 2. Zone 2: Concretionary caliche, high $CaCO_3$ content, contains pebbles of volcanic rocks. Zone 3: Sandy caliche, friable, clastic fraction is fine sand, the abundance of calcite concretions decreases downward. Zone 4: Fine sand, minor $CaCO_3$.

Both profiles exhibit deposits developed in sediments of the Santa Fe Formation (Bryan and McCann, 1937; Wright, 1946) with characteristics of young deposits; the hard upper limestone on the top did not develop, the carbonate content is relatively low, the diagenesis of the sediments is not pronounced, the mineralogy is more related to the parent sediment, the string textures and structures of the mature deposits are absent.

The Profile 1 shows three caliche deposits (Figure 6A); each one of them exhibits characteristics that are similar to those of the Profile 4. Unconformities can clearly be seen at the top of samples 3-2 and 3-4, but the contact between samples 3-5 and 3-6 is not readily apparent.

Profile 5 (Figure 5) is located in Rio Arriba County, New Mexico (NE 1/4, Sec 24, T 21 N, R 10 E) on the north side of State Route 76 at a point one mile west of Truchas (Cañada Ancha). This profile represents a deposit formed is sediments of the Truchas Formation (J. P. Miller, personal communication, 1960) and illustrates a case of a poorly developed caliche deposit; the parent rocks were coarse clastic sediments derived predominantly from coarse grained highly siliceous igneous rocks and from metamorphic rocks. The predominant characteristics are those of the clastic fraction and a conglomeratic caliche has resulted. This is an intermediate case between that of Profile 3 and those of Profiles 4 and 1; its features are those of a very young deposit.

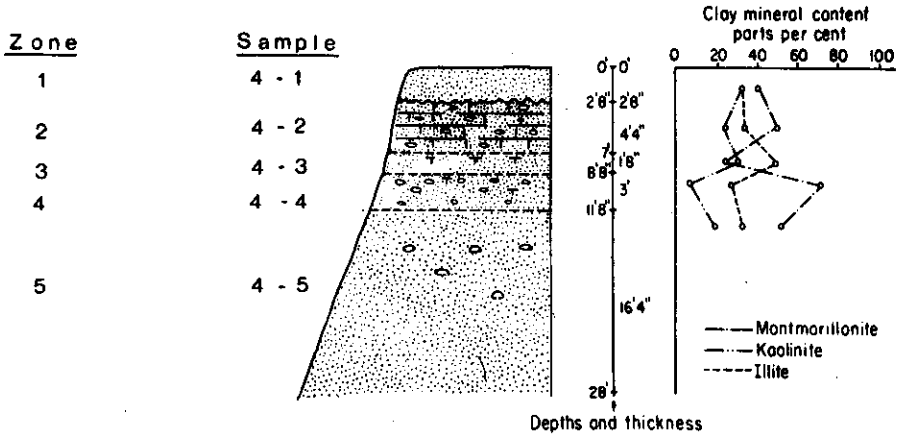

FIG. 5.—Profile 5 from the Rio Grande Depression, at Rio Arriba Co., New Mexico. Zone 1: Coarse sand, pinkish tan, apparently rests unconformably upon Zone 2. Zone 2: Conglomeratic caliche, castic fraction consist of coarse sand, granules and pebbles of igneous and metamorphic rocks. Zone 3: Very coarse sand, some granules and pebbles, partly cemented with $CaCO_3$. Zone 4: Very coase pebbly sand, minor $CaCO_3$. Zone 5: Coarse and $CaCO_3$ rare to absent, gravels and sands in irregular sequence underlie the sample.

CHEMICAL ANALYSES OF CALICHE PROFILES.—Complete chemical analyses of samples representing well developed caliche profiles (Aristarain, 1970) from the High Plains indicate that Ca, C, O and H were added in relative abundance to the upper parts of the deposits, their abundance decreasing rapidly downward. Mg, and Fe^{3+} were also added with decreasing amounts from top to bottom of the deposits. The chemical processes that occurred in young deposits were less intense as compared with those of mature deposits.

The decreasing chemical action toward the bottom suggests that the caliche forming solutions moved downward.

MINERALOGY.—The mineralogy of these deposits was studied with special reference to clay minerals (Aristarain, 1971b). The clay minerals identified are illite, montmorillonite and kaolinite; small amounts of chlorite were also found.

The composition of the clays along the caliche profiles changes. The variations observed in mature deposits show that illite is the most abundant clay mineral and its relative amount markedly increases toward the top of the profiles. The relative content of illite varies inversely to both montmorillonite and kaolinite content; the variations of these two minerals are approximately parallel (see Aristarain, 1971a).

