PETROGRAPHY AND GEOCHEMISTRY OF LOWER PERMIAN CORNSTONES IN SOUTHWESTERN OKLAHOMA

By

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PETROGRAPHY AND GEOCHEMISTRY OF LOWER
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OKLAHOMA

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CHAPTER I

INTRODUCTION

This study describes surface outcrops of Lower Permian cornstone (fossil caliche) deposits in southwestern Oklahoma, south of the Wichita mountains (Fig. 1). Exposures are widespread but small; thus correlation is difficult. The principal objective of the study was to provide stratigraphic, geochemical and sedimentologic information necessary to interpret the Lower Permian environment, especially climate and soil-forming processes. Emphasis is on the petrography and geochemistry of the cornstones; they are compared with recent and fossil analogues. The areal and stratigraphic distribution of cornstones in the study area is shown in Plate 1.

Buckland (1821) first defined ancient occurrences of cornstones as being:

> . . . composed of marl or marlstone filled with concretions of compact limestone, presenting the fracture and colour of mountain limestone, and varying in size from that of a pea to blocks of many tons, and sometimes spreading itself into thick and compact beds, to the almost total exclusion of the marl. The knotted character which these concretions assume resembles that of a conglomerate animal gland, and the small acini or kernels of which they are composed usually separate under the blow of the hammer. The transfusions of their outer portions and projecting points into the substance of the marlstone, shows them not to be fragments

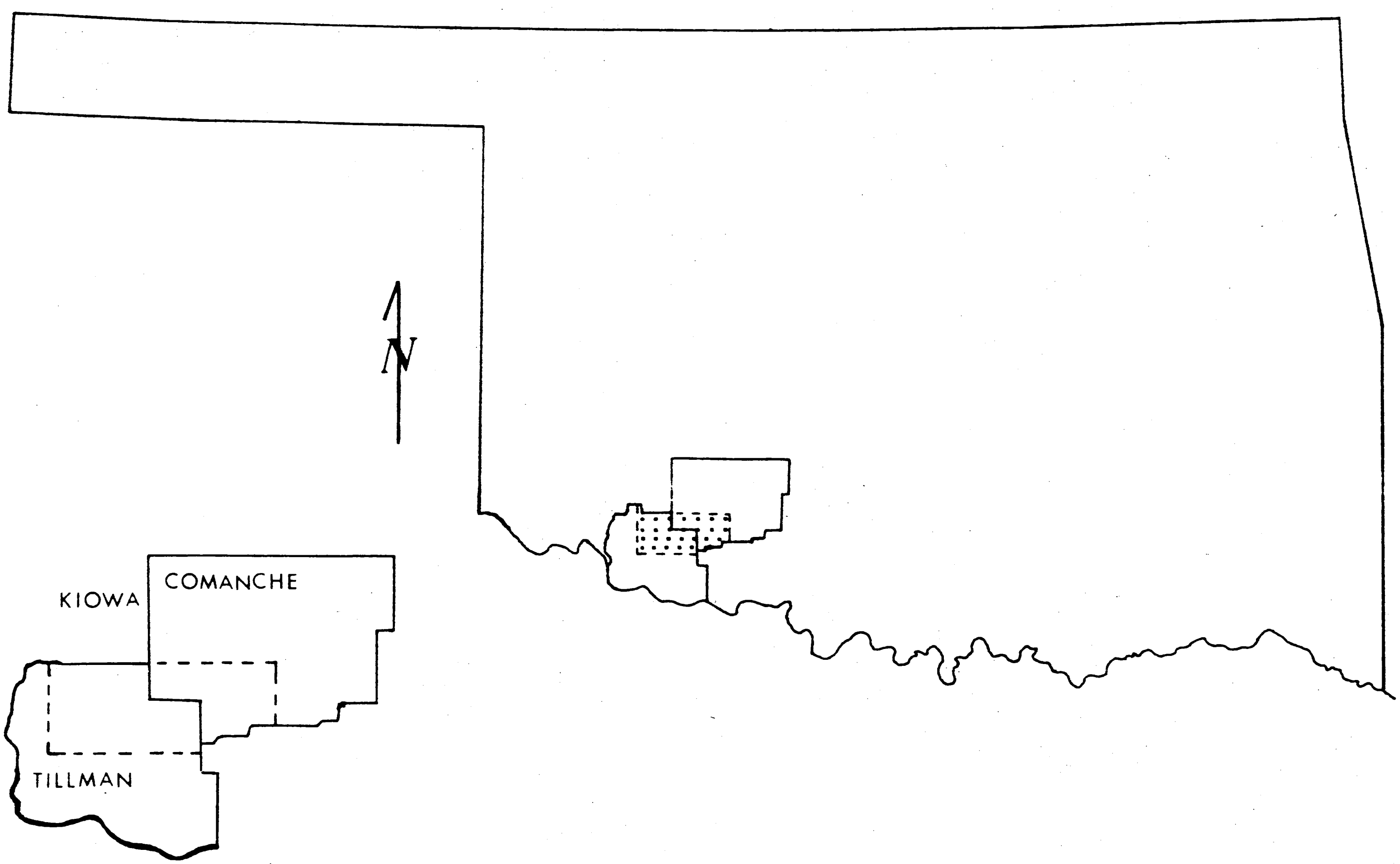


Fig. 1.-Index map of the study area, Southwestern Oklahoma

> resulting from the destruction of any older rocks of transition limestone, but concretions of contemporaneous origin with the marlstone, in which they are imbedded (p. 512).

Since then, a number of other workers have attempted to define the term mainly from a genetic viewpoint (Bretz and Horberg, 1949; Brown, 1956; Swinford et al., 1958; Black and Tynes, 1965; Gile et al., 1966; Aristarian, 1970; Reeves, 1970). Of these, the writer suggests the following modification of Esteban's (1976) definition: fine grained, authigenic carbonate deposits resulting from soil-forming processes which show a vertical zonation in well-developed profiles. Color is white to various shades of gray and brown. Three rock types are normally developed: (1) massive - chalky, (2) nodular - crumbly, (3) compact - laminated and/or pisolitic crust. Their vertical position, horizontal extent and development in the profile is variable. They generally grade downwards into the host-rock through a carbonate-impregnated transition zone. Fabrics consist of irregular shrinkage cracks, veins, and vugs. The latter may be void or partially to completely infilled with calcite, dolomite, clays, iron oxides and other minerals. Minor fabrics include poorly-laminated micrite and microspar and drusy, equant and isopachous sparite. The microspar (in particular) and sparite often show evidence of neomorphism.

Discussion of all these carbonates has been confused by a multiplicity of terms describing essentially similar phenomenon, e.g. calcrete, cornstone, caliche, duricrust, race, paleosoil, calcareous nodule beds, kunkur, croute calcaire, kafkalla, lavara and omdurman lime. Of these terms, "cornstone" has precedence in the description of ancient occurrences. It is used in this work in accordance with the preceding definition. The term "caliche" is used to discuss recent carbonate accumulations.

Previous Work

During the present study, accumulations of pedogenic carbonate have been encountered at several localities in the Post Oak formation, the Hennessey group, and the Garber Sandstone south of the Wichitas (Plate 1). These accumulations are very similar to calcareous horizons developed in other ancient arid-zone alluvial facies, e.g. the continental Devonian ("Old Red Sandstone") of Britain (Allen, 1974a, 1974b; Leeder, 1973), the Permian of Britain (Steel, 1974) and the Triassic of Connecticut (Hubert, 1977). In all of these deposits, an analogy has been drawn with Pleistocene and Holocene pedogenic profiles. In particular, studies have compared the similarity of the ancient profiles with the Cca horizons in semi-arid soils and the evidence that the profiles developed <u>in situ</u> (Gile, 1970).

Detailed work on the cornstones present in southwestern Oklahoma has not been undertaken, although workers have noted the existence of caliche or carbonate concretions in mudstones associated with sandstones and/or conglomerates (Bunn, 1930; Chase, 1954; Johnson and Dennison, 1973;

Morrison, 1977). Al-Shaieb et al. (1977) found subtle radioactive anomalies associated with some of these carbonate horizons. They concluded that these deposits record formation of carbonate on depositionally-starved flood plains in a semi-arid climate.

CHAPTER II

METHODOLOGY

Approach

A four-fold approach was used in this study:

Lithologic Profiles. A field study of the thickness and lithology of the cornstones, relating vertical variation to progressive development stages (Appendix A).

Petrography. Thin section examination, using petrographic and cathode luminescence microscopy to study texture and fabric of the cornstones and their diagenetic features. Twenty thin sections were examined and analyzed in detail including the x-ray mineralogy of the carbonate portion.

Geochemistry. Analysis of samples to determine their major and trace element composition. Ba, Sr, Ca, Mg, Na, Mn, K and Fe were determined so as to aid in the reconstruction and determination of the prevalent geochemical conditions during and after the cornstone formation.

Clay Mineralogy. The composition of the clay minerals associated with the cornstones was determined by the x-ray of oriented sections. A detailed description of the techniques employed is provided in the section on clay mineralogy.

Sampling

The cornstones were sampled in the field so as to best represent the different types within a profile. Where exposures are widespread, two samples were collected per mile. On outcrops with distinct profiles, samples were collected from each zone. A total of 36 profiles were examined. Clay samples were obtained for selected profiles.

Chemical Analysis

After cutting the samples (to examine their macroscopic texture and mineralogy), they were crushed in a ceramic jaw crusher. Pulverisation in a Specs ball mill, using two tungsten carbide balls, was followed by sieving. Samples of 80 mesh or finer were finally utilized.

Analysis was done with a Perkin-Elmer 403 double-beam atomic absorption spectrophotometer. Analytical procedures and settings were recommended by the manufacturer. Samples were prepared by dissolving 1 gm of rock powder in 40 ml solution of 10% hydrochloric acid. They were digested in a teflon or glass beaker by heating on an electric hot plate for six hours at a temperature of 150^{o}F and then for eighteen hours at room temperature. This solution was filtered. Five ml of 5% lanthanum chloride was added to ensure accurate determination of barium and strontium. The solution was diluted to 50 ml with distilled water.

Insoluble residues were dried and weighed.

A total of 65 samples were analyzed. Results obtained are given in Appendix B.

CHAPTER III

GEOLOGIC SETTING

Structural Framework

The study area contains parts of three major structural elements: the west-northwest trending Wichita-Criner uplift, the Hollis basin and the Muenster-Waurika arch (Fig. 2). These elements, which may have strongly influenced Late Pennsylvanian and Permian sediment deposition are part of the southern Oklahoma aulacogen (Burke and Dewey, 1973; Hoffman et al., 1974; Pruatt, 1975; Wickham et al., 1976; Powell and Phelps, 1977), initiated during Late Precambrian to Early Cambrian. The aulacogen rifted and subsided from Late Cambrian to Mississippian and was uplifted and deformed during Pennsylvanian to Early Permian.

Rifting was characterized by block faulting and accompanied by the emplacement of mafic and felsic extrusives and intrusives as in the Wichita mountains (composed of metamorphic, gabbroic, rhyolitic, granitic and basic layered igneous rocks). Considerable thicknesses of shallow water sediments were deposited during the subsidence stage of the aulacogen formation (Wickham et al., 1976), while the deformation stage was characterized by compressional tectonics. Subsidence of the Ardmore and Anadarko basins coincided with episodic uplift

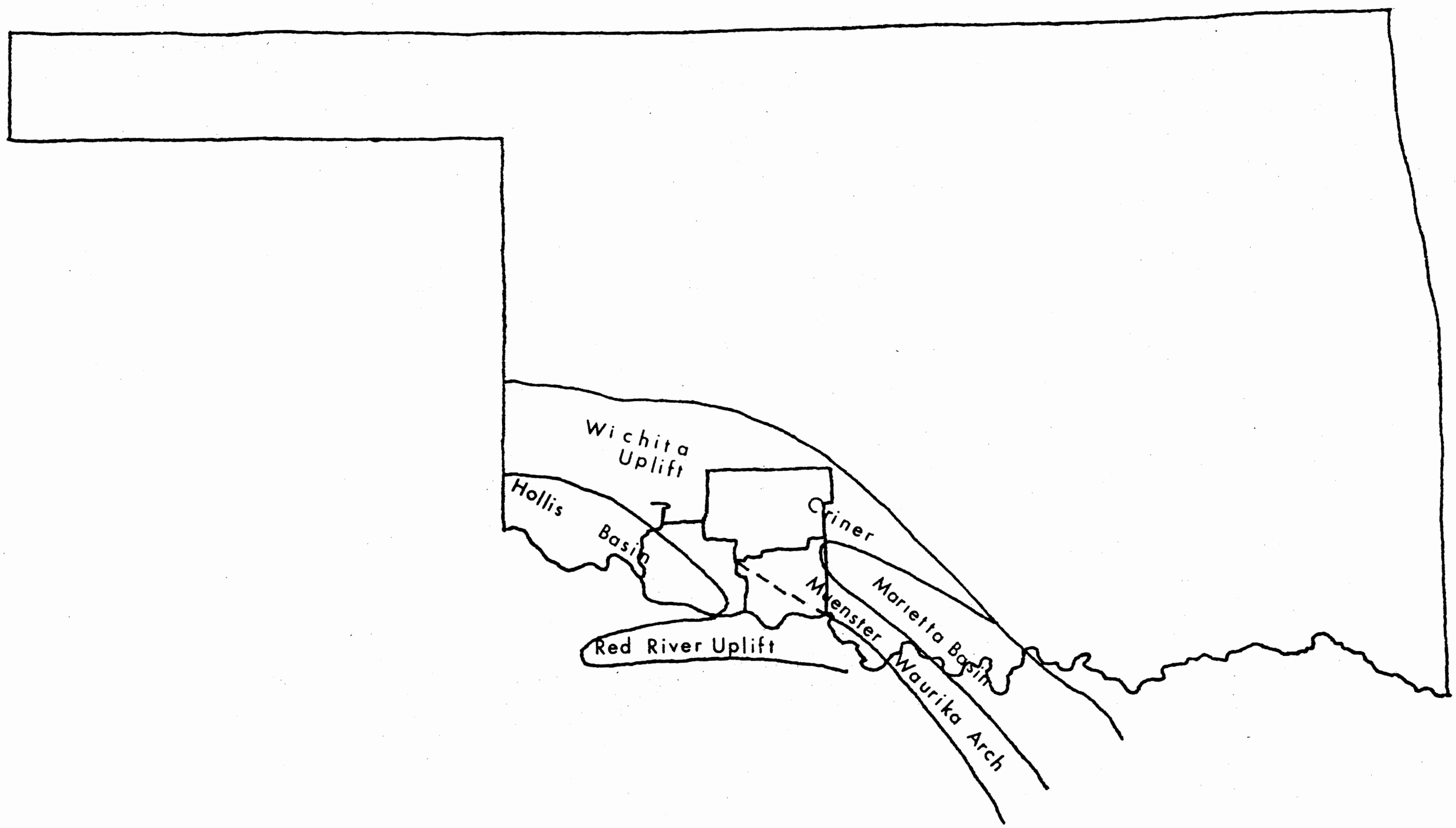


Fig. 2. - Structural setting of Southwestern Oklahoma

of the Wichita-Criner and Arbuckle uplifts. Hoffman et al. (1974) have related the compressional phase to the subduction which formed the Ouachita fold belt.

Principal basement faults within the study area are the North Fork and Waurika-Muenster faults. Both are northwest trending, high-angle normal faults downthrown on the southwest side. They cut through Pennsylvanian strata.

Permian sediments in the area represent the zeugeosynclinal stage of clastic sedimentation during Carboniferous and Permian (Ham et al., 1964). Tectonic activity had essentially ceased by the end of Pennsylvanian time; but minor folding of Permian strata over older Pennsylvanian structures took place. The surface faults and folds in the study area are mostly expressions of the predominantly northwest trending basement structures.

Stratigraphic Setting

The cornstone deposits occur in Lower Permian strata. The stratigraphic column utilized is that shown in the Hydrologic Atlas of the Lawton Quadrangle (Havens, 1977) (Fig. 3). Away from the Wichitas the strata are divided into the Sumner and Hennessey Groups. The Sumner has been subdivided into the Wellington and Garber Formations.

Chase (1954) considered the Post Oak formation adjacent to the Wichitas, to be a facies equivalent of the Garber Sandstone, Wellington formation and the upper part of the Pontotoc Group. Havens (1977) equates it with the Hennessey

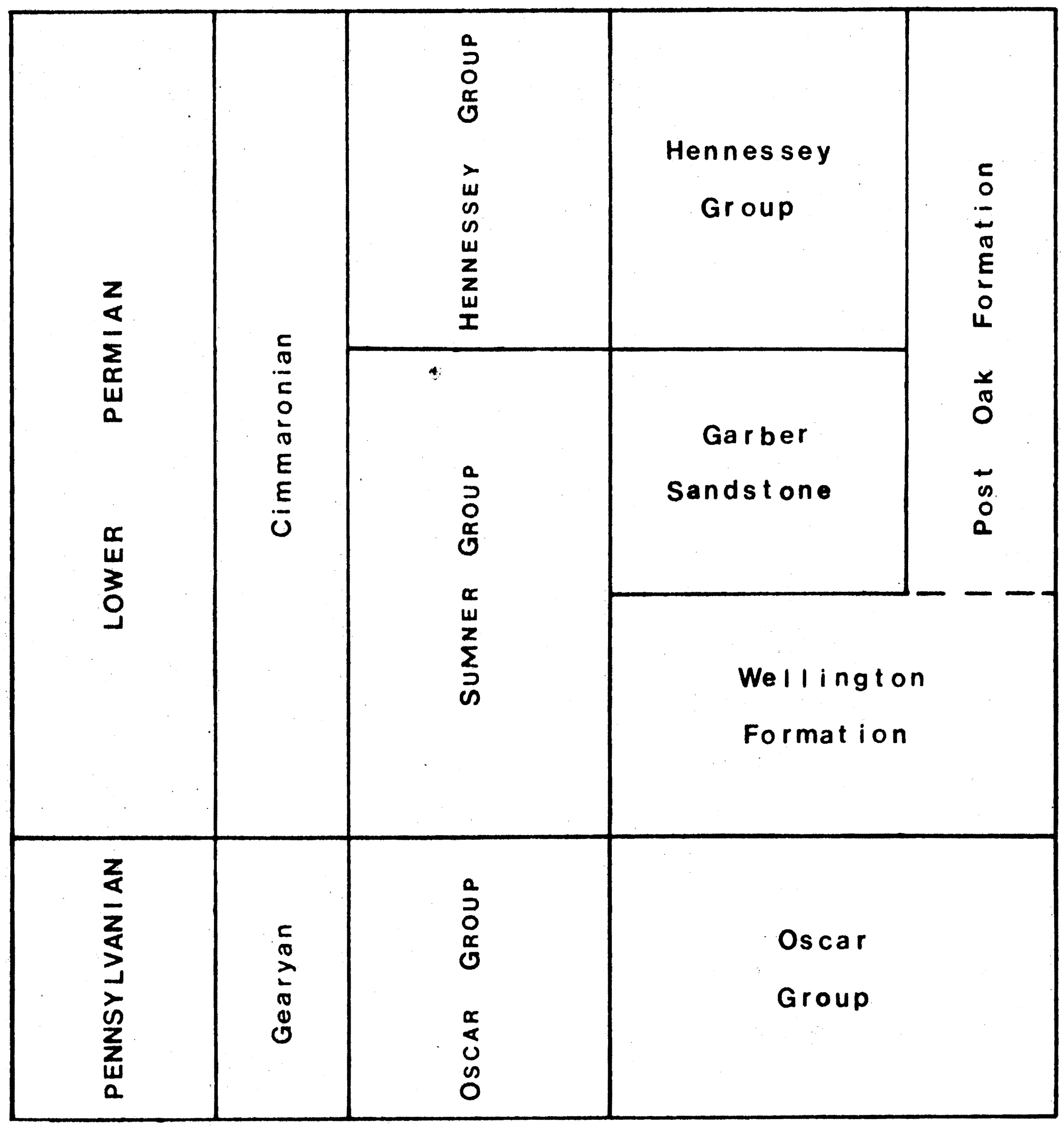


Fig. 3.-Stratigraphic nomenclature and correlation of surface Pennsylvanian - Lower Permian strata in the study area (from Havens, 1977).