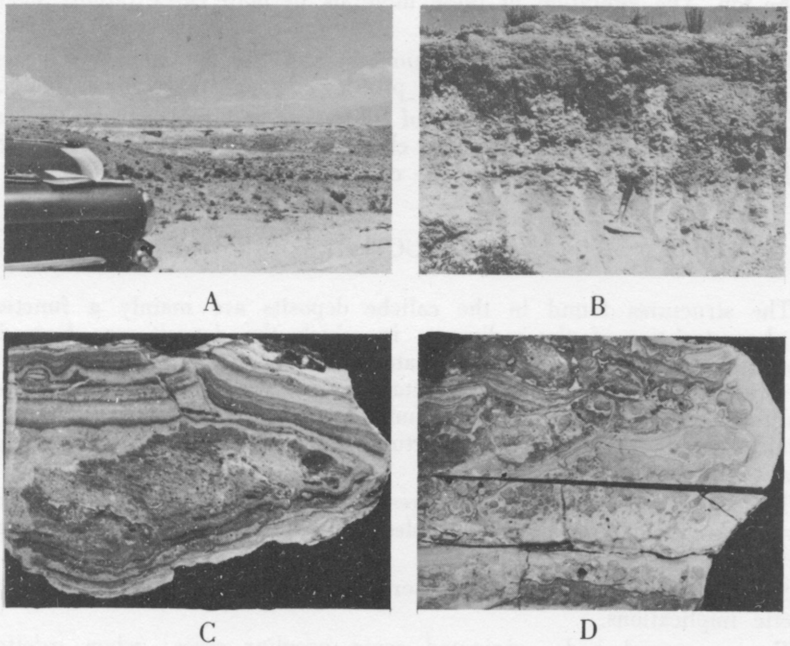

FIG. 6.—A.: View of the general area of Profile 1. Three caliche deposits occur at this point, the lowest is not clearly shown in this photograph, the upper part cf a caliche profile showing stalagmite-like of $CaCO_3$ developed in the capping soil. C: Specimen showing the typical banded texture of mature caliche deposits; 1/2 actual size. D: Specimen showing the irregularity of the banded sectors; 1/4 actual size.

The changes in relative abundance of the clay minerals and the direction of these modifications indicate that the diagenetic chemical agents played an important role in the present composition of these minerals and that the altering solutions moved downward.

Young deposits have a similar clay mineral association but do not apply those relationships; Figure 1, 3, 4, and 5 of profiles from the Rio Grande Depression indicate the clay mineral content parts per cent (relative amounts) and show this situation.

The remaining mineralogy is quite simple; the dominant minerals are calcite and quartz, the second being subordinate. Both comprise more than 95% of the upper parts of the mature deposits. Feldspars are rare at the top of the mature accummulations, their amount increase toward the bottom of the profiles; on the contrary, young deposits show almost fresh feldspars at the top. The alteration of these minerals in both cases rapidly decreases toward the bottom of the deposits.

Calcite replaces all the other minerals and the amount of replacement, that it is intense at the top of the profiles, disappears at lower levels.

The decrease of the intensities of alteration and replacement toward the lower zones of the caliche deposits clearly indicates a downward movement of the solutions that transported the carbonate.

STRUCTURES

The structures found in the caliche deposits are mainly a function of the characteristics of the sediments in which the deposit was formed, the amount of epigenetic calcium carbonate deposited, the duration of the process, the presence (or absence) of vegetation and the climatic and hydrologic conditions under which the accumulation occurred. In some places these variables produced significant structural or textural variation within short distances at the same deposit.

The most characteristic structures are: layered, earthy, concretionary, compact, conglomeratic, cupped pebbles, veined, porous, brecciated, stalagmite-like "intrusions" and cross-bedding.

Several of these structures deserve special attention because of their genetic implications.

Former gravel beds originated some peculiar cases; when calcite was deposited cementing very coarse clastic layers, conglomeratic structures resulted. In some areas limestone conglomerates were formed, the pebbles being of marine origin or originated from the erosion of a former caliche (Figure 7A).

In certain deposits, with limestone pebbles at the top of the profiles during calichification time, the upper part of the pebbles was dissolved while banded calcite was deposited beneath them. The pebble shapes resulting from the solution processes are very curious. During the early stages the pebbles acquired some facets on their upper surfaces (see Aristarain, 1971b, Figure 4); Bryan (1929) termed them solution faceted limestone pebbles. As solution proceeded, cup-like or shell-like (pelecypods) forms developed (Figure 7B); Bretz and Horberg (1949) have named them cupped nodules or cupped pebbles. The cupped pebbles occasionally have small stalagmite-like projections rising from the interior of the cup; these are a part of the pebble proper.

These pebbles are loose or in other instances, after attaining a great stage of solution, were preserved from total destruction because calcium carbonate was deposited in the entire layer forming a cemented mass in which cups were included (Figure 7C). The position of the cupped pebbles in the profile is the same as indicated in Figure 7C; they were cut along a vertical plane to better show their shape. Note the younger envelope of calcium carbonate deposited under the pebbles, the development of which must have been simultaneous with solution.

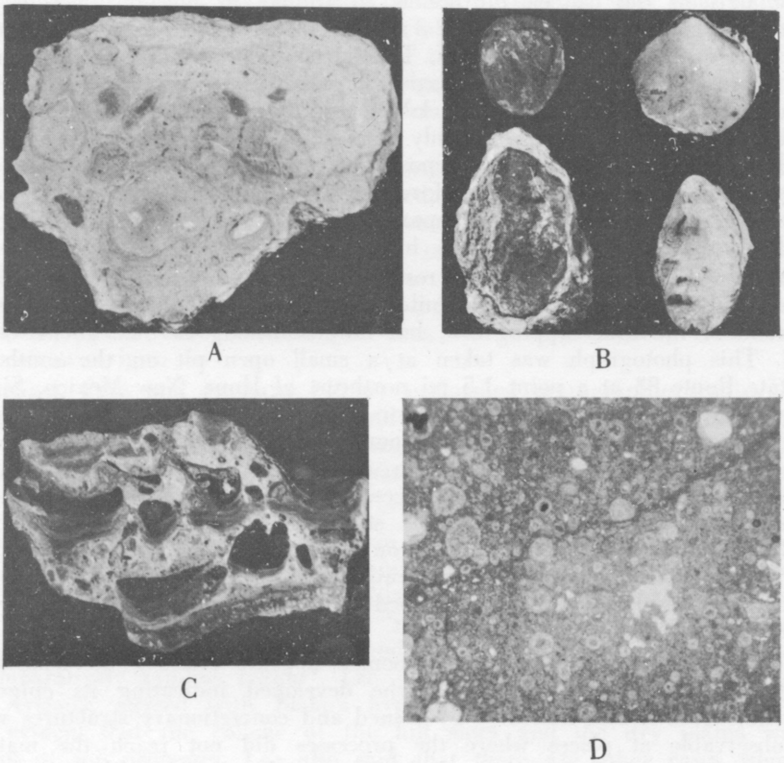

FIG. 7.—A: Hand specimen showing pebbles of caliche enveloped and cemented by banded calcite; 3/4 actual size. B: Vertical view of cupped limestone pebbles; 1/3 actual size. C: Specimen showing cupped pebbles cemented by calcite; 1/2 actual size. D: Photomicrograph of sample 5-1, Profile 2, showing oolitic texture; plane polarized light, 20X.

This structure proves conclusively that the waters that transported the calcium carbonate during the formation of these deposits were moving downward.

The layering of caliche may be incipient or well developed. The layers are irregular both in thickness and lateral extension. The thickness ranges from a few tenths of an inch to 10 inches, the length never extending than a few yards. There are some minor thin sandy beds irregularly intercalated among the layers or small pockets of very pure calcite filling former cavities. Well developed layered caliche is characteristic of the deposits from the High Plains presenting maturity features, but it was not observed at the Rio Grande Depression localities.

Because of this layering and because the chemical composition of the upper part of the caliche profiles is so similar to marine limestone (see Aristarain, 1970, figure 6 and table 3), caliche deposits are sometimes confused with outcrops of marine sediments. This is specially true when sediments of this origin crop out in adjacent areas. Fiedler and Nye (1963) state that the deposits of caliche in the Blackdom terrace of the Pecos River at New Mexico, for example, are commonly mistaken for Permian limestone. It is worthy of note that old caliche deposits may have been confused with other types of limestone and were therefore overlooked in field studies. No caliche deposits older than Pliocene are reported in the literature, but careful studies should surely show their presence in earlier geologic times.

A type of structure that has resulted in contradictory interpretations is that shown in Figure 6B. Stalagmite-like "intrusions" of $CaCO_3$ cementing the sand of the thin capping soil, but do not belong to the caliche deposit itself. This photograph was taken at a small open pit on the south side of State Route 83 at a point 1.5 mi northeast of Hope, New Mexico. Similar evidence was presented by some authors to indicate that the caliche deposits were formed by waters moving up from the water table by capillary action. The sediments overlying the caliche deposit in that area, however, are younger than the calichification process and the stalagmite-like bodies are younger than the capping soil. This structure is interpreted as the result of the accumulation of rain water on the hard, impervious caliche; this water later, loaded with $CaCO_3$, was raised by the pull of roots of vegetation or by capillary action and absorbed and/or evaporated producing the precipitation of calcite.

In some places the deposited carbonate appears crossing the bedding of the former sediments in which caliche developed indicating its epigenetic character. This is also indicated by veined and concretionary structures which are observable at places where the processes did not reach the maturity stage or at the middle section and the bottom of mature profiles.

Earthy structure appears where a very fine clastic fraction was predominant in the sediment before calichification. Porous structures present cylindrical eloganted cavities which mainly indicate the action of roots.