Group and Garber Sandstone. South of the Wichitas, the Post Oak interfingers with shales, sandstones and arkose of the Wichita Formation.

Four distinct facies of conglomerate in the Post Oak have been mapped by Chase (1954). These are designated as: Ppo-1: limestone conglomerate; Ppo-2: granite boulder conglomerate; Ppo-3: rhyolite porphyry conglomerate; Ppo-4: granite-gabbro conglomerate with zeolite-opal cement. Ppo-2 and Ppo-3 are quantitatively the most important facies.

Close to the Wichitas, the Post Oak consists of conglomerate interbedded with lenses of sandstone (Chase, 1954). It dips away from the mountains and clast size decreases down dip as conglomerates grade into and interfinger with red coarse-grained, cross-bedded arkosic sandstones, siltstones and mudstones. Based on the feldspar content, absence of marine indicators and presence of cornstones and alluvial bed forms, Al-Shaieb et al. (1977) have interpreted the Post Oak as an alluvial fan/braided river deposit which formed in a tectonically quiet setting under a semiarid climate.

Coarser lithologies of the Post Oak are developed as laterally impersistent channels with pronounced erosional contacts, and basal channel-lag deposits of exotic and intraformational clasts (Al-Shaieb et al., 1977). Close to the Wichitas, they are multistoried but become discrete and lenticular and are separated by siltstones and mudstones distal to the mountains.

Evidence from sedimentary structures, paleocurrents and texture indicate deposition of the Post Oak was by small, probably ephemeral streams draining the Wichita mountains. Deposition was as alluvial fans (piedmont) immediately adjacent to the mountains. A few kilometers from the mountains, the paleoenvironment was an alluvial plain across which small braided-streams of low competence flowed; frequent avulsion is indicated (Al-Shaieb et al., 1977; Morrison, 1977). At the surface, the Post Oak is over 150 meters thick, and is much thicker in the subsurface (Havens, 1977).

Overlying the Wellington formation, the Garber Sandstone is a reddish-brown, fine grained sandstone. At the base, the Asphaltum Sandstone consists of a series of gray to buff calcareous sandstones, generally massive, friable and medium-grained but locally laminated and thinly bedded (Bunn, 1930). The thickness of this sandstone varies from 3 to 18 mm and it is interbedded with shales. A nodular limestone conglomerate occurs in some areas (Bunn, 1930).

The Hennessey Group has been divided into the Fairmont Shale, the Purcell Sandstone, and the Bison Shale (Aurin et al., 1926; Green, 1936). It consists of reddish-brown to gray calcareous, blocky shales and tan, fine-grained, lenticular crossbedded sandstones. The Group is 40 to 60 mm thick (Havens, 1977).

CHAPTER IV

CORNSTONES

Types

Cornstones are accumulations of authigenic carbonate developed as prominent features of flood basins, alluvial fan surfaces, or the subpiedmont borderlines of alluvial plains. They may be replacive and/or displacive relative to the host sediment. In older profiles, brecciation and expansion features develop. Profiles develop progressively and thicken with age. A variety of types or stages have been recognized by various workers (Gile, 1970; Mercier and Vogt, 1974; Reeves, 1974; Steel, 1974). A slight modification of Steel's (1974) classification is summarized below:

<u>Type 1</u>. Small (1-6 cm in diameter), irregularly-shaped nodules composing less than 10% of the rock. Are characteristically white, crumbly, and uncemented. Young profile.

<u>Type 2</u>. Larger carbonate nodules (up to 10 cm diameter), occupying less than 50% of the rock in the upper part of the profile. There is a downward gradation into cornstone of Type 1. Early mature profile.

<u>Type 3</u>. The carbonate appears mostly as nodules of variable size or horizontal sheets and is carbonate

cemented. Carbonate occupies more than 50% of the rock but clastic sediment can still be clearly seen within the carbonate framework. Grades downward into cornstone of Type 2. Mature profile.

Type 4. Carbonate exists as beds within which only rare patches of clastic sediment are seen. Nodules are larger and harder in the upper part. The cement in the lower part may be chert and/or carbonate. There is usually a downward gradation to Type 3. Late mature profile.

Type 4a. Distinct horizons of laminar, brecciated or pisolitic carbonate, usually as a capping to Type 4. The carbonate may be silicified and thin beds of carbonate may alternate with chert. Old age profile.

The sequential arrangement of cornstones (in which Type 1 grades into Type 2, etc.) is interpreted as recording stages of growth. There is usually an upward increase in carbonate content and degree of cementation through the profile. Meanwhile, downward growth continues until a plugged horizon is formed. Thereafter, growth is mainly upward. Leeder (1975) has given the following limits to the time taken for the development of various stages:

Stage 1: minimum 1000, maximum 4500 years;

Stage 2: minimum 3500, maximum 7000 years;

Stage 3: minimum 6000, maximum 10,000 years;

Stage 4: minimum 10,000 years.

Based on the preceeding classification, cornstones in the study area have been classified into different types (Appendix A). Figure 4 shows the cumulative number of cornstone types in each stratigraphic horizon.

Field Character

Cornstones in the study area are most commonly hosted by mudstones; some are developed in sandstones and/or conglomerates. Vertical profiles of various sorts are exposed in road cuts and stream channels; elsewhere cornstones are evidenced by nodules scattered on the ground. Most vertical profiles are young, i.e. immature, but some show mature profiles.

As noted, the cornstones are mostly developed in the finer lithologies of fluviatile units, principally reddish mudstones. Locally greenish mudstones are intimately associated with the cornstones. Horizons formed in sandy sediments display a different morphological sequence; nodules are less well-defined and sparitic cement is more in evidence. Detailed descriptions of the sampled localities are in Appendix A.

The following six morphologies were observed: (1) brecciated, (2) nodular, (3) indurated (carbonate impregnated), (4) massive, (5) laminated, and (6) conglomeratic. The position of horizons of each form on a vertical profile varies.

Brecciated Horizons

These are most frequently developed at the top of

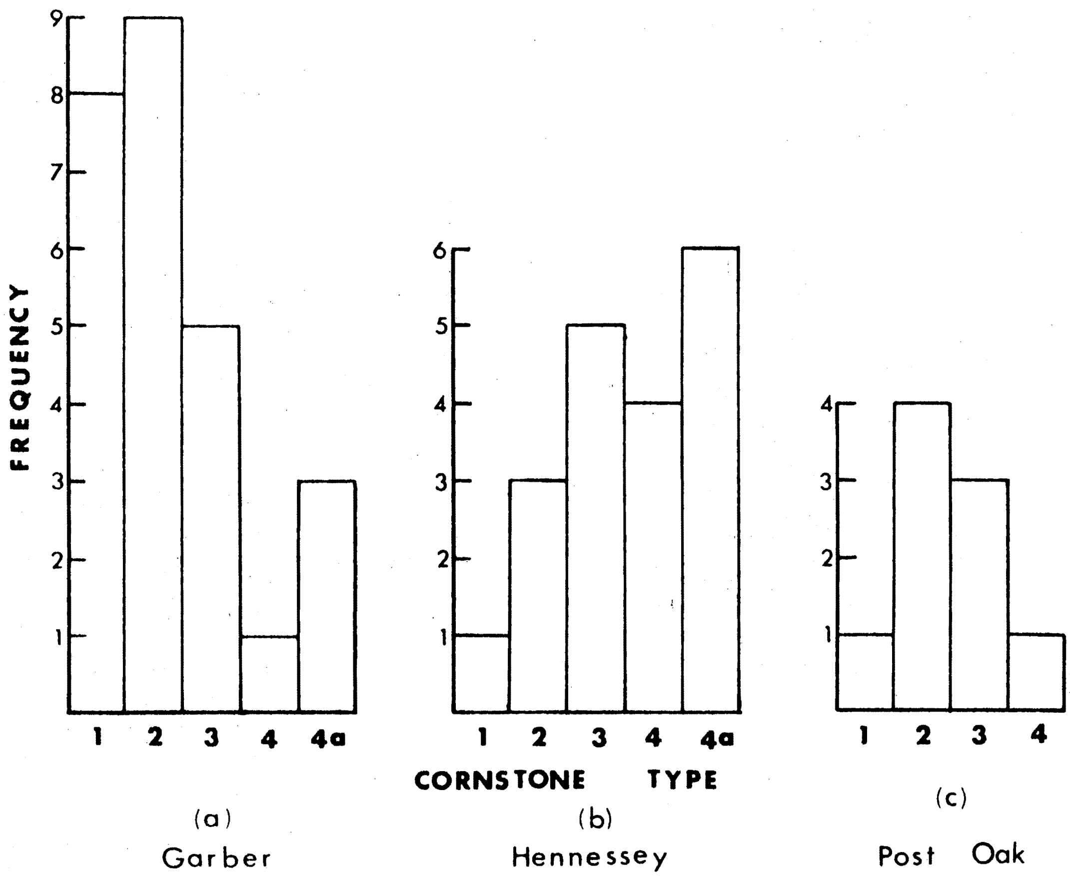


Fig. 4.-Histogram showing the number of cornstone types in each of the host formations.

profiles (Figs. 5, 6, 7, and 8) though they may also occur at a lower level (Fig. 5). The horizons appear rubbly, comprising angular and fragmented blocks which appear to have been brecciated.

Nodules

Nodular forms are common and widespread. The matrix is mainly red in colour but streaked and mottled with green. The nodules, irregular to botryoidal in shape, are usually less than 1 to 8 inches in diameter. Cylindrical forms, inclined to bedding, are developed in a few cases (Figs. 5, 8, 12, 13, and 21). Toward the top of a profile the nodules grow progressively larger, more numerous and more closely packed (Figs. 9 and 11).

Internally, the nodules contain cross cutting, irregular and bifurcating vugs partially to completely filled with calcite, clay, iron oxide and rare barite.

Indurated Crusts and Carbonate Impregnated Horizons

Carbonates of this type are non-laminar, and may be chalky; the thickness of the crust varies. They are commonly gray in color and frequently appear cracked.

Where the host is a sandstone, a transition zone of carbonate impregnation exists between host and cornstone. The degree of plugging and carbonate content increases upwards in the profile. The plugged horizon may be absent, (e.g., profile G-4).

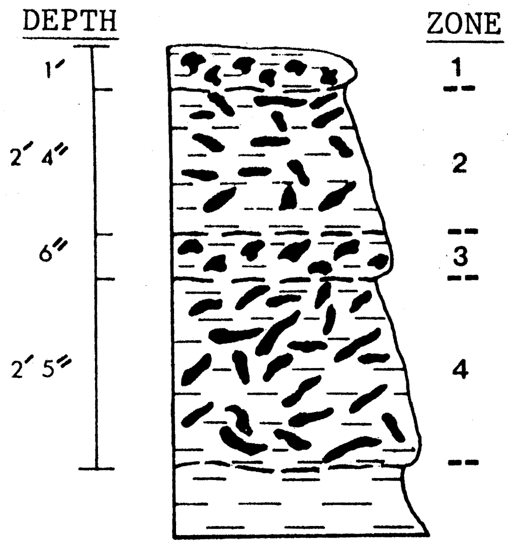


Fig. 5.-Measured section of profile G-9 showing cylindrical and brecciated cornstones in Sec. 13, T1N; R17W. Photo at locality Fig. 8.

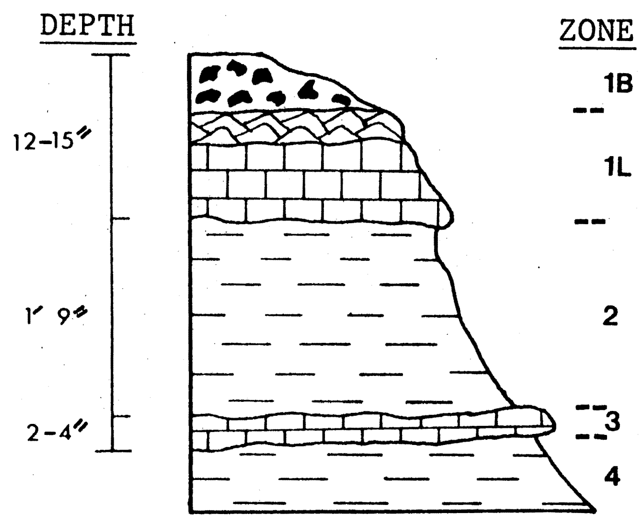


Fig. 6.-Measured section of cornstone in profile Y-1 in Sec. 11, T1S, R15W.

See Fig. 7 for Photo.

Fig. 7.-Two laminated (dolomitic) cornstone zones overlain by brecciated cornstones.

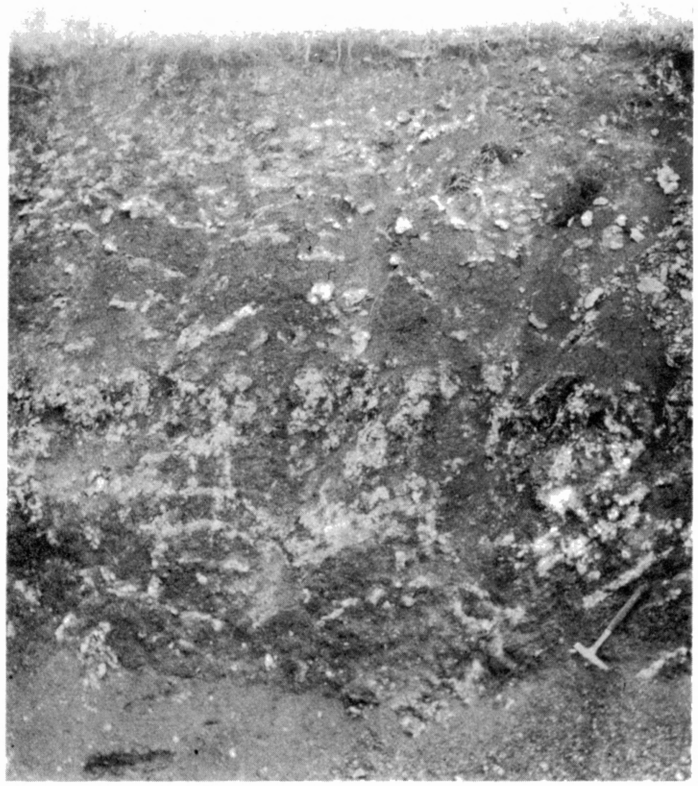


Fig. 8.-Inclined cylindrical nodular and brecciated cornstones (profile G-9). Note the variation in the directions of inclination of nodules.

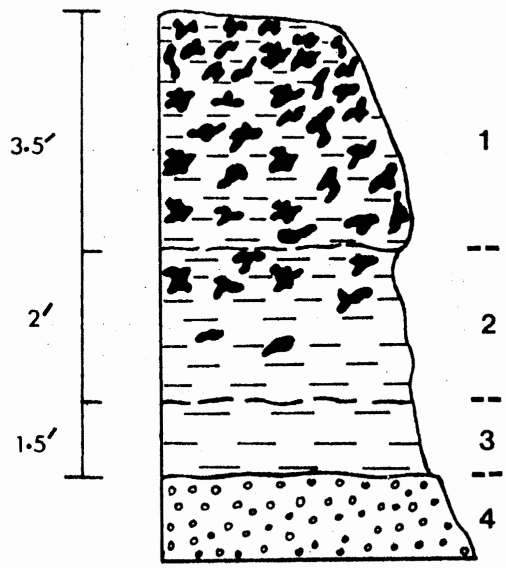


Fig. 9.-Measured section of profile I-1 illustrating a progressive downward decrease in content of nodules in Sec. 3, T1N, R15W. Photo Fig. 11.

Fig. 10.-Irregular to botryoidal nodules (N) (profile I-1) associated with mudstone. Note upward increase in size and content.

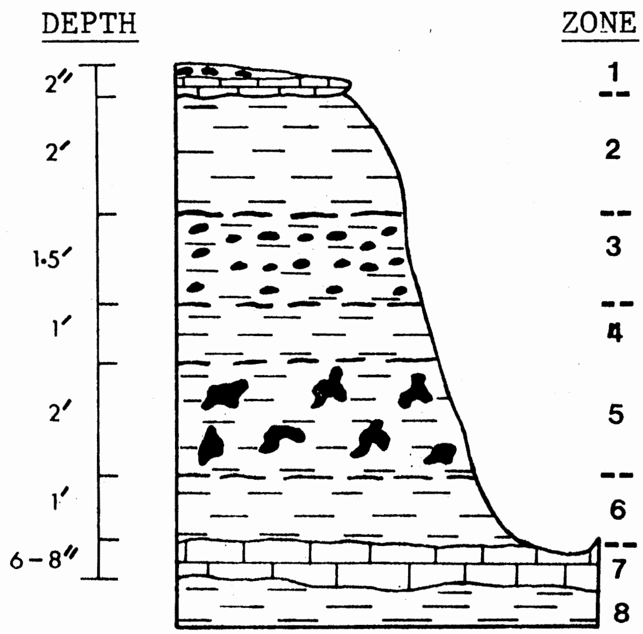


Fig. 11.-Measured section of profile H-5 showing different cornstone types developed in one locality. Sec. 25, T1N, R17W.

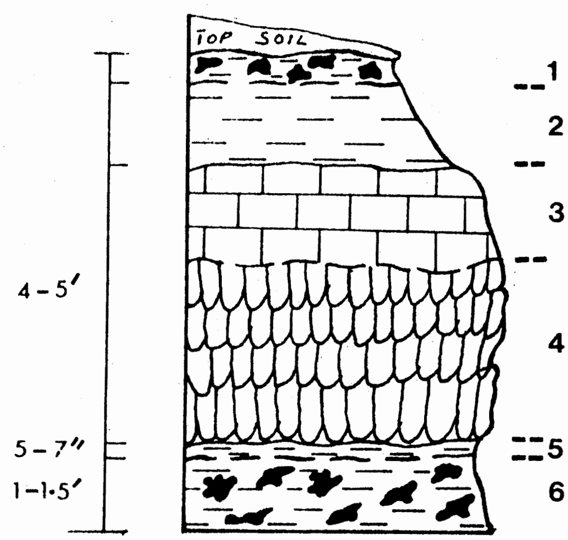


Fig. 12.-Measured section of profile H-8, in Sec. 4, T1N, R16W. Photo Fig. 14.

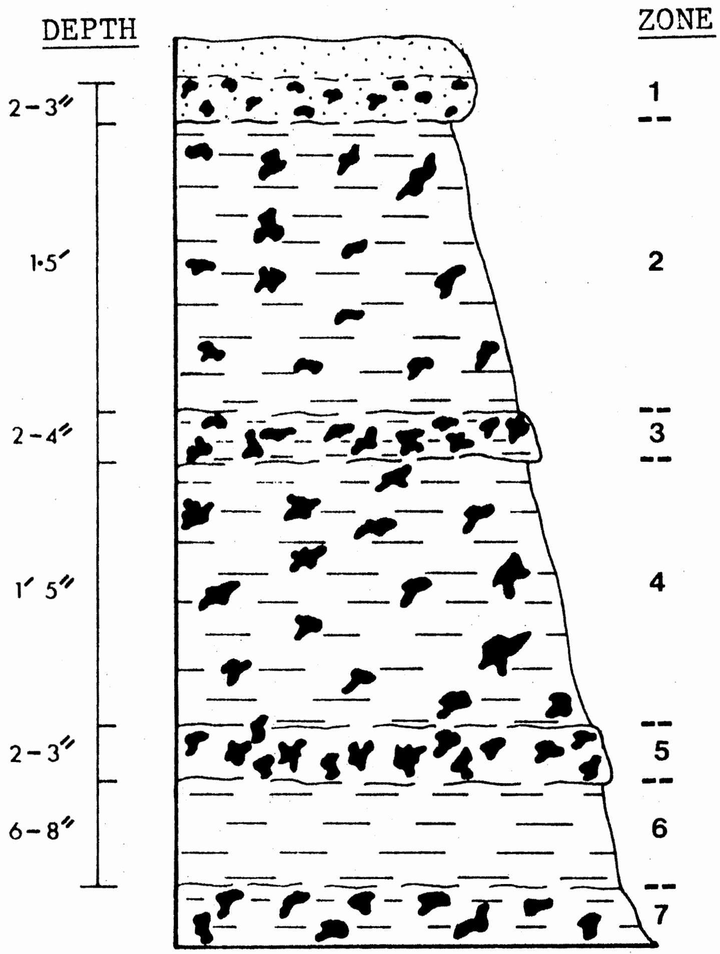


Fig. 13.-Measured section of profile E-3, Sec. 15, T1S, R15W.

Massive Cornstones

Only one profile contained this form of cornstone (Figs. 12, 14, and 15). It is essentially an indurated, non-laminar, discontinuous carbonate of variable thickness. The uppermost part of the horizon is brecciated and pseudo-pisolitic. The lower part shows compact, vertical pillars.

Laminated Forms

These occur as beds of variable thickness, (1 to 8 inches) (Figs. 6, 7, 11, and 16). Most are dark purple-gray but profiles H-4, H-5, H-6 contain light grayish-green bands. These horizons commonly exhibit gently undulating, poorly-defined laminae. The laminae truncate another and increase in the upper part of the cornstone.

Within the carbonates are subhorizontal dolomite/calcite filled veins. Both horizontal and vertical vugs are filled with calcite and/or dolomite. Some clay infilling was observed in a few horizons.

On the lower surface of some profiles are hexagonal and radiating dessication cracks (Fig. 17). The upper surface of horizon H-6-1 has many small nodular protuberances. Horizon Y-1-1 shows tepee structures, 4 to 5 inches across (Figs. 7 and 16).

Cornstone Conglomerates

These were observed mainly in the Garber Sandstone (Figs. 18, 19, 20, 13, 21, and 22) with only one example in the

Fig. 14.-Massive cornstone
(profile H-8) with vertical
pillars developed at the
base.

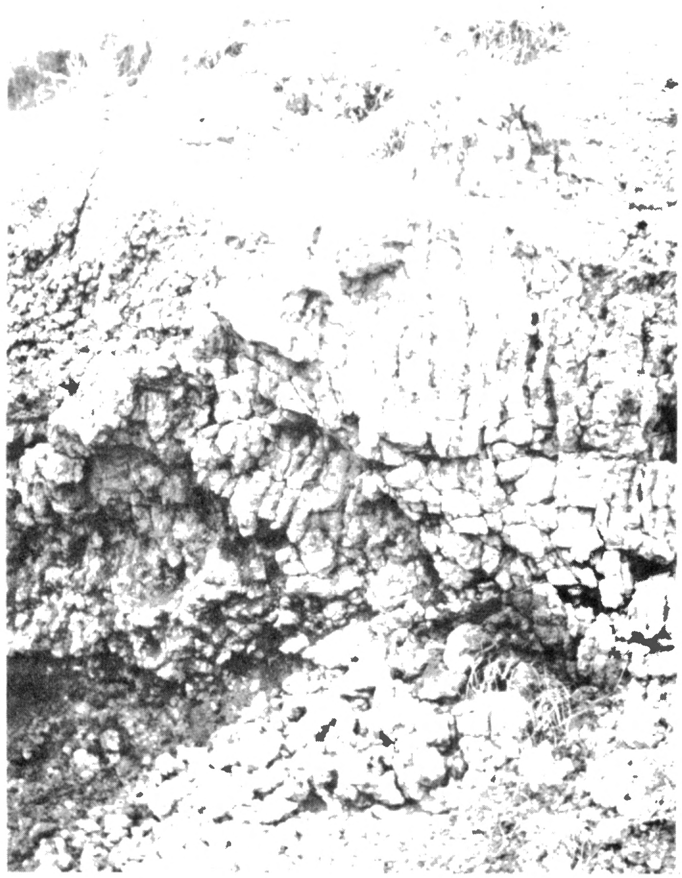


Fig. 15.-Close-up of massive corn-
stone (profile H-8).
Note the presence of mud-
filled joints some of
which appear to be
hexagonal.

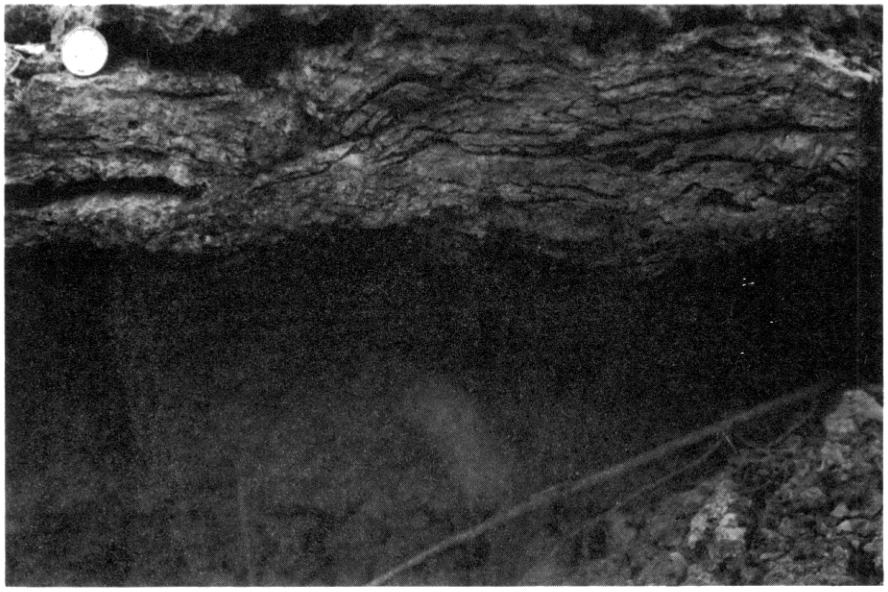


Fig. 16.-Laminated (dolomitic) cornstone layer (profile Y-1). Tepce (pseudo-anticlinal) structures are developed at the top.

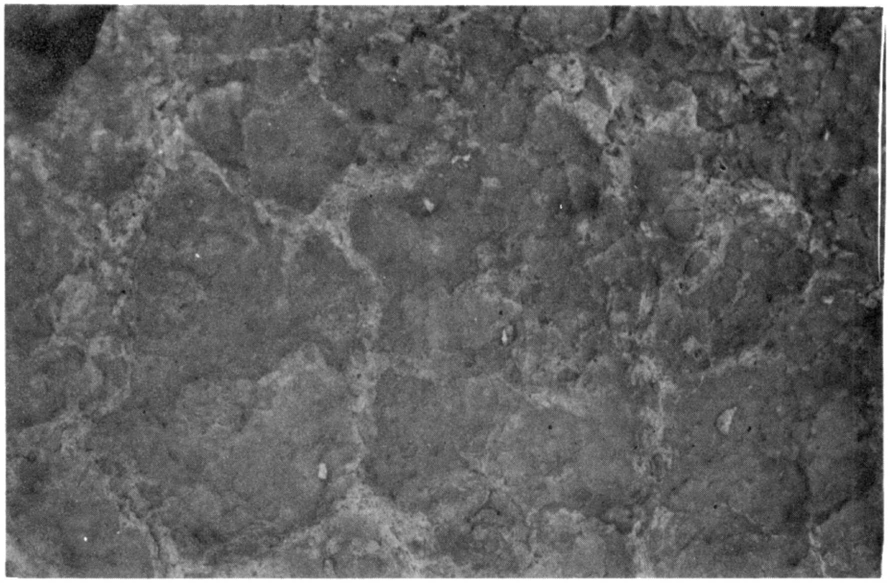


Fig. 17.-Polygonal mudcracks at the base of a cornstone layer.

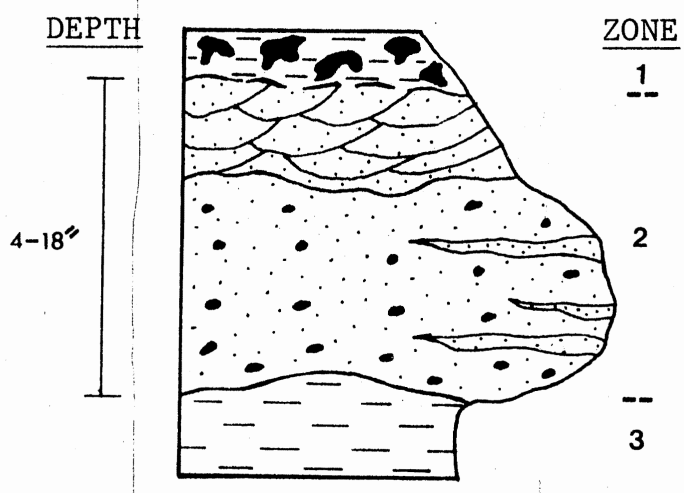


Fig. 18.-Measured section of profile G-2 in Sec. 26, T1N, R14W. Photos Figs. 22, 23 and 24.

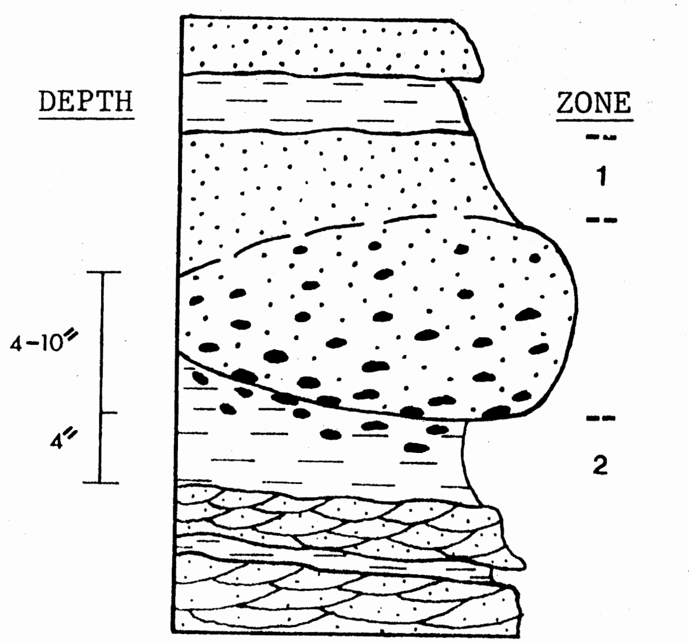


Fig. 19.-Measured section of profile D-2 in Sec. 32, T1N, R16W along Tillman-Comanche County Line. Showing channel-fill cornstone conglomerate.

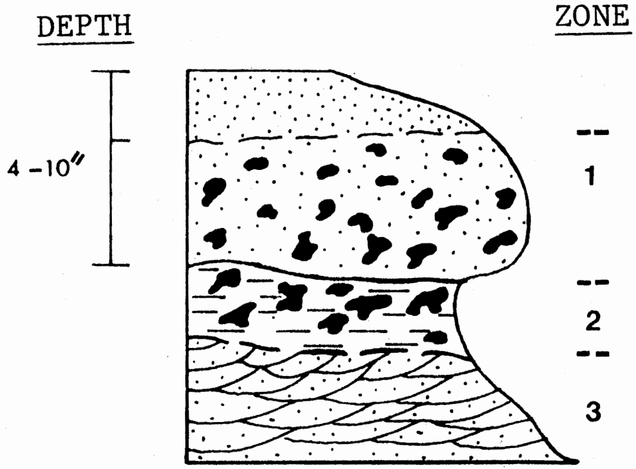


Fig. 20.-Measured section of profile E-1, Sec. 14, T1S, R15W.

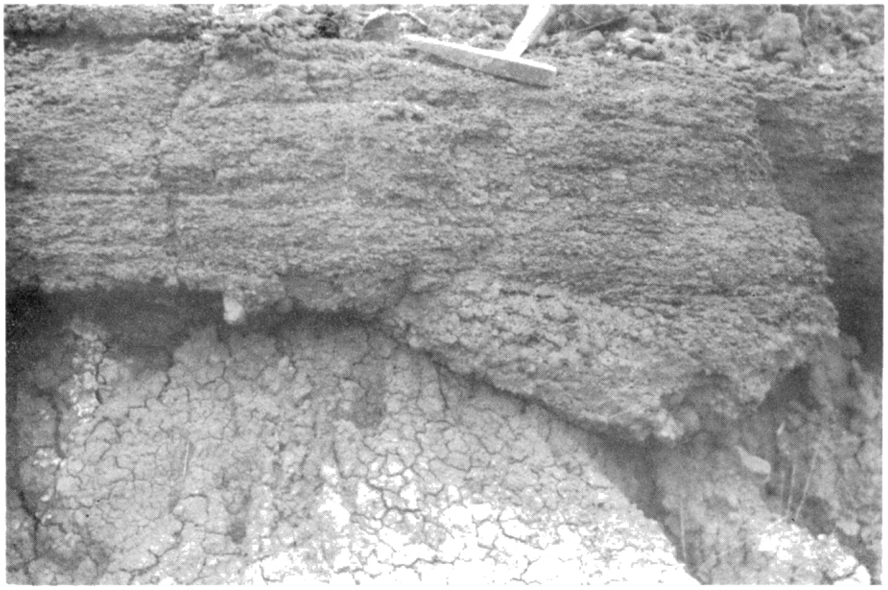


Fig. 21.-Channel-fill cornstone conglomerate in the Garber Sandstone (profile G-2).

Fig. 22.-Close-up of the nodular cornstone conglomerate in profile G-2.

Post Oak (Fig. 23). They occur as channel-fill deposits (Fig. 24) consisting of medium to coarse grained sandstones in units 4 to 12 inches thick which contain numerous reworked cornstone fragments. These fragments are usually well-rounded and are less than 1 inch in diameter. Sparite is the common cement in these sandstones.

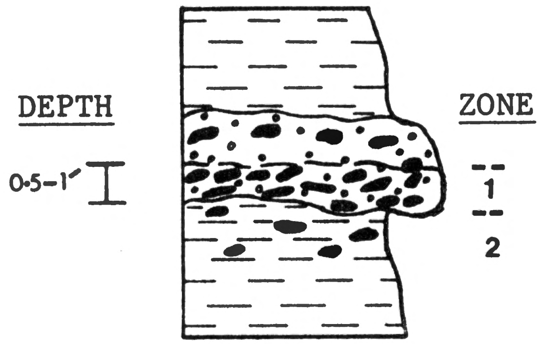


Fig. 23.-Measured section of profile M-1 showing cornstone conglomerate in the Post Oak in Sec. 31, T1N, R15W.

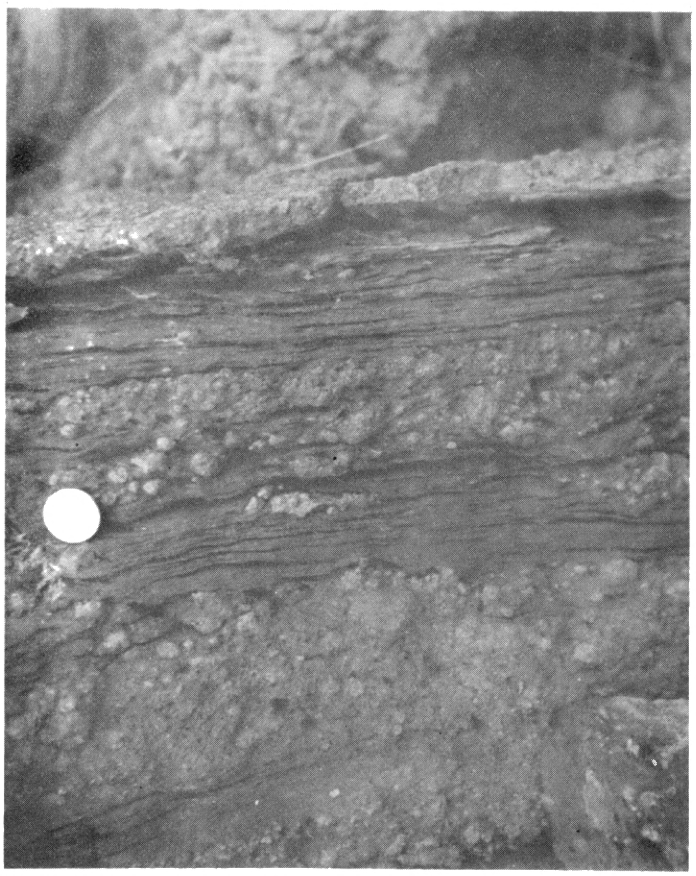


Fig. 24.-Cornstone nodules embedded in the laminae of the Garber Sandstone channel (locality G-2).

CHAPTER V

CLAY MINERALOGY

Objectives

The objectives of the clay mineral study were threefold: (1) to determine if any similarities exist between the clay fraction of the different cornstone profiles both within and among the three stratigraphic divisions; (2) whether or not the clay minerals within the cornstones are the same as those in the host mudstones; and (3) to determine possible contributions of clay mineralogy to environmental reconstruction.

Sample Collection, Preparation, X-ray Identification and Relative Quantitative Estimation of the Clay Minerals

Samples were collected from several locations in the study area. Sampling of profiles was designed to detect any vertical and/or horizontal changes in the clay content. Also, vug-filling clays in some cornstones were analyzed for comparison with the surrounding host clays.

Clays collected from zones associated with a considerable amount of carbonates were treated with acetic acid buffered at pH5 with sodium acetate (Grim, 1968) in order to dissolve the carbonates. The clay fractions, all less than 2 microns in size, were separated by sieving, dispersed in distilled water, pipetted onto porcelain slides and allowed to air dry.