Another characteristic structure of these deposits is that of auto-brecciation, which is found mostly in layered zones. Figures 7A and 7D show polished slabs of banded caliche, angular contacts between banded areas, are observable. This structure is attributed to self-breaking due to the force of crystalization of the calcite during its deposition. It is thought to have ocurred near the surface of the ground with small or negligible vertical pressure. In some instances a set of bands ends abruptly against another set producing sharp contacts that suggests fracturing. These fractures are interpreted by several authors as self brecciation (Price, 1925; Bretz and Horberg, 1949). In these cases the bands located in a higher position in the profile always envelope the lower ones. If the waters that formed the bands had moved upward then the youngest bands would be the lowest. This would contradict the pattern described above. The waters in this instance, therefore, must also have moved from top to bottom.

Price (1925) described caliche pseudo-anticlines in central Tamaulipas, Mexico, attributed to the growth of caliche. This author observed that strata beneath that structure are horizontal, that the caliche layers dip up to 17°, that the maximum vertical uplift is 15 ft, and that the lenght along the axis reaches till 2000 ft. Similar phenomena were described by Jennings and Sweeting (1961) in the Fitzroy Basin, Western Australia.

Concluding, the analysis of the described structures indicates that the calcium carbonate of caliche deposits is epigenetic and that the transporting solutions moved downward through the sediments.

TEXTURES

The textures characteristic of the caliche deposits are those seen in chemical and clastic sediments, depending upon the amount of calcite added. As previously stated, the principal mineral component is calcite and their crystals are almost always from very fine to cryptocrystalline. When the rock is composed essentially of a nonclastic fraction the textures are microcrystalline and cryptocrystalline (Pettijohn, 1957), although in some rare instances the texture is mosaic mesogranular.

A banded texture is found at the upper part of the mature profile (Figures 6C and 6D). In most instances the banded zones are approximately parallel to the surface of the ground but they may have any position in relation to the surface. The bands are very thin, ranging from 5 to 15 μ, although hand specimens suggest that they are thicker. They exhibit white and dark layers which are due to a variable content of iron oxides and clay minerals, and in some cases to minor manganese content. The bands are formed by cryptocrystalline calcite, but sometimes comb textures are observed.

These features of the bands are thought to be the result of rapid deposition and related to an intermittent and limited supply of saline waters with little changes in chemical composition. They also suggest that deposition occurred in "open" spaces, although there is the posibility that the growing bands either segregated the clastic minerals or diluted them by increasing greatly the volume of the former sediments; replacement is another mechanism to eliminate the clastic grains. Figure 6D represents a specimen of sample 5-1 (Profile 2), showing the irregularity of the banded sectors. This photograph is similar to that presented by Elias (1931, p. 146) which he described as algal or chlorellopsis limestone (see below).

Related to these banded zones another characteristic texture is commonly associated with mature deposits, that is oolitic texture. A photomicrograph of the same sample 5-1 (Figure 7D) illustrates an example of this texture. The size of the oolites is extremely variable, ranging from 0.03 mm to 0.25 mm. The nucleous of many of them consists of a grain of quartz, or clastic calcite. The photomicrograph was taken from a thin section of the specimen presented as Figure 6D. The oolitic area lies between the bands of the center and the upper part of the hand specimen. In some cases the oolites reach till 1.6 mm in diameter and in one sample a pisolitic texture was observed.

There is also a porous texture whose origin is similar to that of porous structure. Veinlets of pure younger calcite are observable crossing the bands in several samples with banded texture, suggesting that growth of roots may have produced the opening and subsequent deposition of calcite which filled the solution cavities.

In other cases there are cylindrical and elongated molds that are attributed to the former presence of roots or to herbaceous stems; some of the cavities are partially filled with minute acicular crystals of calcite. This type of texture gave rise to the name porous caliche. In Profile 3 of a former paper (Aristarain, 1970) the Zone 2 is porous caliche; this zone is covered by a layered caliche that is very hard, compact and without voids. No break in the process of sedimentation from porous to compact caliche is observable. This situation strongly suggests that vegetal action is related to the accumulation of calcite in the area of this profile and that the upper layer of the caliche profile developed from former porous layers of caliche.

In a attempt to find this relationship between porous caliche and soil processes in present environment, an area was sampled where a modern forest soil exhibits a horizon cemented with calcium carbonate. The area is located in Taos Co., New Mexico, on the west slope of the Sangre de Cristo Range, on the west side of State Route 3, 1.5 mi north of Fort Burgwin Research Center. Thin sections from this horizon show also elongate and cylindrical molds, partially filled with calcite; this similarity suggests that both samples have the same genesis and it also suggests the syngenetic character of voids and calcite deposition for this case.

The addition of calcium carbonate to sands produced a series of rocks, ranging from sandstone cemented with calcite to fine grained limestone. Intermediate stages of calcareous sandstones and sandy limestone are also common rocks. In the first case the subrounded grained clastic minerals exhibit a high degree of grain to grain contact and the amount of cement is relatively small. When calcite cement reach approximately 50% of the specimen the grain contacts are fewer and the clastic minerals begin to show evidence of replacement by calcite and alteration. With further calichification, grain contacts are entirely absent, $CaCO_3$ increases to high values, the almost only clastic mineral is quartz which is partially replaced by calcite and plagioclase is present in very minor amounts.