Thirty-five samples were analyzed using a Philips-Norelco x-ray diffractometer at a rate of $2\theta^{o}$/2min., using a Cuk α characteristic radiation. Samples were analyzed in their untreated state, and after a one hour heat treatment at $500^{o}C$. Samples were also treated with ethylene glycol in a dessicator for 24 hours to determine the presence of expandable-layer clays. Mixed-layer clays were identified using the chart by Lucas, Camez and Millot (1959).

Relative proportions of each clay mineral present in the samples were calculated, using a planimeter to measure the area under each (001) peak (Carroll, 1970). The sum of the areas was considered as equal to one hundred percent. Table I shows the relative amounts of clay minerals present in the various samples.

Distribution

The main clay minerals present in the cornstone profiles of the study area are: montmorillonite, illite and kaolinite. Chlorite is rare, occuring mostly in the mixed-layer structures. Within the profiles, minor vertical variations in the relative proportions of clays occur. On the other hand, there are substantial variations between the stratigraphic units in which they were developed.

TABLE I

RELATIVE PERCENTAGES OF CLAY MINERALS IN THE CORNSTONES

HOST: GARBER SANDSTONE

SAMPLE	PERCENTAGE				MIXED-LAYERED CLAYS	
NO	SMEC.	ILL.	CHL.	KAO.	SPECIES	%
D-1-2	-	14	-	14	Mont.-Chl.	72
D-2-2	83	8	-	9	-	-
E-1-2	92	3	-	5	-	-
E-3	91	2	-	7	-	-
G-1*	-	26	-	20	Mont.-Chl.	53
G-2*	-	22	-	19	Mont.-Chl.	59
G-9	89	6	-	5	-	-
Y-1-2	94	2	-	4	-	-
Y-1-4	-	61	-	3	Mont.-Ill.(?)	36

HOST: POST OAK FORMATION

SAMPLE	PERCENTAGE				MIXED-LAYERED CLAYS	
	SMEC.	ILL.	CHL.	KAO.	SPECIES	%
I-1-1*	92	5	-	3	Mont.-Ill.(?)	-
I-1-2	95	3	-	2	-	-
I-1-3	96	2	-	2	-	-
I-2-1	96	2	-	2	-	-
I-2-2	91	3	-	6	-	-
M-1-1	72	18	-	10	-	-

TABLE I (Continued)

HOST: HENNESSEY GROUP						
SAMPLE NO	PERCENTAGE				MIXED-LAYERED CLAYS	
	MONT.	ILL.	CHL.	KAO.	SPECIES	%
H-2	-	23	33	17	Illite-Chl.	27
H-3	-	14	-	27	Mont.-Chl.	59
H-4-2*	81	10	-	9	-	-
H-4-3	81	10	-	9	-	-
H-5-3	92	4	-	4	-	-
H-5-4	-	11	-	5	Mont.-Chl.	84
H-5-5	-	12	-	5	Mont.-Chl.	83
H-5-6*	-	15	-	4	Mont.-Chl.(?)	81
H-5-8	77	8	-	15	-	-
H-6	87	6	-	7	-	-
H-8-2	93	1.0	-	6	-	-
H-8-4*	94	2.0	-	4	-	-
H-8-4 base	89	2.0	-	9	-	-
H-8-5	94	3.0	-	3.0	-	-
X-2*	-	34	7	15	Ill.-Chl.(?)	44
X-2-2	-	30	-	17	Mont.-Chl.	53
X-3*	-	10	79	11	-	-
R-1-1	-	50	15	9	Ill.-Chl.	26
R-1-2	-	46	12	11	Ill.-Chl.	31
R-1-3	-	45	9	10	Ill.-Chl.	36

* Vug-filling clays

Mont. = Montmorillonite
Ill. = Illite
Chl. = Chlorite
Kao. = Kaolinite

A comparison of the mean values for clay occurrences between the host formations (Fig. 25) shows the predominance of discrete and mixed-layer montmorillonite. A few profiles in the Hennessey however do not register any montmorillonite. Kaolinite and illite are common in all the profiles with locally high occurrences. Hennessey cornstones register the highest mean values for these two clays in addition to the lone occurrence of distinctive chlorite. Mixed-layer clays were noted only in the Garber and Hennessey cornstones.The montmorillonite-chlorite assemblage is most common, while the illite-chlorite combination is confined to the Hennessey.

Discussion

Ross (1943) considers the chemical character of altering solutions, climate and biotic factors as the fundamental factors in clay mineral formation. The one affects the other. Thus variations in the clay minerals and relative content reflect differences in the parent rocks, drainage and depositional conditions, chemistry of circulating solutions, and perhaps tectonic conditions. Localized variations in these conditions, the nonuniform character of the fluvial sediments as well as post-depositional diagenesis probably account for the differences noted within a few horizons and between the profiles.

Because montmorillonitic assemblages are dominant, conditions favorable for their formation were probably prevalent except where they are absent. These conditions are:

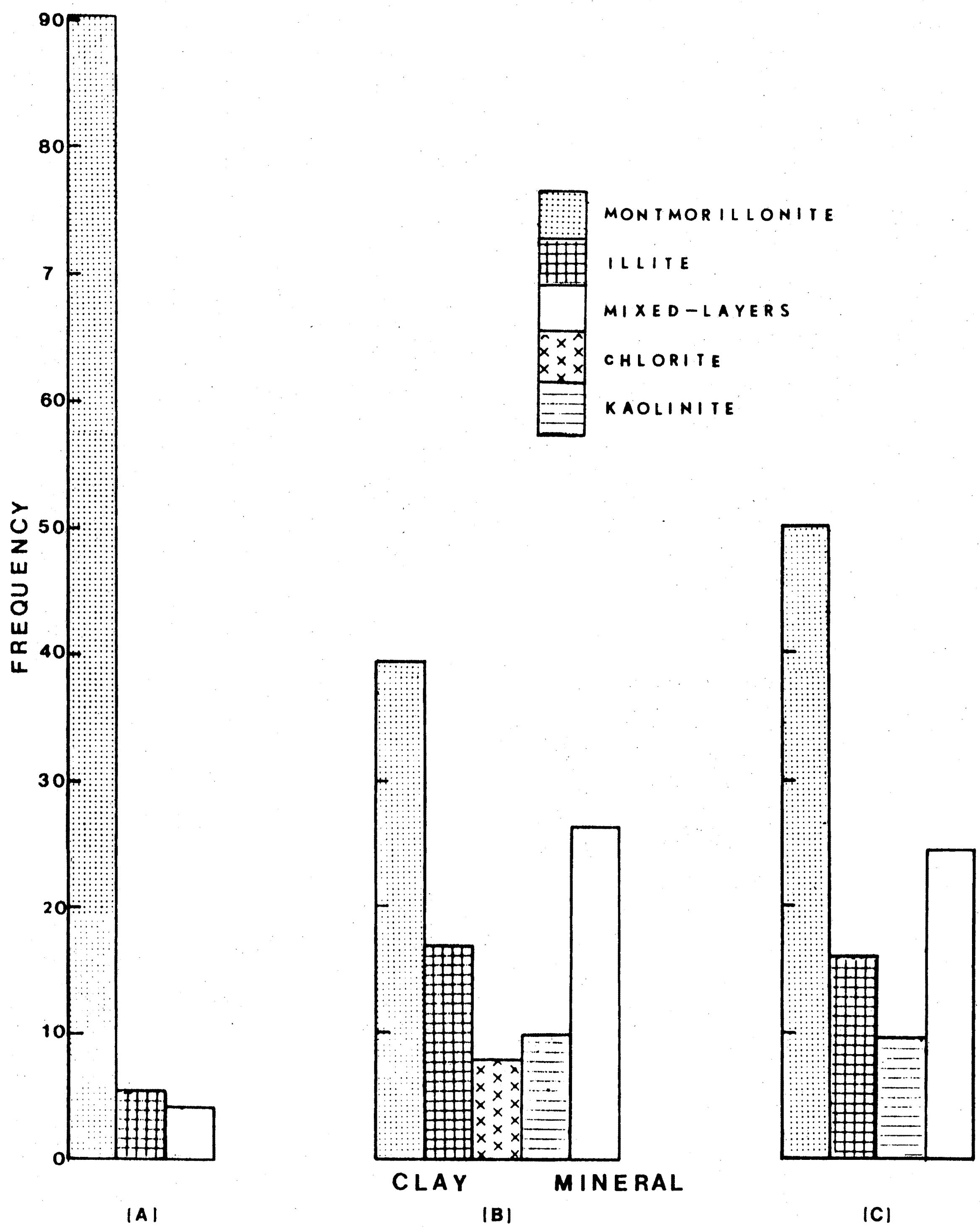


Fig. 25.-Histograms showing average clay mineral composition in the following hosts: (A) Post Oak, (B) Hennessey, and (C) Garber.

(1) Alkaline conditions with active Mg^{2+}, Ca^{2+}, Fe^{2+}, Na^{+} ions present. These flocculate and cause the retention of silica in the reaction in addition to decreasing the activity of H^{+} ions. (2) Semi-aridity with evaporation exceeding precipitation. This results in a higher concentration of dissolved ions and silica. (3) Ineffective leaching due to stagnant water and water logging and availability of rocks with low effective permeability. (4) The dissolution of metal ions and silicic acid (H_4SiO_4) from hydrolysing silicates. (5) High SiO_2 relative to Al_2O_3 and very low K^{+} ions (Keller, 1970).

The above processes were probably so domineering that the amount of detrital minerals were low. Thus illite is generally sparse in the cornstones. However, during early diagenesis, the presence of locally high K^{+} concentration in these interstitial solutions could result in the formation of illite. Most of the K^{+} ions probably originated from the alteration of feldspars. Hence the noted increase in illite content in some localities; in particular R-1 which is close to a granitic rock body.

Most kaolinite is formed by increased circulation of waters and acidic leaching of primarily feldspars and micas as well as silicates. Millot quoted by Grim (1968) stated that the presence of calcium ions tends to block the formation of kaolinite. Grim (1968) also states that weathering processes indicate that kaolinite forms from calcareous parent material only when the carbonate has been removed.

The constancy of kaolinite in the cornstone profiles, its relatively low content compared to other clays and the importance of diagenetic processes suggest an in situ origin for kaolinite. In places, it appears to be partly detrital. Much of the authigenic kaolinite probably came from feldspar alteration and diagenesis of the originally abundant montmorillonite. Using Gibbs free energy values, Brookins (1975) provides a general picture of the Mg-Al-Si-O-H system (Fig. 26). This shows that kaolinite can be formed from both chlorite and montmorillonite if the pH increases or $[Mg^{2+}]$ decreases. Because of its relative immobility and amphoteric nature, Al is considered to be non-reactive. According to Huang and Keller (1972), this may not be true.

Mixed-layer structures are intermediate stages produced in weathering environments, and by diagenesis. Evaporitic or temporary evaporitic conditions are particularly favorable for the production of chlorite-montmorillonite. Mg^{2+} and K^{+}-rich alkaline environments have illite and chlorite forming via mixed-layer intermediates (Dunoyer de Segonzac, 1970). Thus the prevalence of chlorite-montmorillonite and chlorite-illite assemblages can be associated with the diagenesis of montmorillonite and illite. Figure 26 shows that chlorite can form from montmorillonite and at the expense of kaolinite in a dissolved silica rich environment by either changing the pH or the activity of Mg (or Al). An increase in Mg content would enhance the formation of chlorite. With dioctahedral chlorite, Brookins (1975) shows that in an Mg-K-Al-Si-O-H

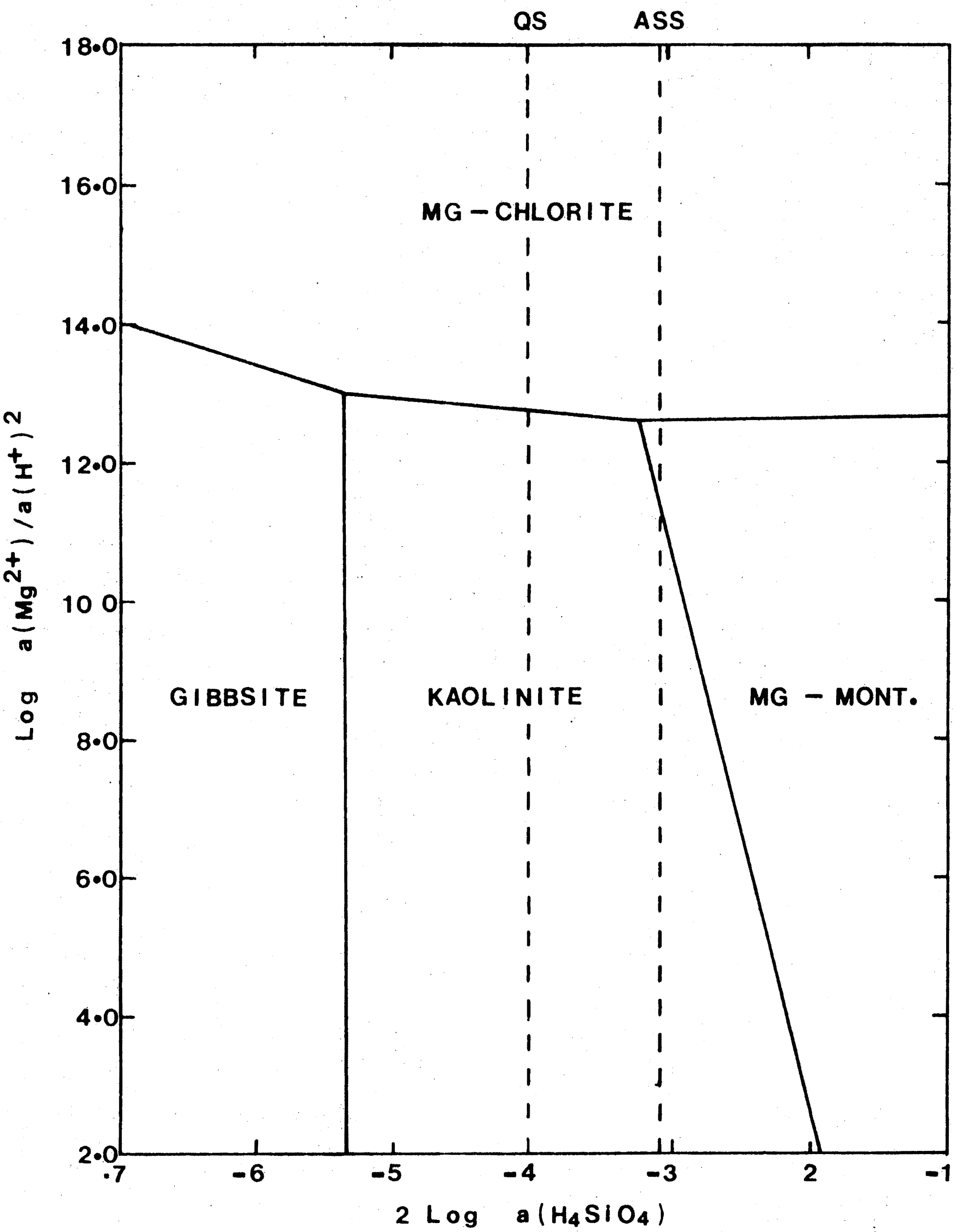


Fig. 26.-System Mg - Al - Si - O - H (25°C; 1 atm.). QS=quartz saturation; ASS=amorphous silica saturation. (From Brookins, 1975).

system, chlorite should form from montmorillonite and any detrital illite assuming quartz saturation (Fig. 27). The transformation from illite is favored by slightly acidic conditions (pH around 6) while that from montmorillonite occurs in alkaline environments.

The distinctive chlorite in the Hennessey may be mostly due to selective transportation. It could also form from montmorillonite.

The clays within the cornstones have the same mineralogy as the outlying clays. It thus appears that the same conditions were prevalent before and during calichification. Variations in the relative content may be due to diagenesis.

By comparing the clay mineral assemblages in these cornstone profiles, some analogies can be drawn with present day vertisols. In the latter, montmorillonite and/or mixed layered clays are dominant. Illite and kaolinite may be present in fairly small amounts. They commonly form in arid and semi-arid areas where leaching is at a minimum (FitzPatrick, 1971). Thus the high proportion of montmorillonite and mixed layer components in the cornstone profiles probably were induced in an arid climate.

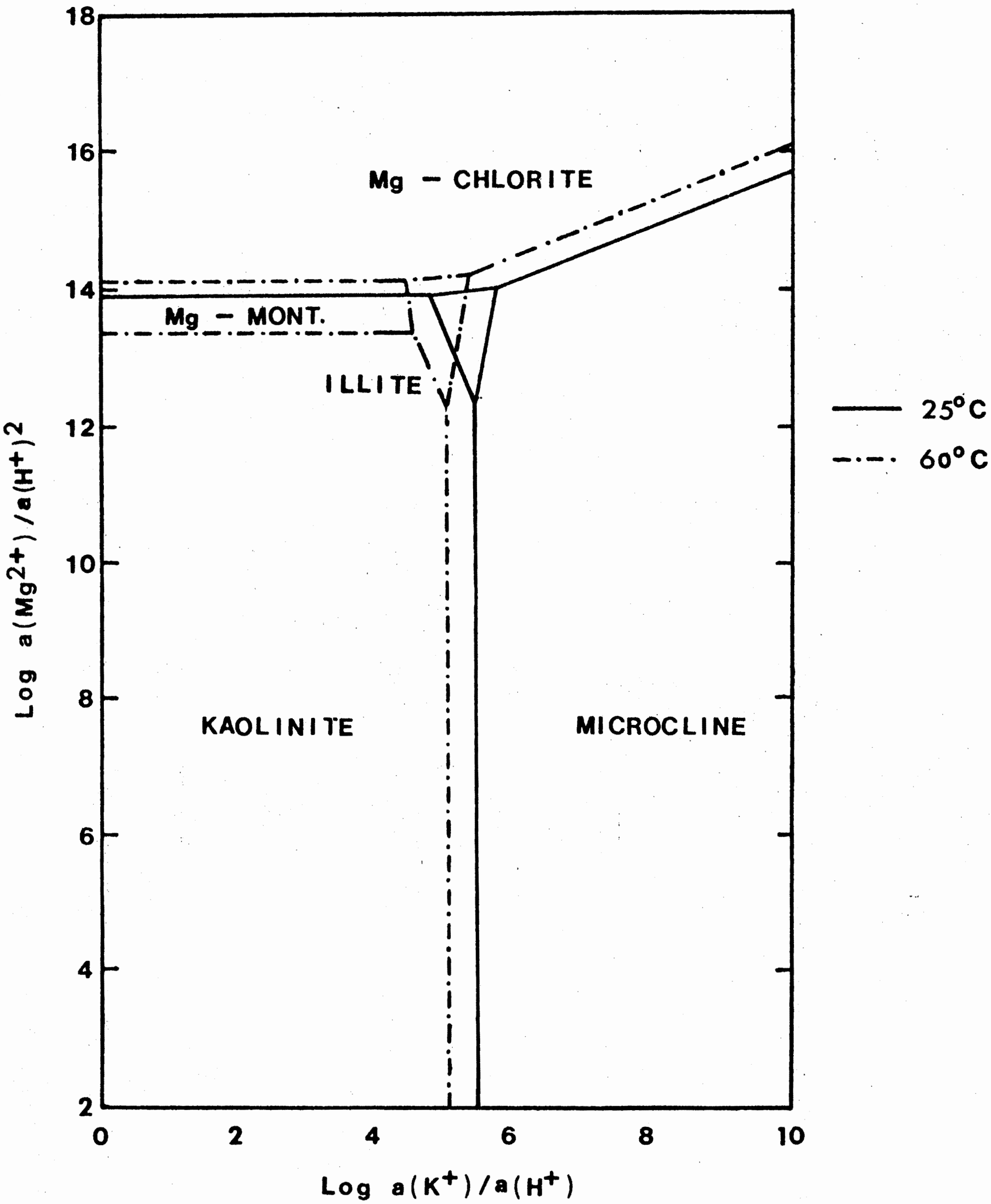


Fig. 27.-System Mg - K - Si - O - H (1 atm) for quartz saturation. MONT= montmorillonite. (From Brookins, 1975).

CHAPTER VI

PETROLOGY AND PETROGRAPHY

Twenty thin sections of cornstone samples from the three host stratigraphic horizons in the study area were examined in detail. Table II lists the carbonate composition of these samples as determined by x-ray diffraction.

Mineralogy

In thin sections, the cornstones are mainly mosaics of microcrystalline calcite and/or dolomite with subdued mottling due to variations in crystal size and clay mineral coating. Within this fabric scattered detrital grains may show deeply corroded margins and some exfoliation splitting (Fig. 28) where calcite growth has forced apart matching portions of grain.

Quartz is the dominant detrital grain and is abundant in the cornstone conglomerates. Simple and polycrystalline varieties occur and the grains are subangular. The grain size ranges from fine to coarse.

Microcline is widespread in the conglomerates together with traces of plagioclase. Orthoclase and rarely perthite occur in most other samples. Considerable amounts of granophyric rock fragments (intergrowth of quartz and

TABLE II

MINERALOGY OF CARBONATE PORTION IN THIN SECTION AS DETERMINED BY X-RAY DIFFRACTION

SAMPLE NUMBER	PROFILE NUMBER	TEXTURE	COMPOSITION	HOST FORMATION
D-1-1B	D-1-1B	Conglomerate	Calcite	Garber
E-1	E-1	Conglomerate	Calcite & dolomite	Garber
EN-2	E-1-2N	Nodule	Dolomite & minor calc.	Garber
C-1	G-1	Nodule	Calcite	Garber
IN-3	I-3-1	-	Calcite	Garber
Y-1T	Y-1-1L	Laminated	Dolomite	Garber
Y-1B	Y-1-3	Laminated	Dolomite	Garber
Y-2NC	Y-2	Nodule	Calcite	Garber
V-1N	V-1N	Nodule	Dolomite	Garber
H-1	H-1	Laminated	Calcite & minor dolo.	Hennessey
HN-3	HN-1N	Nodule	Calcite & minor dolo.	Hennessey
H-2	H-2	Laminated	Dolomite	Hennessey
OX-2	X-2B	Brecciated	Dolomite	Hennessey
X-2	X-2N	Nodule	Dolomite	Hennessey
IN-1	I-1-1	Nodule	Calcite	Post Oak
IN-2	I-2-1	-	Calcite	Post Oak
M-1-1B	M-1-1B	Conglomerate	Calcite	Post Oak

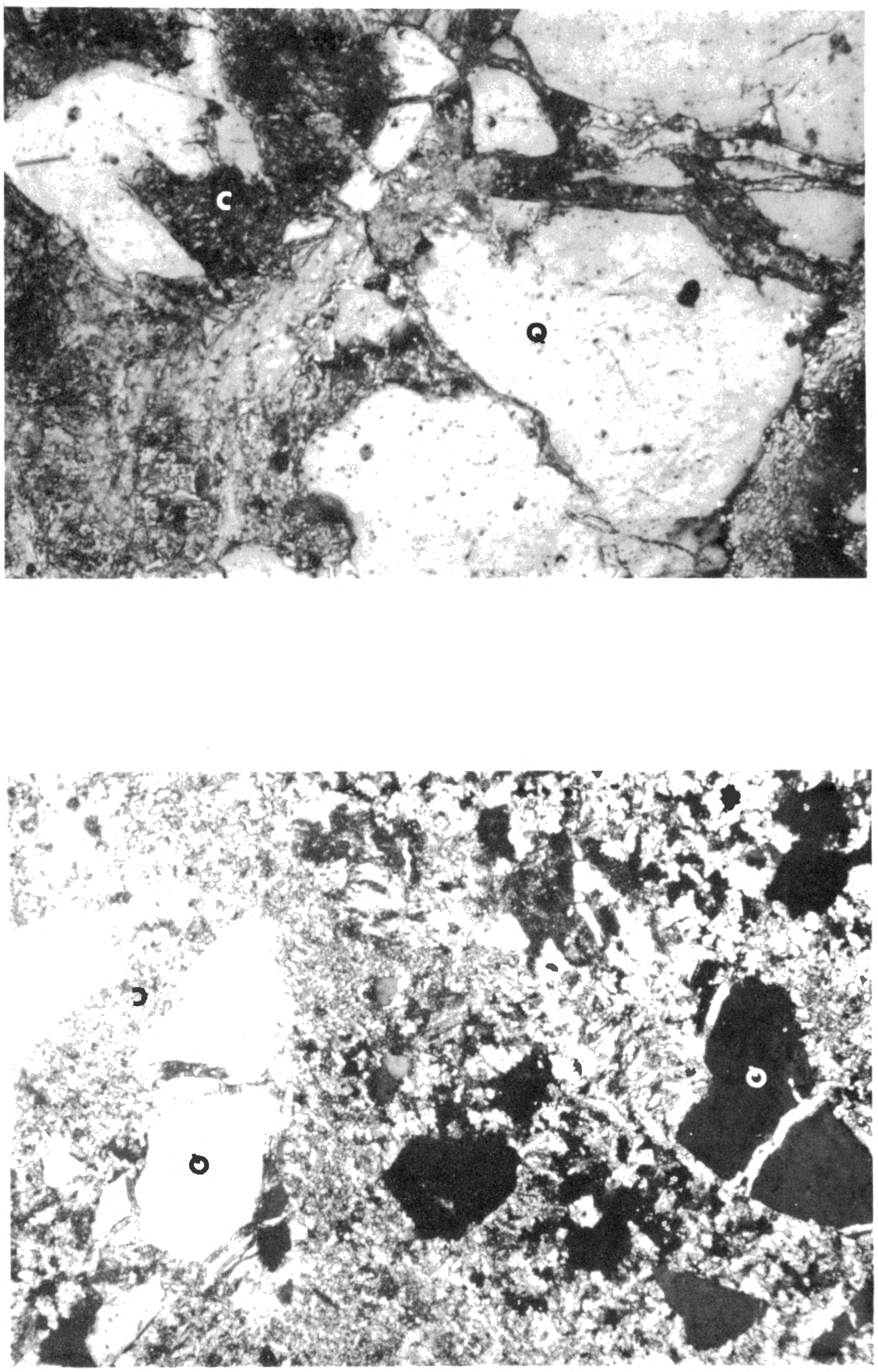


Fig. 28a and b.-Displacement and corrosion of split quartz (Q) grains by calcite (C). Note the occurrence of some calcite-filled embayments due to advanced corrosion(crossed nicols; 2.5 X 1.7 mm.).

feldspar) were also noted in the conglomerates.

Barite is an important authigenic vein and vug-filling mineral in several samples. Crystals include tabular, granular, and plumose or feathery forms (Figs. 29 and 30).

Minor detrital components include angular to subrounded grains of zircon. Also pyrolusite streaks and dendritic networks. Haematite is mainly a late coating on the matrix and sparite although it partially fills the vugs in one sample.

The clays are mostly detrital but some constituents may be authigenic. They coat the microcrystalline carbonate matrix and walls of voids in addition to occurring as fine aggregates that partially fill pores.

Texture

The cornstones show a complex texture of laminations, pseudo-pisolitic structures, veins, fractures, vugs, and conglomerates. The following is a discussion of each of these fabrics:

<u>Laminations</u>. Four thin sections of laminated cornstones were examined. The laminae are poor, discontinuous, commonly fine and irregular and consist of alternating layers of microspar and micrite. These occur as linings of microspar along the margins of voids and subhorizontal fractures that disect the matrix. A few of the laminae are partly to completely filled with barite and coarse

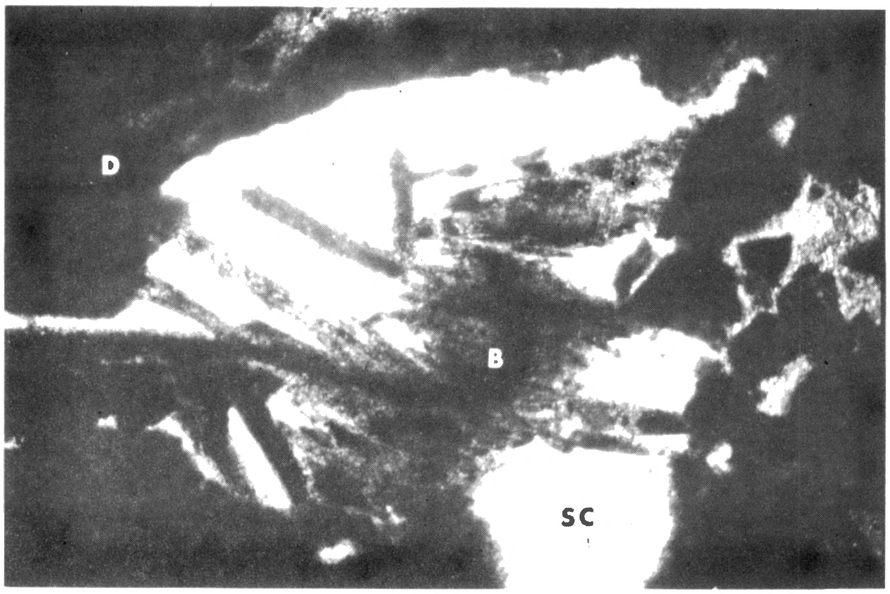


Fig. 29.-Euhedral barite (B) crystals occurring in coarse sparry calcite (SC) and dolomite (D). It may be early in part(crossed nicols, 2.7 x 1.7 mm).

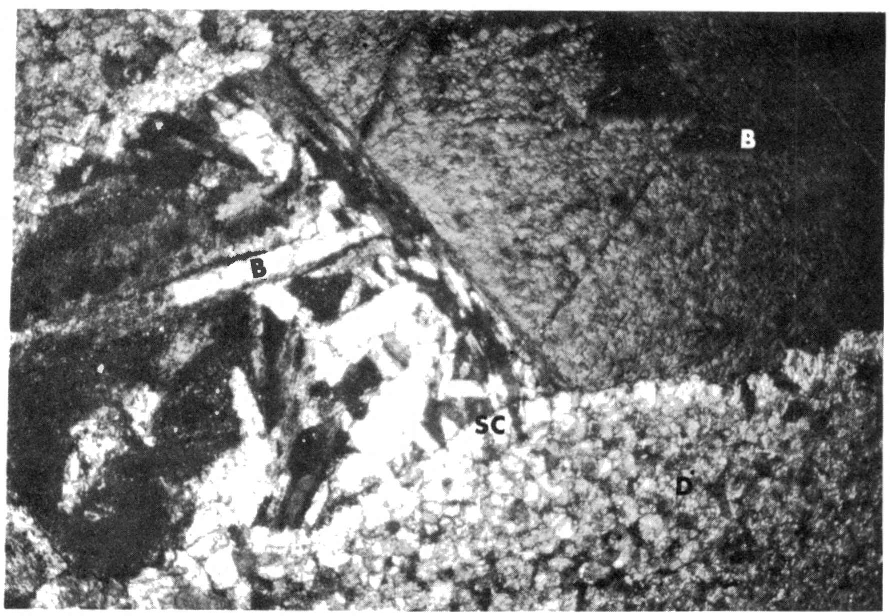


Fig. 30.-Varieties of vein-filling barite (B) and their relation to the dolomitic matrix (D) and sparry calcite (SC) cement (crossed nicols, 2.5 x 1.7 mm).

sparite (Fig. 31). The laminae are thin and pinch out and also show some swelling perhaps due to solution enlargement.

Pseudo-pisolitic Structures. These are locally common in many of the samples and are composed of micrite with clay as a major impurity. Concentric to spherical fractures filled with fine, equigranular, sparite cement surround most of them. The clay may be peripheral due to the displacive action of the sparite cement.

Veins, Fractures and Vugs. Most specimens show abundant fractures, vugs and veins commonly 0.1 to 6 mm wide. Some of these contain clastic grains, haematite, muscovite flakes and clays. The walls are fairly smooth and frequently show mammillary protrusions, probably due to solution enlargements. These may be rimmed or completely infilled by a sparry cement fabric, exhibiting different morphologies for each.

The vugs are randomly distributed, irregularly round to elongate and occur mainly as interparticle voids. They are mostly enclosed in a clay coated greyish-brown micrite matrix and are found mainly in dolomitic samples (Fig. 32).

Fractures and veins are also irregular and show variable (morphologies) patterns corresponding to the terminology used by Choquette and Pray (1970) including shrinkage voids. They exhibit complex bifurcating and crosscutting relationships through time with repeated fracture and

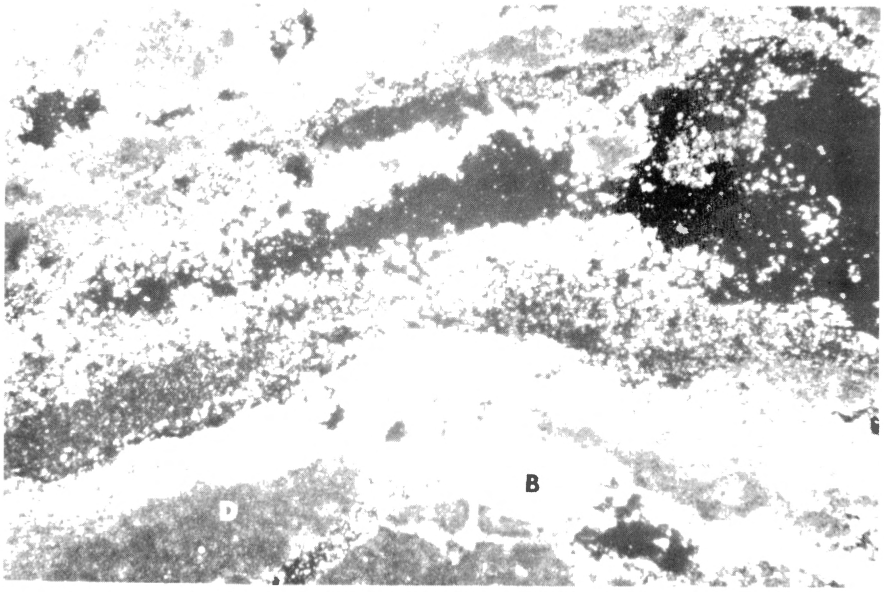


Fig. 31.-Laminated texture with barite (B) as a late vug-filling cement and dolomitic (D) matrix (crossed nicols, 2.5 x 1.7 mm).

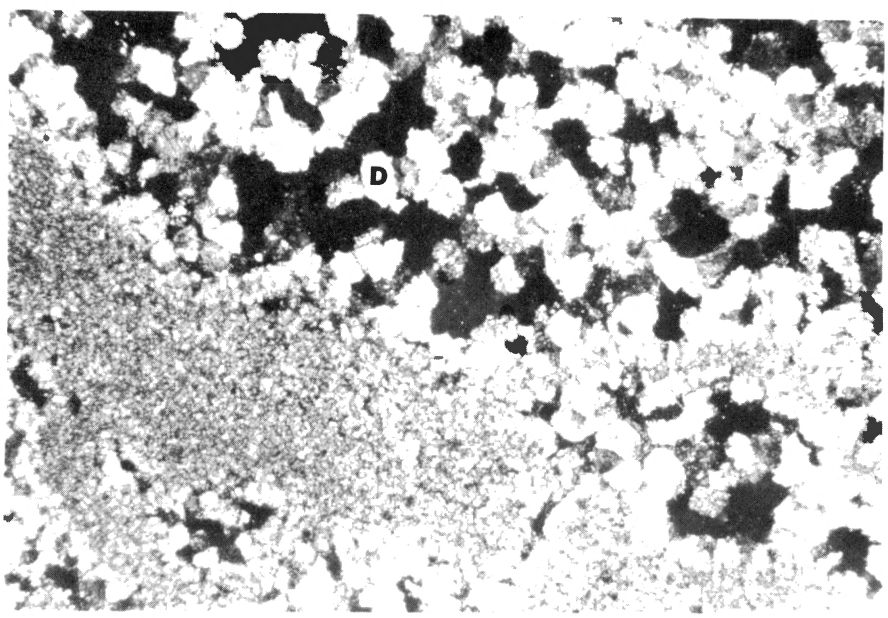


Fig. 32.-Interparticle voids and equigranular dolomite grains (crossed nicols, 2.5 x 1.7 mm).

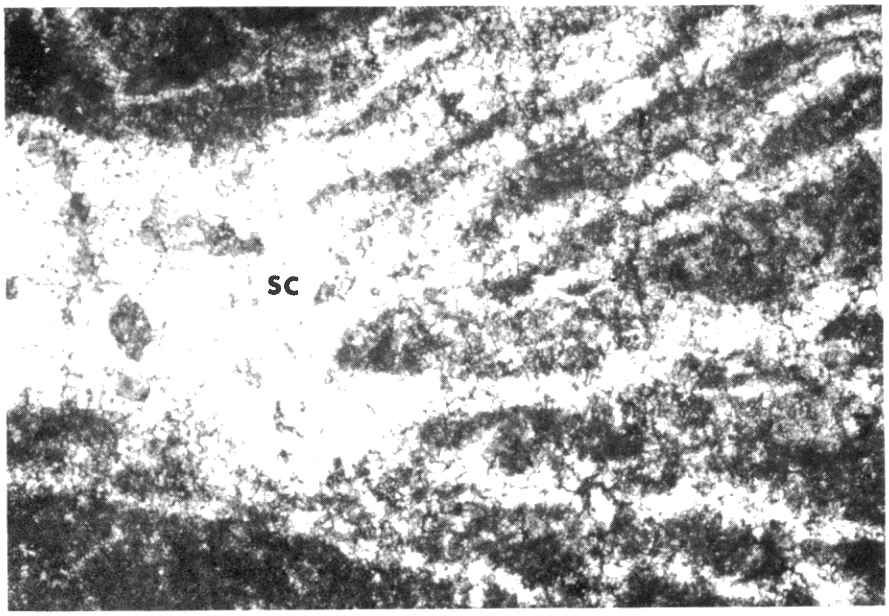
infill. Most of them pinchout toward the edge into the micritic matrix (Fig. 33a and b). The points of divergence and convergence are commonly wider; sometimes enclosing a fragment of the micritic matrix. They frequently cut across the matrix and cement and may also be arcuate to concentric.