In another stage the texture is island and sea, quartz is floating in a groundmass of cryptocrystalline calcite as a result of replacement and also because of the tendency of calcite to force apart clastic minerals during its deposition (Carozzi, 1960). The Zone 4 of Profile 1 from Rio Grande Depression (Figure 1) presents good examples of this texture.

DISCUSSION OF THE GENETIC HYPOTHESES

FLUVIAL HYPOTHESIS.— The fluvial hypothesis was first proposed by Hill and Vaughan (1898) to explain the origin of tepetate (caliche) deposits of the Edwards Plateau and Rio Grande Plain. They stated that $CaCO_3$ was dissolved from the surface, transported in solution by torrential streams and deposited because of evaporation. They also considered that incrustations around the margins of the bolson plains of northern Mexico were produced in the same way. Others, Johnson (1901), Trowbridge (1926), Wright (1946) ,have agreed that rivers are partially responsible for the accumulation of $CaCO_3$.

Bretz and Horberg (1949) have described small Recent calcareous crusts formed along the present valleys of the Pecos and Black Rivers, near Loving and Black River villages (New Mexico) respectively.

The solubility of $CaCO_3$ decreases markedly with increase in temperature, other factors being held constant (J. P. Miller, 1952; Garrels and Dreyer, 1952). It was argued, therefore, that cold waters descending from the mountains to desert areas deposited the disolved $CaCO_3$ as their temperatures increased and thus formed the caliche deposits.

The terraces of certain rivers, such as the Pecos River at New Mexico (Orchard Park and Blackdom terraces) are capped by caliche deposits. Fiedler and Nye (1933) stated that in many wells "caliche" occurred at various depths in the fill of the Pecos Valley. This fact would suggest a fluvial (or a soil) origin. However, in most rivers the ratio of dissolved materials to total load is very small; then it seems evident that rivers have not contributed to the formation of extensive caliche deposits to a mayor degree, at least the detrital load is assumed to be mostly calcareous.

Because of the great areal extent of the deposits, the fluvial hypothesis would imply that throughout the region the source rocks were so disposed that they provided a nearly exclusive supply of $CaCO_3$ during the periods of calichification, but provided none $CaCO_3$ during intervening periods. This spacial distribution of source rocks is absolutely unreasonable.

Although there is no doubt that small accumulations of $CaCO_3$ could be formed locally by the action of rivers, it is untenable that large areas could had been formed by a river or a system of rivers acting simultaneously.

LACUSTRINE HYPOTHESIS.—There is evidence that small $CaCO_3$ playa deposits were formed by temporary lakes (Lonsdale, 1926). But some authors have concluded that all the caliche deposits were formed in lakes. Herrick and Johnson, as quoted by Bryan (1909), described the caliche deposits capping the mesas near Albuquerque and Santa Fe, New Mexico, as the Albuquerque and Santa Fe marls; they attributed their origin to precipitation in lakes caused by a damming of the Rio Grande.

Hay (1895) proposed the lacustrine origin for all the Tertiary calcareous deposits of the Plains and named the upper caliche deposit as the Plains Marl. Trowbridge (1932), referring to the "Reynosa Formation" in the Lower Rio Grande region of Texas, stated that perhaps some of the limestone (caliche) was formed by stream-waters flowing into lagoons and shallow flats where they evaporated and deposited their dissolved salts.

Breazeale and Smith (1930) reported that caliche deposits on the mesa land around Tucson, Arizona, "were deposited from small lakes or playas, or from shallow pools of stagnant water", and that precipitation of carbonate was probably accelerated by aquatic plants. These authors pointed out that caliche deposits formed by other processes are also found in Arizona.

Theis (1936) suggested that the water table in Ogallala time was very close to the surface of the ground. As Pleistocene time was approached, cooler and moister conditions resulted in the rise of the water table, thereby forming many pools in which $CaCO_3$ was precipitated by algal or inorganic action. Fry (1945) stated a similar hypothesis.

The uniformity, continuity and lateral extent of the caliche deposits are not compatible with an origin related to small pools; however, Elias (1931) stated that the peculiar banded textures from the top of the Ogallala Formation in Wallace County (Texas) have small, spherical bodies similar to those described by Bradley (1929) from the Green River Formation. This author described these bodies as cells of a fossil algae and proposed to designate them as *Chlorellopsis bradleyi;* only photographs of hand specimen were presented. The banded limestone was named algae limestone, Chlorollepsis limestone or algae reef. Elias attributed the origin of the banded textures to the combined action of inorganic and algal agents. He concluded that the limestone "was deposited on the nearly flat bottom of a very large shallow lake at close of Ogallala time".

Elias suggested that these deposits are different from caliche deposits of arid climates. However, the general description of the profile given by him coincides with that of the caliche deposits of the High Plains. He also described semi-cemented mortar beds which are present at different stratigraphic horizons in the Ogallala sediments. Sands, partially cemented by $CaCO_3$, contain stem-like and root-like bodies that, in some places, are very numerous and form "a tangled mat like that formed by roots in ordinary sod". Fossils of fruits often occur above the calcareous beds.