Conglomerates. Conglomeratic samples examined show an upward increase in clastic content and they contain subrounded to round or spherical carbonate fragments composed mainly of micrite (Fig. 34). Towards the base of the layers, these fragments are larger, subangular to subround; partially due to solution. The micrite matrix is variably recrystallized into radial spherulitic microspar and/or pseudospar. Fractures, partially to completely infilled with sparry calcite cement are common in the basal, carbonate fragments. Coarse crystalline sparite mostly fills the interparticle voids. One sample, however, shows a radial fibrous microspar cement.

Diagenesis

Cementation

The chief cements observed are sparry calcite and barite. The sparite cement is nonuniform and consists of a number of morphologies and multiple generations. Crosscutting and intergranular voids are characteristically lined with fine isopachous and/or bladed spar which grades into a larger



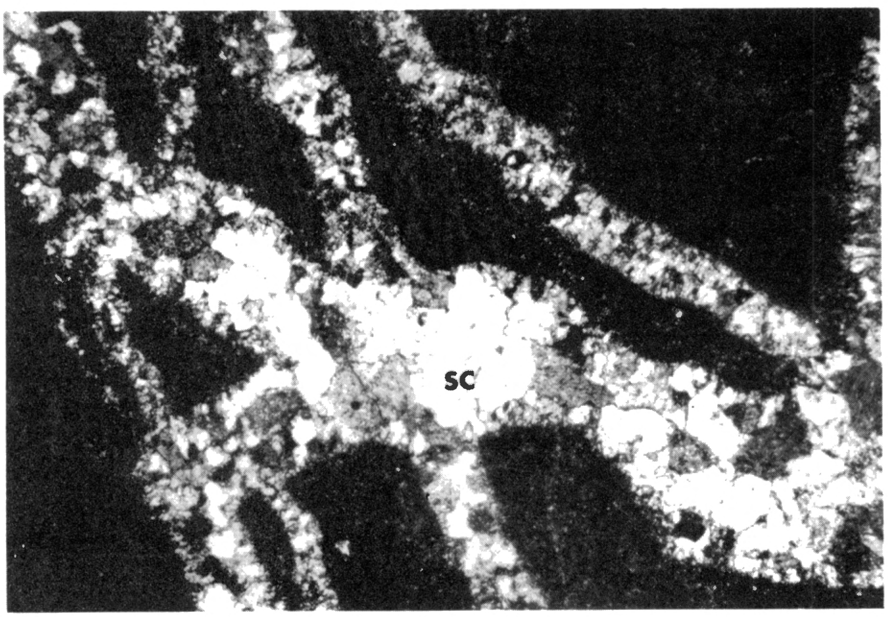


Fig. 33a and b.-Bifurcating and crosscutting fractures infilled with sparry calcite (SC). (Crossed nicols, 2.5 x 1.7 mm.)

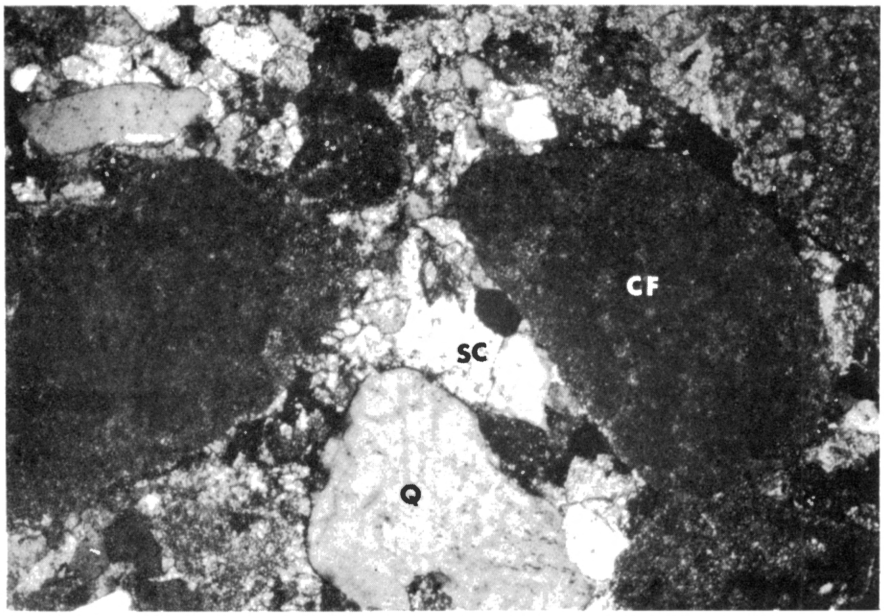


Fig. 34.-Reworked cornstone fragments (CF) in a channel-fill conglomerate with quartz (Q) and sparry calcite (SC) cement (crossed nicols, 2.5 x 1.7 mm).

blocky spar (Fig. 35). This may either be equigranular or enlarge centripetally forming a drusy mosaic (Fig. 36). Also, clusters of radiating wedge-shaped crystals were noted (Fig. 37a and b). Meanwhile, intraparticle voids are smaller and dominantly filled with isopachous and fine equant spar. On the other hand, incompletely filled voids are mostly rounded by terminated crystals and patches of cement locally form bridges across them (Figs. 38 and 39). The presence of coarse sparry crystals is readily visible under cathodoluminescence. Also, some of the late sparite may be ferroan.

In general, the cements are irregularly distributed and the type and number of generations vary from one void to the next. The complexity of cement patterns seems to be related to the pore size.

Grain and crystal relationships indicate that barite is mostly a late vug and vein-filling cement (Figs. 30, 31, and 40). It generally follows the isopachous or terminated sparite and where present the coarse sparite cements. Also, pseudomorphism of calcite after gypsum (Fig. 41) was observed in one poorly laminated, dolomitic sample.

Recrystallization

Recrystallization of the microcrystalline calcite matrix was observed in a few samples including a few carbonate fragments in the conglomerates. The resulting fabric is mainly a radial spherulitic microspar and pseudospar. Two generations of the latter were noted in one sample (Fig. 42) the last

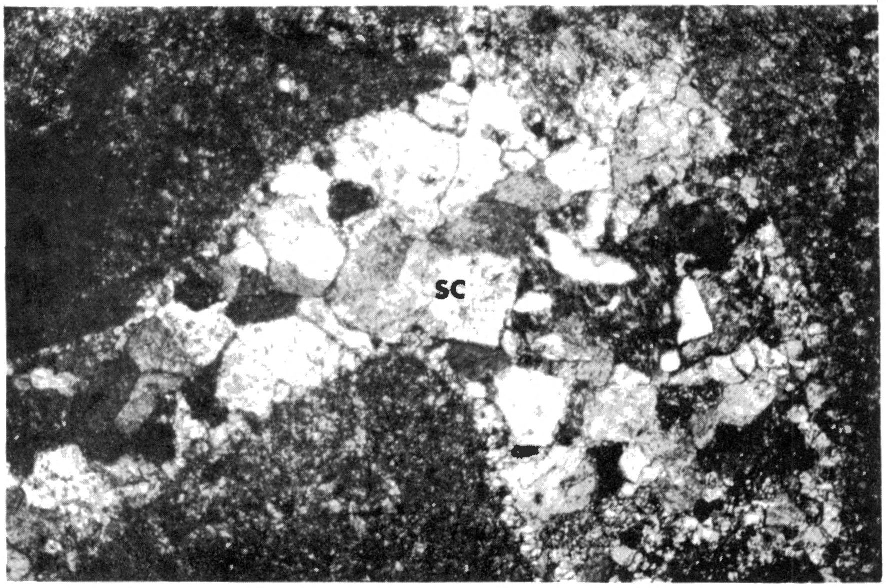


Fig. 35.-Sparry calcite (SC) cement with early isopachous sparry lining the veins (crossed nicols, 2.5 x 1.7 mm).

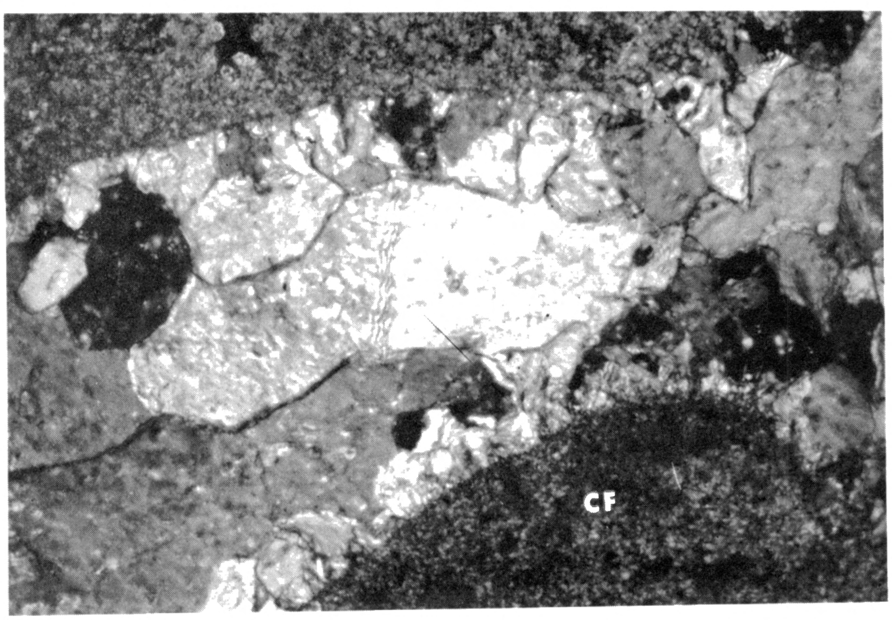
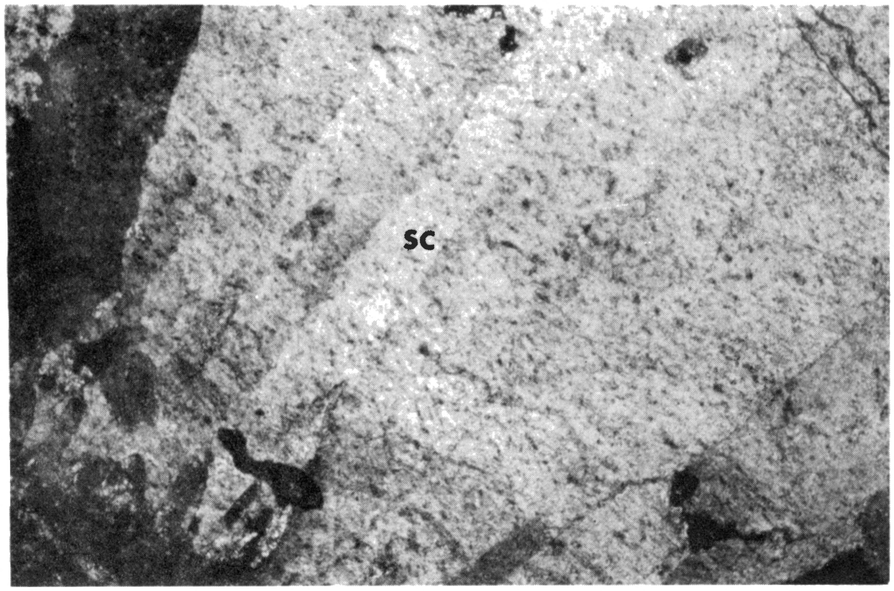


Fig. 36.-Fracture-filling drusy calcite cement (crossed nicols, 0.7 x 0.5 mm). Cornstone fragment (CF)



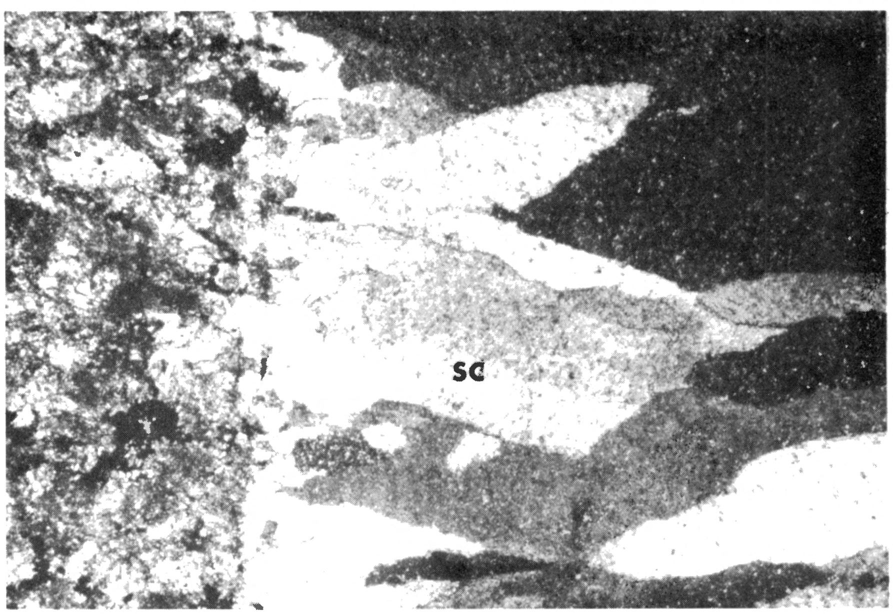


Fig. 37a and b.-Wedge-shaped radial sparry calcite (SC) cement. Note the growth lines cutting across the width of the crystals, suggesting growth by accretion (crossed nicols, 2.5 x 1.7 mm).

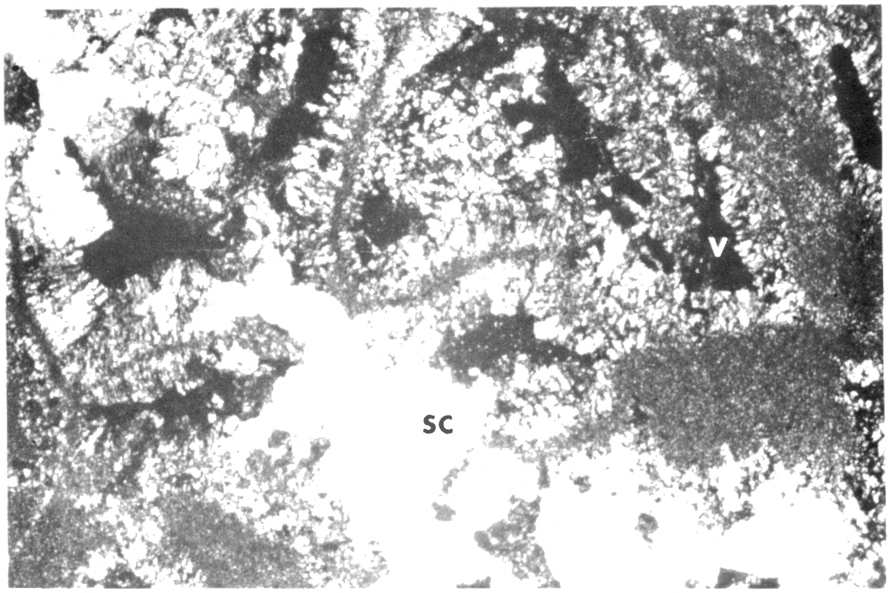


Fig. 38.-Terminated sparite crystals lining the walls of incompletely filled voids (V). (Crossed nicols, 2.5 x 1.7 mm.)

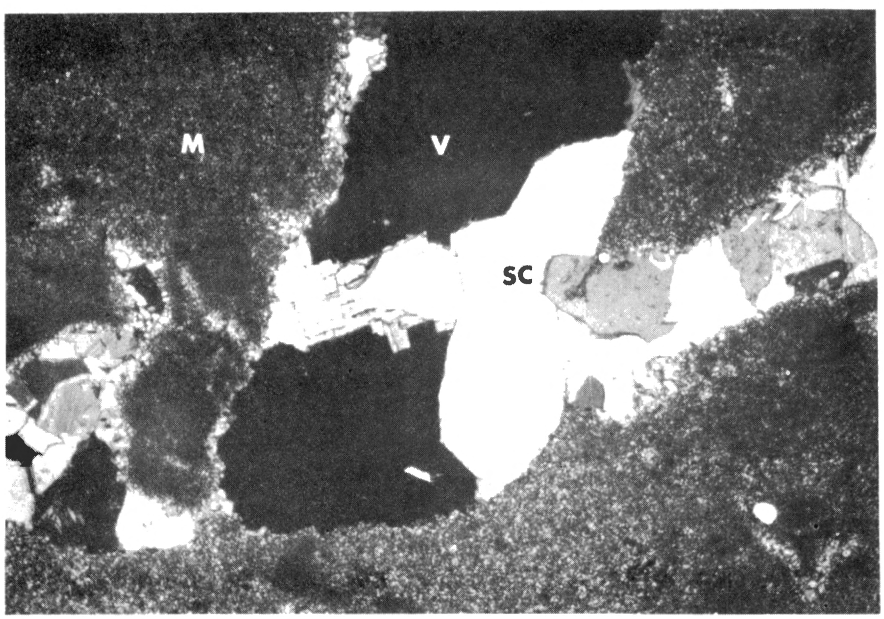
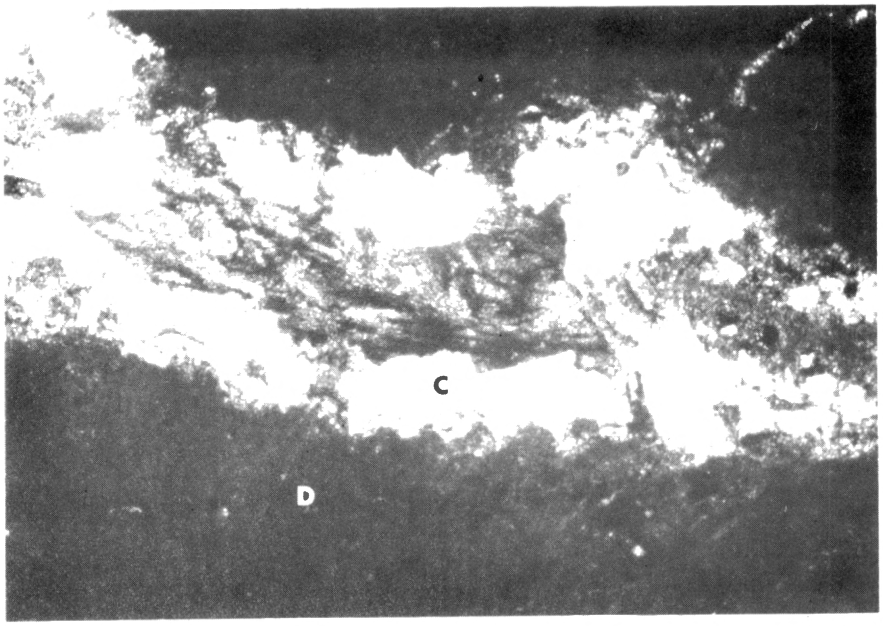


Fig. 39.-Micrite (M) and sparry calcite (SC) textures with bridge cement forming across the incompletely filled voids (crossed nicols, 2.5 x 1.7 mm).



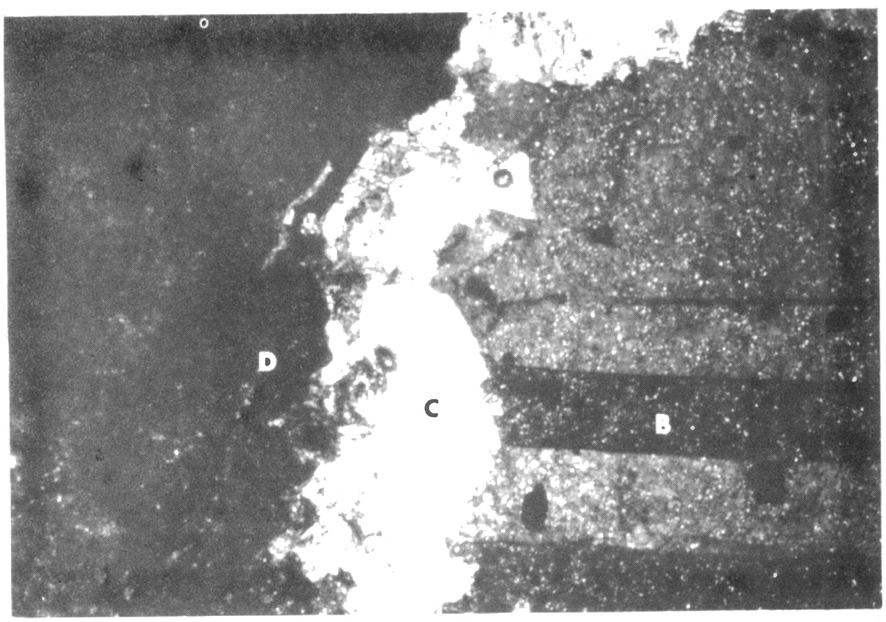


Fig. 40a and b.-Dolomite replacing calcite and void-filling plumose and tabular barite crystals (crossed nicols, 2.5 x 1.7 mm).

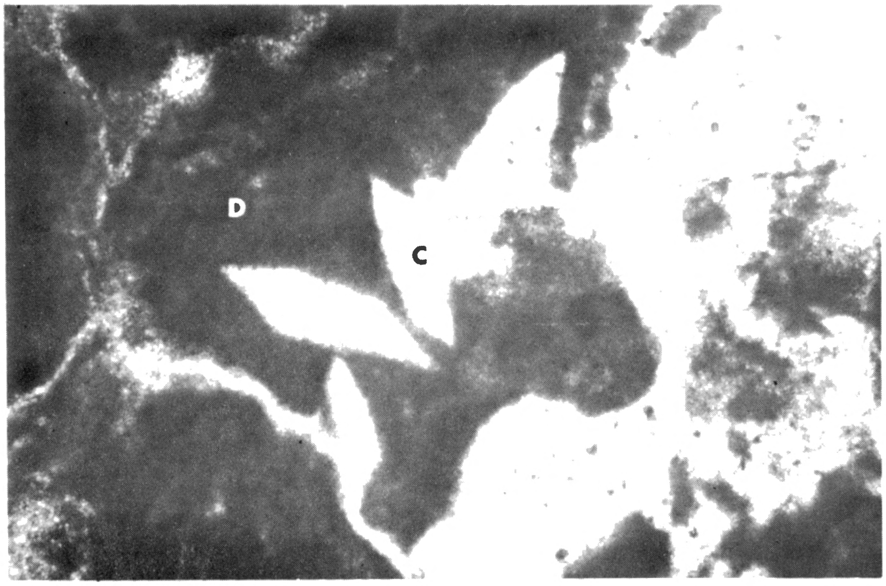


Fig. 41.-Pseudomorphism of calcite after gypsum (crossed nicols, 2.5 x 1.7 mm).

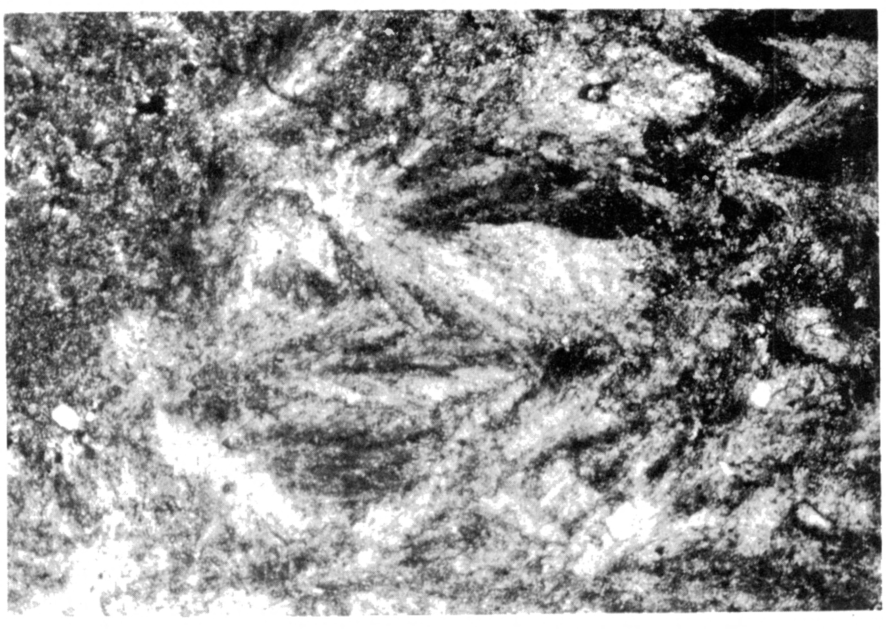


Fig. 42.-Recrystallization of micrite into radial fibrous microspar (crossed nicols, 2.5 x 1.7 mm).

generations being coarser than the first. The relationship with the crosscutting veins and cements indicates that the neomorphic process did overlap in time with the lithfication of the microcrystalline matrix.

Replacement

The replacement by the carbonate cement of detrital constituents is common, particularly in the conglomerates. Quartz often shows etched discordant margins while grains in a more advanced stage of solution show calcite-filled embayments (Fig. 28). Potash feldspar grains are often coated with calcite. Also, the preferential replacement of feldspar intergrowths in granophyric rock fragments is common in these conglomerates (Fig. 43). Under cathodo-luminescence, the extent of feldspar replacement in these fragments can be readily seen.

Cathodo-Luminescence

Cathodo-luminescence petrography was used in this study to: (1) observe the extent of feldspar replacement in granophyric rock fragments; (2) check mineral identification and homogeneity in some of the samples; (3) observe compositional and structural variations of some of the minerals.

With cathodo-luminescence, five major mineral constituents, four of which showed different colors, were observed. The quartz shows a dull bluish luminescence, while the feldspar exhibited a bright blue to blue color. Barite did

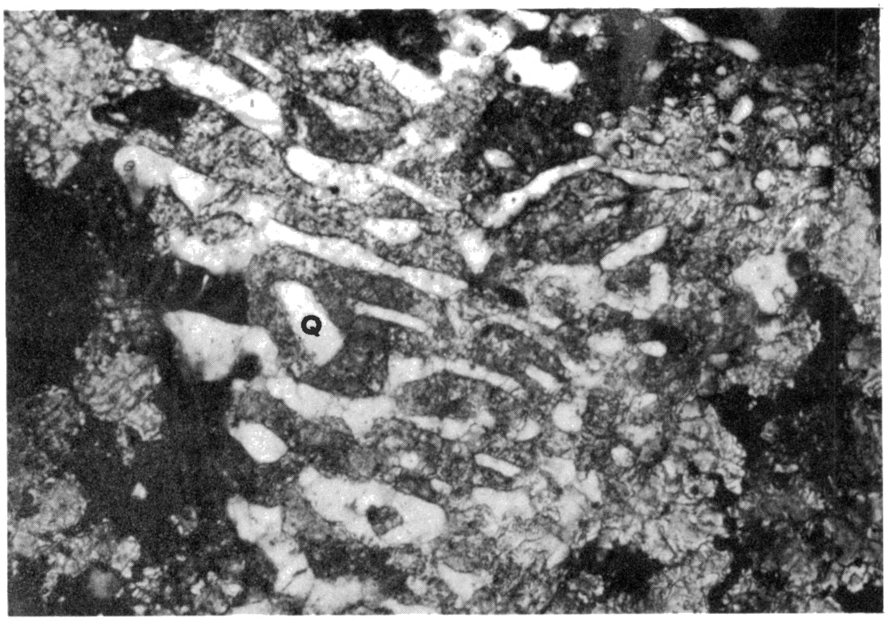


Fig. 43.-Calcite corroding quartz and replacing feldspar in granophyric rock fragment (crossed nicols, 0.7 x 0.5 mm).

not luminesce. Calcite was brilliant orange and in one sample showed an orange-red color while dolomite exhibited a dull red luminescence. The granophyric rock fragments showed shades of dark blue and blue colors respectively representing quartz and potash feldspar. Portions replaced by calcite were bright orange.

Structures not easily observable under the normal petrographic microscope were readily revealed. Grain boundaries also could be clearly seen.

Calcite cement distribution and morphologies could readily be evaluated. Sparry intergrowths, calcite scalenohedra lining pores as well as zoning or banding in the sparry calcite cement were instantly visible under luminescence (Fig. 44). These periodic bands are indicative of growth by accretion and qualitatively reveal chemical variations. The orange luminescence is due to substitution of divalent manganese while iron is mostly responsible for quenching the luminescence (Smith and Stenstrom, 1965).

Zoning of dolomite also is visible. The iron-rich rims are dark (Fig. 45). In this specimen, the intergranular cement is calcite. Also, secondary dolomite crystals coating barite and replacing calcite could be observed (Fig. 46).

Minute amounts of silt size feldspar and quartz stand out as bright luminescence colors. Pseudomorphism of calcite after gypsum is shown to be complete.

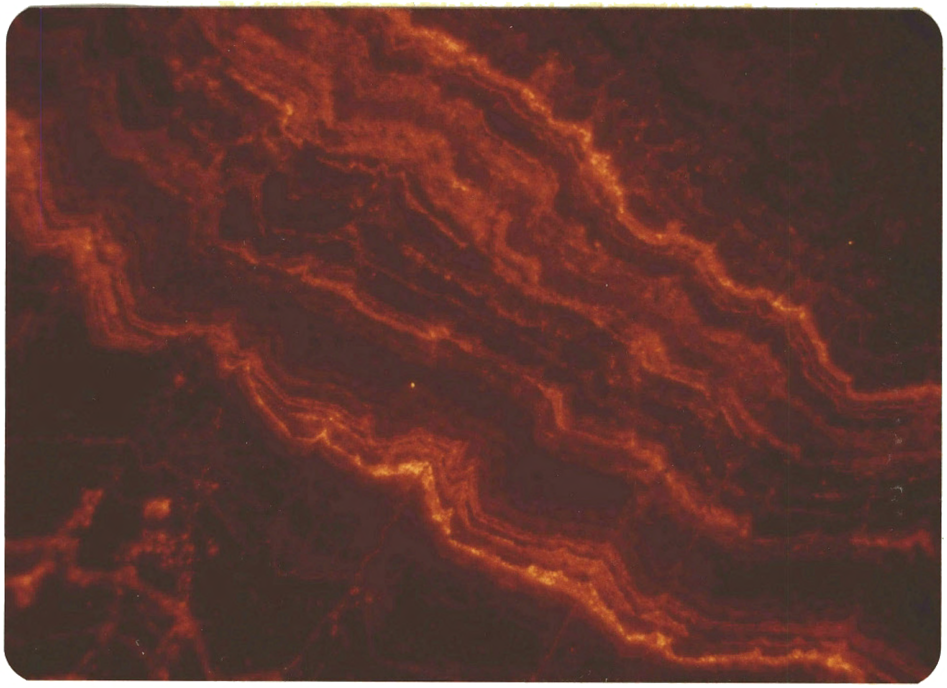


Fig. 44.-Cathode-luminescence photomicrograph of banding in sparry calcite. Orange and dark bands are due to manganese and iron substitution respectively.

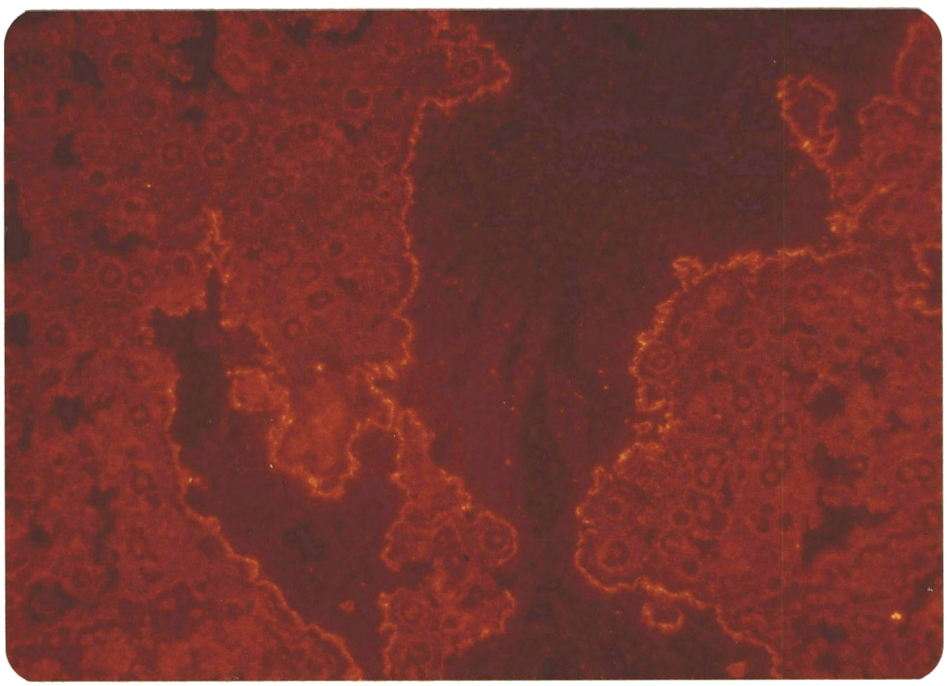


Fig. 45.-Cathode-luminescence photomicrograph of zoning in dolomite with calcite intergranular cement.

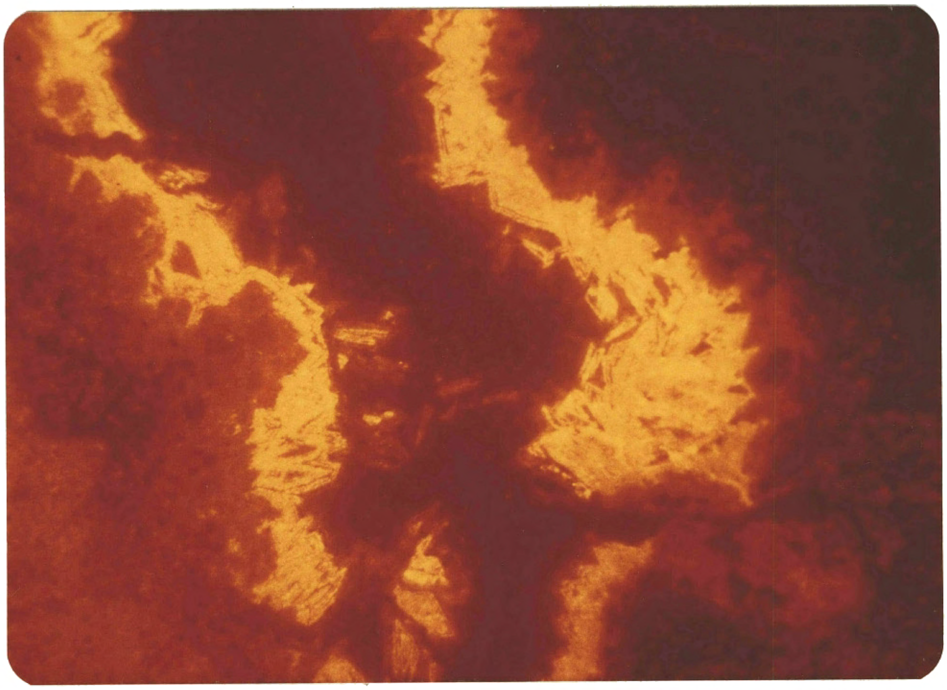


Fig. 46.-Cathode-luminescence of dolomite (red) replacing calcite (orange) and coating barite (non-luminescent).

Paragenesis

The diagenetic sequence of cement is variable; depending on the crosscutting relationship of the fractures and vugs and type of cornstone. Development of fractures and vugs in the lithified micrite provided the loci for the precipitation and accumulation of cement. In most of the cornstones, the following diagenetic sequence is observed: (1) walls of fractures and vugs are coated with either an early isopachous spar, or are lined with terminated crystals; (2) continued cement growth led to the development of a drusy mosaic. However, in its absence, coarse sparite or equigranular crystals are noted as intermediate forms with the formation of later wedge shaped and/or blocky sparite cement (Figs. 35, 37, and 38). In some samples, there seems to have been simultaneous development of drusy as well as wedge-shaped and blocky sparry cements at different positions. The final phases of cementation involved the precipitation of barite and haematite in some cases.

In laminated samples, microspar is the earliest cement forming as a pore-lining. This is followed by the precipitation of coarse sparite and barite.

Because of their open framework, conglomeratic cornstones contain mostly a coarse anhedral sparite interparticle cement. This cement replaced the clay matrix, corroded the quartz margins, granophyric rock fragments and feldspars.

Discussion and Conclusions

Most thinly laminated beds and a few nodules (Table II) are highly dolomitic. The dolomite has a fine grained and muddy texture and is associated with clays, haematite and manganese dioxide. The existence of this dolomitic matrix limits the period of dolomitisation to a very early stage. Dolomite is also observed (1) as small rhombs particularly in some laminated specimens. These may have formed from the recrystallization of the dolomitic matrix in addition to the growth of new rhombs; and (2) granular mosaic of secondary equigranular forms.

The clay mineral coating on the micritic matrix may have played a role in the precipitation of the carbonates. Clay sample analysis show that montmorillonite is the dominant clay mineral. Its high cation exchange capacity could have aided in the adsorption of Mg and Ca ions from solution. Similarly, the absence of abundant neomorphic fabrics may be due to a higher Mg/Ca ratio of the pore solutions. Folk (1974) indicates that neomorphism arises from the removal of Mg ions from rocks in surface waters of low Mg/Ca ratio.

The gypsum relicts due to replacements by calcite (Fig. 41) possibly indicate an evaporitic environment. Hence, the variations in carbonate mineralogy may be related to processes occurring in a restricted depositional environment. Bifurcating and crosscutting fractures as well as shrinkage cracks pinching out towards the edge suggest swelling during wetting and drying (Brewer, 1964). Clays may have been flushed out by pore solutions in advance of the precipitation of sparite cement. In the section on field appearance, mention was made of the presence of basal polygonal shrinkage cracks in some of the horizons. These could have served as depots for the rapid precipitation of carbonates. Montmorillonite possibly enhanced the formation of fractures.

The late void-filling barite cement in most of the samples suggests a semi-arid climate with evaporitic tendencies and restricted circulation (Folk, 1974).

Mammillary protrusions and irregular walls in the pores as well as the presence of intraparticle vugs indicate that solution played a substantial role in the expansion and formation of pores.

The grains of potassium feldspar, granophyre and angular monocrystalline quartz suggest that the conglomerates are texturally and mineralogically immature. Transportation was for a short distance by stream and deposition in a shallow environment. Hence these were formed in areas of ineffective winnowing. Later chemical conditions were conducive for their replacement. Meanwhile, the mostly subrounded to round carbonate fragments (Fig. 34) suggest that they are reworked and deposited as channel-lag material. Reworking was either in place or within a very short distance at some localities due to the lower clastic content at the base of these conglomerates. Their micritic matrix, sparry calcite-filled fractures, clay coating, etc. are the same as those noted in the cornstones of the area. Hence, they are interpreted as essentially reworked cornstone nodules.