The strongest point presented in favor of the lacustrine hypothesis is the presumed fossil content. The paleontological finding claimed by Elias has not been corroborated by other authors. Charles B. Read (personal communication, 1960), paleontologist of the U. S. Geological Survey, considered that the banded textures were not the result of algal action.

Smith (1940) presented very convincing arguments against the existence of the lake suggested by Elias. No remmants of lacustrine characteristics have been found, and it is highly questionable to assume that all the geomorphic evidence of a former large lake has been eliminated by erosion, specially in view of its recent age. Furthermore, the emplacement of a large lake on the Ogallala sediments, with the shallowness necessary for development of algal colonies, would require tilting amounting to hundreds of feet. No evidence of this movement can be found. Considering the validity of these objections it is logical to conclude that this lake did not exist.

Price (1940) suggested that caliche deposits were formed by soil processes, and that indurations found with the caliche, including oolites, pisolites and algal limestones were probably formed by evaporation or plant activity on moist surfaces and in lakes of humid periods. Price, Elias and Frye (1946) announced the discovery of algal-reef bodies in the caprock of the Llano Estacado and the Mescalero Plain; this finding would confirm Price's (1940) suggestion. However, the characteristic banded texture of the Elias' algal limestone is a common feature throughout all the Llano Estacado and the terraces of the Pecos River. To accept the thesis that the bodies described by Price, Elias and Frye were formed by algal activity, is almost tantamount to accepting the premise that all the caliche deposits were formed by such process.

It also could be considered that lakes existed in the middle of an extensive caliche deposit, just as those observable today on the surface of the High Plains, for example, and that algae limestone was formed in such lakes. However, while studying caliche deposits of New Mexico, it was found that oolitic texture and structures similar to those described for the "algae limestone" are common in the mature caliche deposits and that they are characteristic of the calichification processes, and not necessarily indicative of a lacustrine origin.

Swineford, Frye and Leonard (1956) performed petrographic studies of the "algal limestone" from Kansas and adjacent states. They concluded that the origin of this limestone was similar to that of the caliche deposits in southeastern New Mexico, namely that it had formed predominantly by soil forming processes.

WATER TABLE HYPOTHESIS.—Johnson (1901) discussed the genesis of mortar beds of the High Plains and pointed out that they apparently mark fluctuations on the ground water table. Blake (1902) thought that the caliche deposits of southern Arizona were the "result of upward capillary flow of calcareous water induced by constant and rapid evaporation at the surface in a comparatively rainless region". Lee (1905) referring to the Salt River Valley, Arizona, agreed with Blake's hypothesis but stated that it seemed equally evident that the caliche of the hill sides and the dry plains was the result of soil processes. Lee also said that there are other cases where deposition of caliche ocurred in subterranean cavities. He suggested that "a relief of pressure is sufficient for the escape of CO_2 and precipitation of $CaCO_3$ at some depth beneath the surface". Bryan (1909) postulated an origin similar to that proposed by Blake to explain the genesis of the Albuquerque marl, although the complementary action of rain water was suggested. Udden (1923) proposed this same combination of hypothesis for the rim rock (caliche) of the High Plains. Guild (1910), Baker (1915), Lonsdale (1926), and R. P. Miller (1937) also adhere to Blake's ideas in general.

Trowbridge (1926 and 1932) proposed deposition of caliche in shallow lagoons, but at the same time he suggested that evaporation from the water table produced $CaCO_3$. Breazeale and Smith (1930) and Frye (1942) mentioned the possibility that deposits may have formed in several different ways, including deposition by upward movement of carbonated waters due to capillary actions. Weeks (1933) stated that the caliche deposits of the Coastal Plain of Texas were formed by a combination of two processes; first by downward moving waters, and second through evaporation or loss of CO_2 from the water table. He considered the second process as the more important. Flandrin, Gautier and Laffitte (1948), who studied the caliche deposits in Algeria, and Du Toit (1954), in reference to the deposits of South Africa, have set forth ideas of genesis similar to those of Blake.

The proposed ideas grouped under this hypothesis, would require a continuous water table with an almost perfect planar upper surface and a lateral extent of hundreds of thousands of square miles in order to explain the formation of a deposit such as the Llano Estacado. This is contrary to facts; studies of the present underground waters in that region show sharp variations and discontinuities of the water table due to local differences in the alluvial sediments of the formation in which caliche deposits were formed. Then a water table located at moderate to deep level, will not explain the extension and uniformity of the caliche deposits.

Therefore, it would be necessary to assume a very superficial level of the water table at the time of the formation of the deposits. Consideration of the variables, affecting solubility of calcium carbonate, shows that under the conditions here discussed, namely a water table near the surface of the ground, temperature and/or evaporation are the only important variables that could produce an extensive accumulation of $CaCO_3$. Variations of pressure, pH, added salts, and total CO_2 in solution are estimated to be potentially factors but only locally.

Regional studies of variations of seasonal and diurnal temperatures of the ground are absent. However, local studies offer some useful information. Flucker (1958) studied the changes of temperature in the air and at several depths in the ground at the campus of Texas Agricultural and Mechanical College. He found that at a depth of 8 ft the average seasonal variations ranged from 27°C (July) to 20°C (January) while the air temperature oscillated from 30°C (July) to 10°C (January), the average annual temperature being 21°C. These figures show how rapidly the seasonal variations of ground temperature decrease with depth. If we consider a water table sufficiently near the surface of the ground so that the temperature of the water, and in consequence the solubility of $CaCO_3$, could be affected by seasonal variations then it is obvious that vegetation and climatic conditions would be such as to prevent the formation of caliche deposits.

Capillarity has been used commonly, in relationship with evaporation, to explain the formation of the deposits. Atterberg measured the height of the capillary rise in different fractions of sand at a constant temperature of 17°C (Terzaghi, 1942). When the diameters of the particles were between 0.5 and 0.2 mm (medium sand) the rise was 24.6 cm, whereas with particle diameters ranging from 0.1 to 0.05 mm (approximately very fine sand) the rise was 105.5 cm.

The clastic fractions of the sediments where caliche deposits were developed, are fine sands and coarser sediments. Then to make really effective this mechanism of $CaCO_3$ deposition by evaporation, the water table must be located within 2 to 3 ft of the surface of the ground. And again in this ease, vegetation will be very abundant and climatic and ground conditions will be such that $CaCO_3$ will not be deposited.

There are other additional reasons to believe that waters rising from the water table were not the cause of $CaCO_3$ deposition. If waters travelled upward, the cementation of the upper part of the deposits would have prevented the continuity of the process after the formation of a relatively thin layer of $CaCO_3$. The fact that in some places the caliche deposits rest on impervious clays would also indicate that, at least, in those cases such direction of movement is impossible. Brown (1956) stated that upward movement of the waters would have produced local uneven thicknesses of the caliche deposits, resulting in greater values in the lower areas, which is contrary to the facts observed in the field.

Although a hypothesis based on a water table located near the ground surface is untenable, in the formation of caliche deposits must have contributed some of the factors discussed under this section. Thus, capillary forces and evaporation, acting upon rain water and air moisture in the superficial loose sediments, facilitated chemical action and mobility and precipitation of $CaCO_3$ and other substances.

SOIL HYPOTHESIS.—Several authors have stated that the caliche deposits resulted principally from soil processes. Lee (1905) transcribed the ideas of R. H. Forbes, who considered that rain water percolating through the ground in regions with scantly rainfall would dissolve carbonates, depositing in the course of time a caliche layer at the depth of water penetration. Lee stated that this is one of three processes that formed caliche deposits.

Hawker (1927) studied the soil of Hidalgo County, Texas, and pointed out several stages of leaching of the carbonates of the soil mass and their accumulation in definite horizons. He considered that these stages are linked with the age of the sediments. In the older stages the upper part of the profiles (3 ft) is entirely leached of carbonates, and caliche is found at 6 to 8 ft below the surface. Instead, the youngest soil does not show evidence of leaching or greater accumulation of soil lime.

Marbut (1927) utilized the presence of caliche as a criterion for semiarid and arid soils. Woolnough (1928) stated that areas of low and seasonal rainfall in Australia contained duricrust, including carbonates. As mentioned above, Breazeale and Smith (1930) reported that the various types of caliche deposits originated from different processes, soil development being one of these. Breazeale and Smith present an excellent example of a $CaCO_3$ horizon cross-cutting other strata, thus indicating its epigenetic character.

Price (1925 and 1933) said that caliche deposits of south Texas resulted from the "accumulation in situ of impure soil lime at the base of a leached top-soil zone, passing through age stages from grains and flakes and aggregations of youth, to continuous but indurated beds of porous, earthy $CaCO_3$ in the mature stage, and represented in old age by indurated limestone". He also stated that old age is only reached in desert areas, that maturity is reached in semiarid areas, and that youthful characteristics are found in the marginal areas of the subhumid or humid zones.

Weeks (1933) considered that the caliche deposits were formed by soil processes and/or rapid evaporation from the water table.

Bryan and Albritton (1943) correlated recent pedologic and geologic events in the Davis Mountain area of West Texas. They postulated a cyclic process whereby the accumulation of $CaCO_3$ corresponds to conditions of aridity, and the intercalated sediments to humid periods. These authors expressed the view that carbonate was deposited because of soil processes. In his study of the fossil and complex soils of the Mexican Plateau, Bryan (1948) confirmed the above correlations.

Similar pedologic and geologic correlations were suggested by Frye and Leonard (1957a) in their paper on the ecological interpretations of Pliocene and Pleistocene stratigraphy in the Great Plains region. They stated that a caliche deposit was formed at the end of the Ogallala deposition, that the Afton buried soil developed a lime-accumulating soil profile, and that the Yarmouth soil developed a caliche deposit.

Bretz and Horberg (1949) studied the caliche deposits in southeastern New Mexico, described numerous profiles, and discussed the different hypotheses of genesis. These authors concluded that most of the features "clearly indicate that soil forming processes were of major importance in producing the caliche deposits".

Brown (1956) investigated the deposits of the northeastern Llano Estacado, Texas, and concluded that they were the result of long continued soil processes operating in an eolian aggrading profile. Swineford, Frye and Leonard (1956), Frye and Leonard (1957b and 1959), Albritton (1958), Moots (1958), Gile, Peterson and Grossman (1966), Hawley and Gile (1966), Ruhe (1967) and Reeves (1970) have also favored the soil hypothesis.

The field observation and laboratory determinations presented in summary way in this paper strongly support the hypothesis that caliche deposits were formed principally by soil processes. Concluding, the principal characteristics favoring this are: (1) continuity and wide lateral extent of the deposits, (2) occurrence of deposits on flat, "stable" physiographic surfaces with gentle slopes, (3) parallelism of deposits with the surface of the ground and superficiality of the carbonate accumulations, (4) relationship between the deposits and present climatic conditions, (5) cyclic character of the accumulations and the existence of several deposits on surfaces of different age, with greater thickness and maturity in deposits on older surfaces, (6) epigenetic character of the $CaCO_3$, (7) calcareous horizons crosscut the bedding of former sediments, (8) correlation of caliche deposits and $CaCO_3$ accumulated in soils with Pleistocene interglacial stages, (9) existence of caliche deposits resting on impervious clays, (10) existence of pseudo anticlines, (11) decreasing calcium, carbon, oxygen, hydrogen, magnesium and ferric iron content with decreasing depth in the caliche profiles, (12) structures of caliche deposits, especially cupped pebbles and brecciated structures, (13) textures of the deposits and in particular porous texture and its comparison with that of $CaCO_3$ horizon in present forest soil, (14) decreasing alteration and replacement of minerals toward the bottom of the profiles, and (15) variations of the mineralogy of the caliche deposits along the profiles, especially clay minerals.

CONCLUSIONS

The characteristics of caliche deposits of New Mexico and the geological history of the region permits us to postulate that these deposits were formed by soil processes operating under conditions of moisture deficiency during all seasons, although the climate was not as arid and warm as that of the area where caliche is found today.

Alluvial sediments, containing relatively large amounts of clastic calcium carbonate, constituted the parent rock in which the deposits were formed. Climatic changes toward more arid conditions must have provided the framework necessary for the initiation of $CaCO_3$ accumulation. The principal agent was, apart from the calcium carbonate itself, the restricted amount of rain water, although biological activity in the soil played an important rôle. Because of this biological action, an increase of total CO_2 in soil water, during certain periods, may have produced decreasing pH values, thus favoring conditions for $CaCO_3$ solution and transport. Soluble salts, that are not leached under arid environments, must have contributed to the solution and transport of calcite.

Calcite accumulated at the depth of penetration of percolating rain waters and was deposited there primarily because of substraction of water by vegetation, and partially because of temperature variations. Long continued action of these processes resulted in important accumulations of carbonate.

It is thought that the period of $CaCO_3$ deposition produced cementation of the sediments, or earthy or concretionary structures, with moderate to high carbonate content. After this period of accumulation, erosion of the upper horizons of the soil profile occurred, and weathering of the calcareous zone under arid climate produced the hard and compact layered caliche with its very high concentration of calcium carbonate. Brecciated and banded textures also developed during this stage. Some deposits did not reach this degree of maturity, and remained, therefore, in the concretionary stage of development. In other cases new sedimentation occurred, followed by a new cycle of soil processes and calichification, increasing the thickness of the $CaCO_3$ layer.

As previously indicated, because caliche deposits are of great areal extent and because of the differences in size distribution and chemical composition of the host sediments, it must be expected that significant structural and/or textural variation will occur from one deposit to another, or from different areas of the same deposit. Variations in the amount and thickness of calcite accumulation must also be expected because of climatic variables that controlled their development. Local influences such as chemical composition of parent rock, type of vegetation, and/or its density, physiographic characteristics and time, must also have controlled the amount of carbonate deposited.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the late Prof. J. P. Miller, to Professors C. S. Hurlbut, Jr., A. V. Jopling, R. Siever and L. Lustig, for reading the manuscript and making many helpful suggestions. Also extends his thanks to Dr. C. B. Read, to Dr. W. S. Motts and A.

Montgomery, because of many stimulating discussions and help during the field trips.

Support of this work by UNESCO, Consejo Nacional de Investigaciones Científicas y Técnicas, Pan American Union, Daly Fund and J. D. Whitney Fund, is gratefully acknowledged.

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