Sparry calcite is the dominant cement in most of the samples. Although several generations are visible, cathodoluminescence studies indicate that the growth of these crystals was mostly sporadic.

CHAPTER VII

GEOCHEMISTRY

Analyses of sixty-five cornstone samples are given in Appendix B. Also, factor analyses are presented in Appendix C. A comparison between the average values for the cornstones in the study area, those from the Corbin Core, Scottish Devonian strata and world-wide averages for these elements in carbonates are presented in Table III. The Corbin core is located north of the Wichitas (6-6N-13W) in the 550 to 782 ft (168 to 238 m) subsurface section. The core contains mainly limestone exotic clasts and the deposit is a distal facies of the limestone conglomerates of the Post Oak. The uppermost 35 ft (11 m) is gray and grayish-green fine conglomerates, sandstones, siltstones and mudstones of fluvial origin. This sequence hosts 21 cornstones.

Five major and three trace elements were determined: Ca, Mg, Fe, K, Na, and Sr, Ba, and Mn. The results for Fe represent the total iron content. The following is a discussion of these elements.

Calcium and Magnesium

Table III shows that Post Oak and Corbin Core samples have higher Ca values than the other units; high Mg contents

TABLE III

AVERAGE ELEMENTAL ABUNDANCES OF CORNSTONES COMPARED WITH AVERAGES FOR GENERAL SEDIMENTARY ROCKS (VALUES IN PARTS PER MILLION)

Element	Average Carbonate[1]	Average Cornstone in S.W. Oklahoma				Average For Scottish Cornstones[2]
		Garber SST	Hennessey	Post Oak	Corbin Core[2]	
Magnesium	47,000	46,980.4	44,521.1	4,519.9	12,742.8	2,771.2
Sodium	400	525.86	473.5	90	1,498.8	416.3
Potassium	2,700	422.76	475.1	128.8	382.6	384.9
Calcium	302,300	259,648	263,462	317,250	314,800	293,384.6
Manganese	1,100	5,248.0	3,789.4	3,189	514.7	1,582.9
Iron	3,800	3,355.48	2,690.7	4,064	1,247.6	1,478.69
Strontium	610	684.24	441.7	202.6	449.5	241.15
Barium	10	1,139.69	895.3	342.0	351.6	73.6

1) From Turekian and Wedepohl, Table 2.

2) Data from unpublished analysis by William Richard Trent; OSU; 1978.

are characteristic in the Garber and Hennessey samples. The distribution plots for Ca (Fig. 47) show relatively small differences as well as a coincidence in the mean values and higher frequency ranges. In the plot for Mg (Fig. 48), Hennessey samples are clustered at the lower values but generally show a random distribution. A bimodal distribution is observed in Garber cornstones while the distribution in the Post Oak shows little variation with values ranging from 2000 to 6000 ppm.

These variations in Ca and Mg suggest differences in environmental conditions, and/or in precipitating mechanisms, and solutions variably enriched in Mg and Ca.

Petrographic and x-ray diffraction evidence (Table II) indicate that the Hennessey and Garber specimens with their high Mg values are mainly dolomitic, while the Post Oak with high Ca values registers calcite as the dominant cement and matrix. Thus the high Mg and consequently high Mg/Ca ratio in the Hennessey and Garber would cause Ca to decrease noticeably. Conversely, the low Mg/Ca ratio in the Post Oak suggests that the Mg content of the solutions was low.

Variation plots of Ca and Mg (Fig. 49) show a lack of association between the two. This possibly represents some replacement of Ca by Mg in the carbonates. Indeed, some dolomite replacement and secondary equigranular dolomite were observed in some samples (Figs. 29, 31, and 40).

When compared to the average for world wide carbonates, the mean Mg values (Table III) in these units are similar or

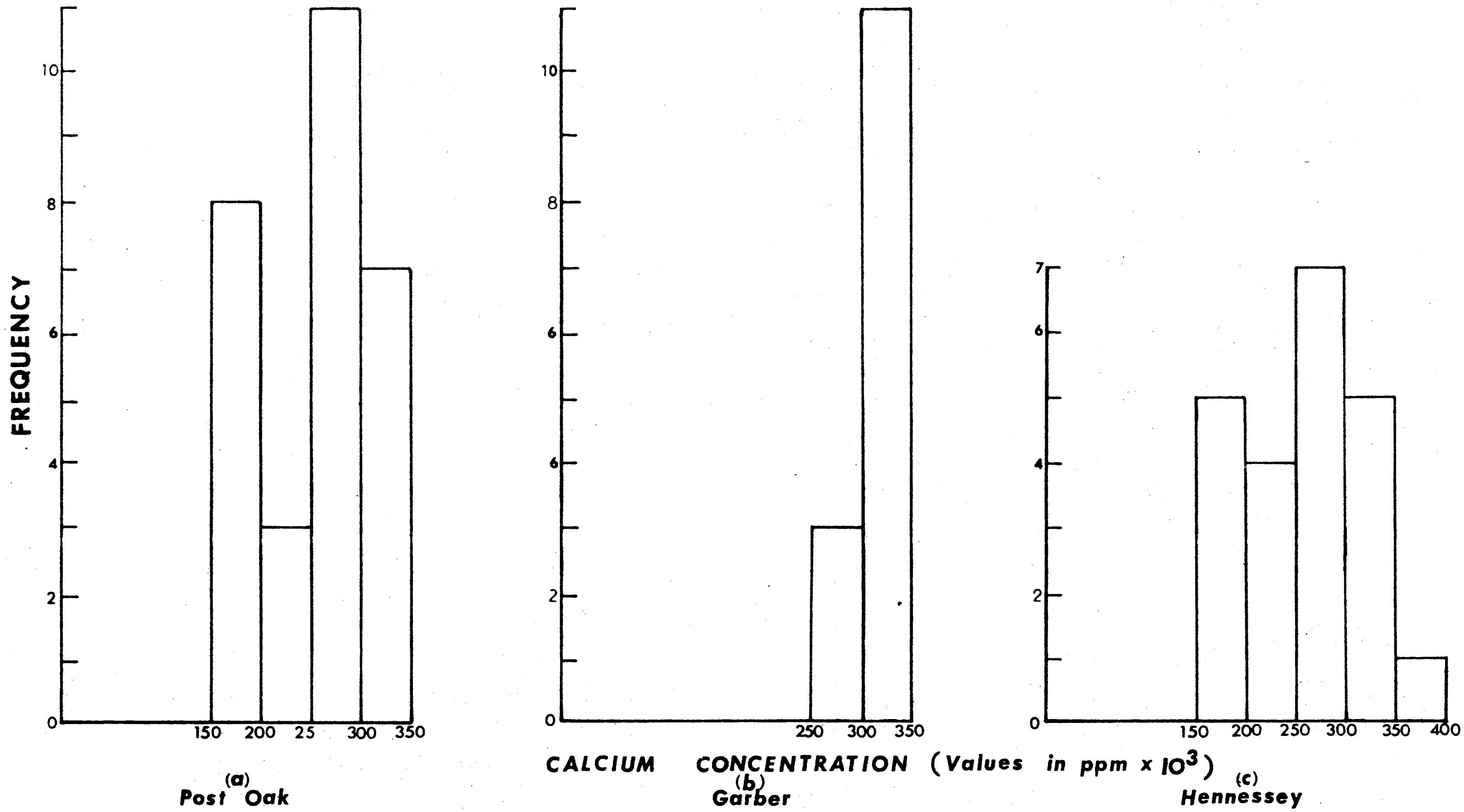


Fig. 47.-Frequency distribution of calcium in cornstones of the three host horizons.

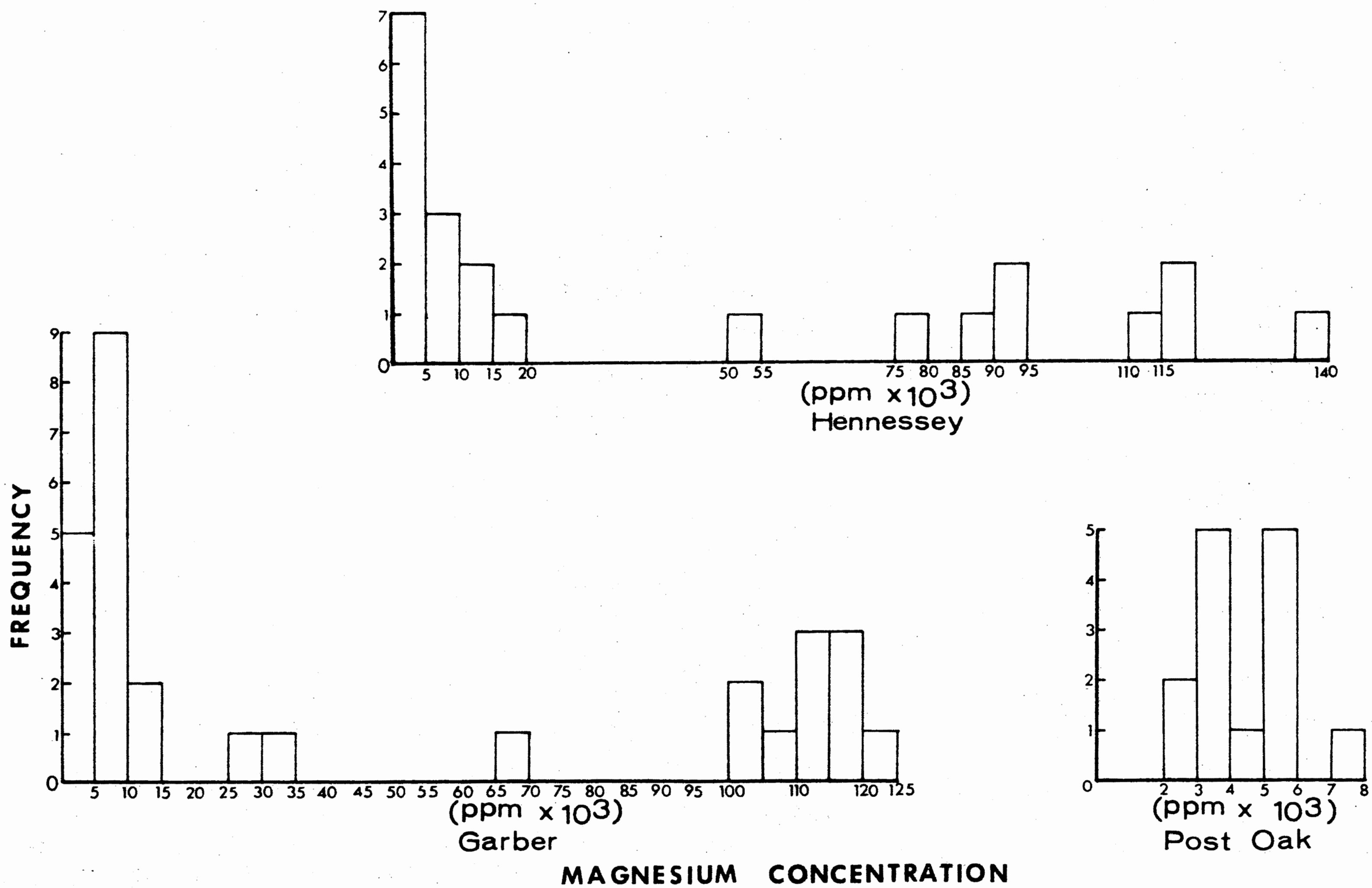


Fig. 48.-Frequency distribution of magnesium in cornstones of the three host horizons.

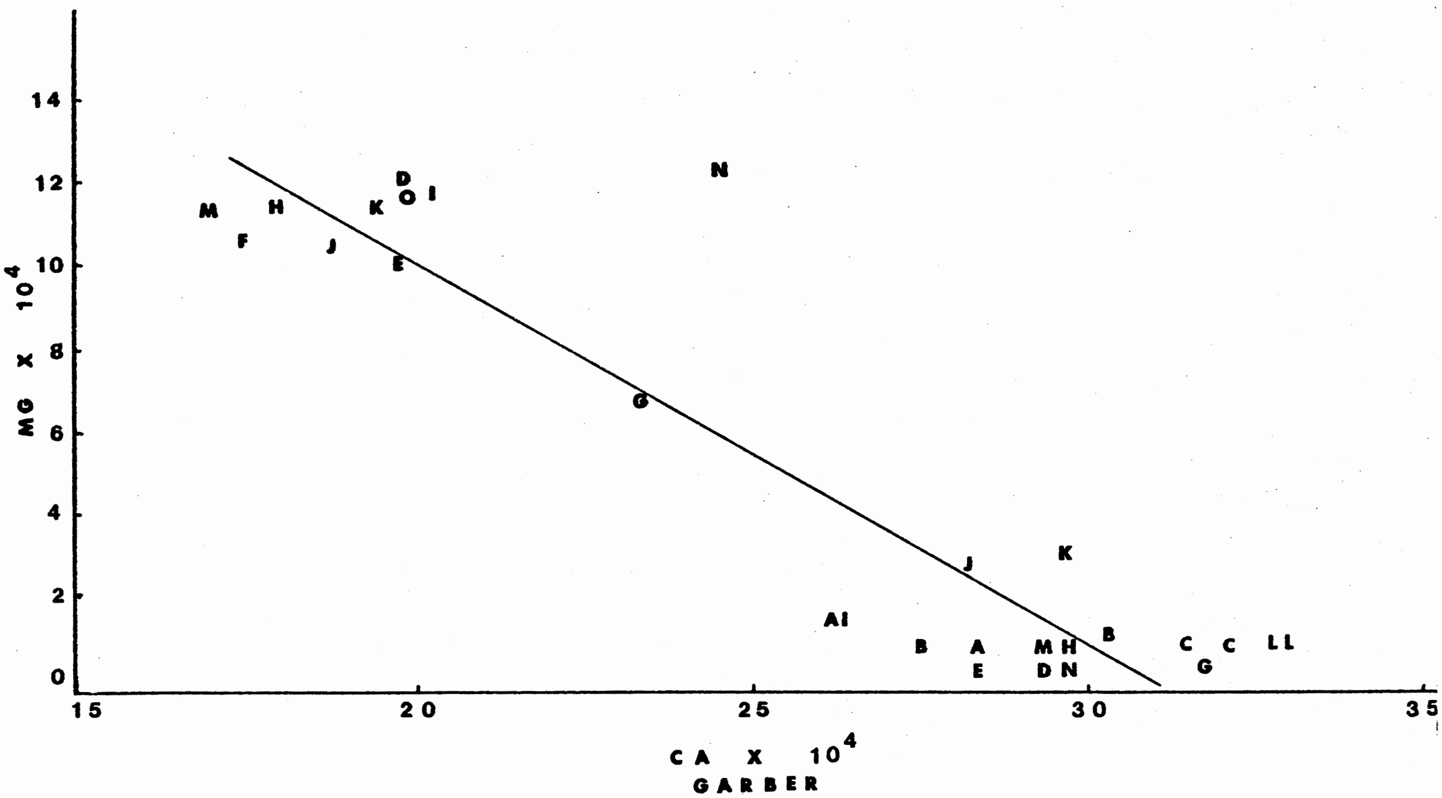


Fig. 49. - Variation plot of Ca Vs. Mg with
with approximate slope.
(Letters represent samplet.)

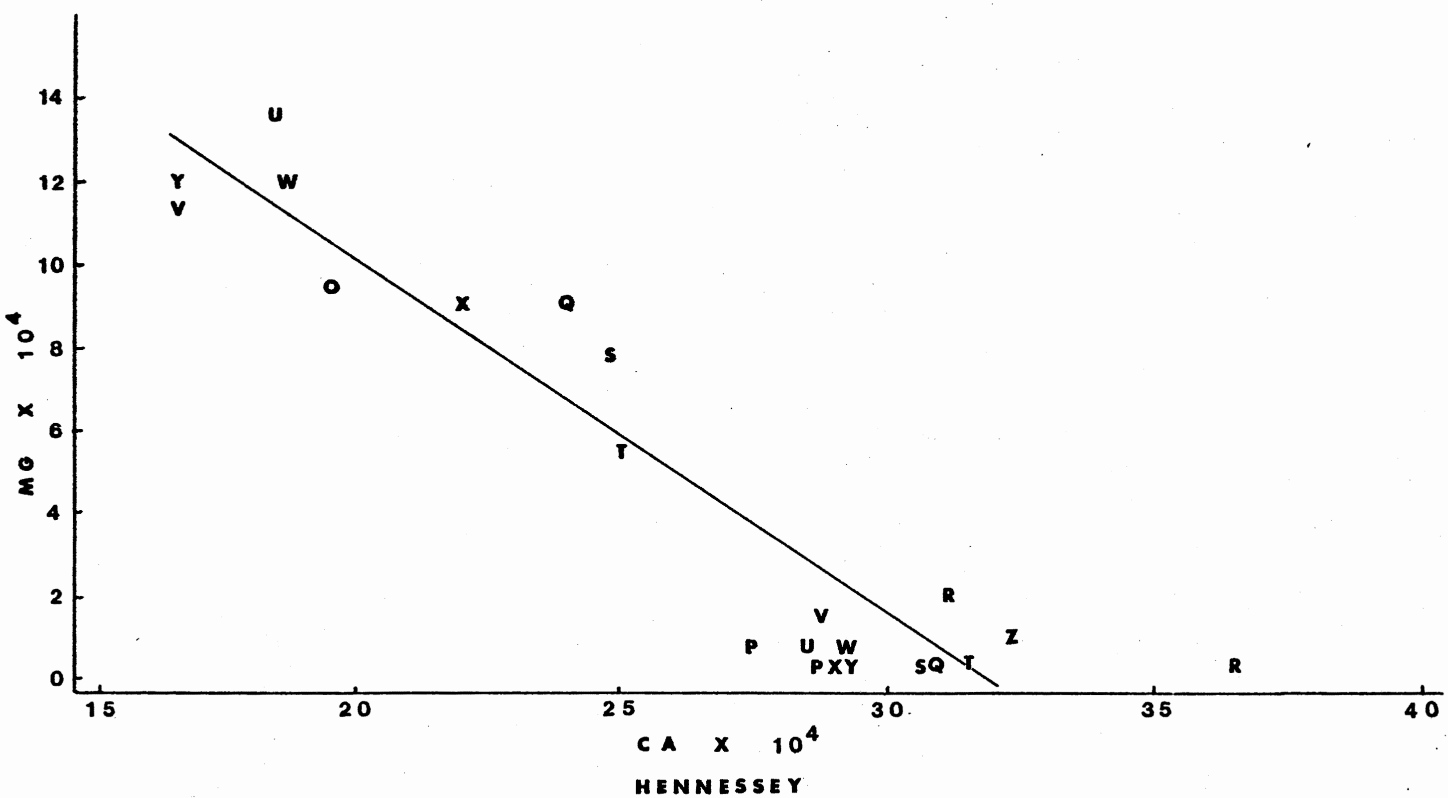


Fig. 49 Continued

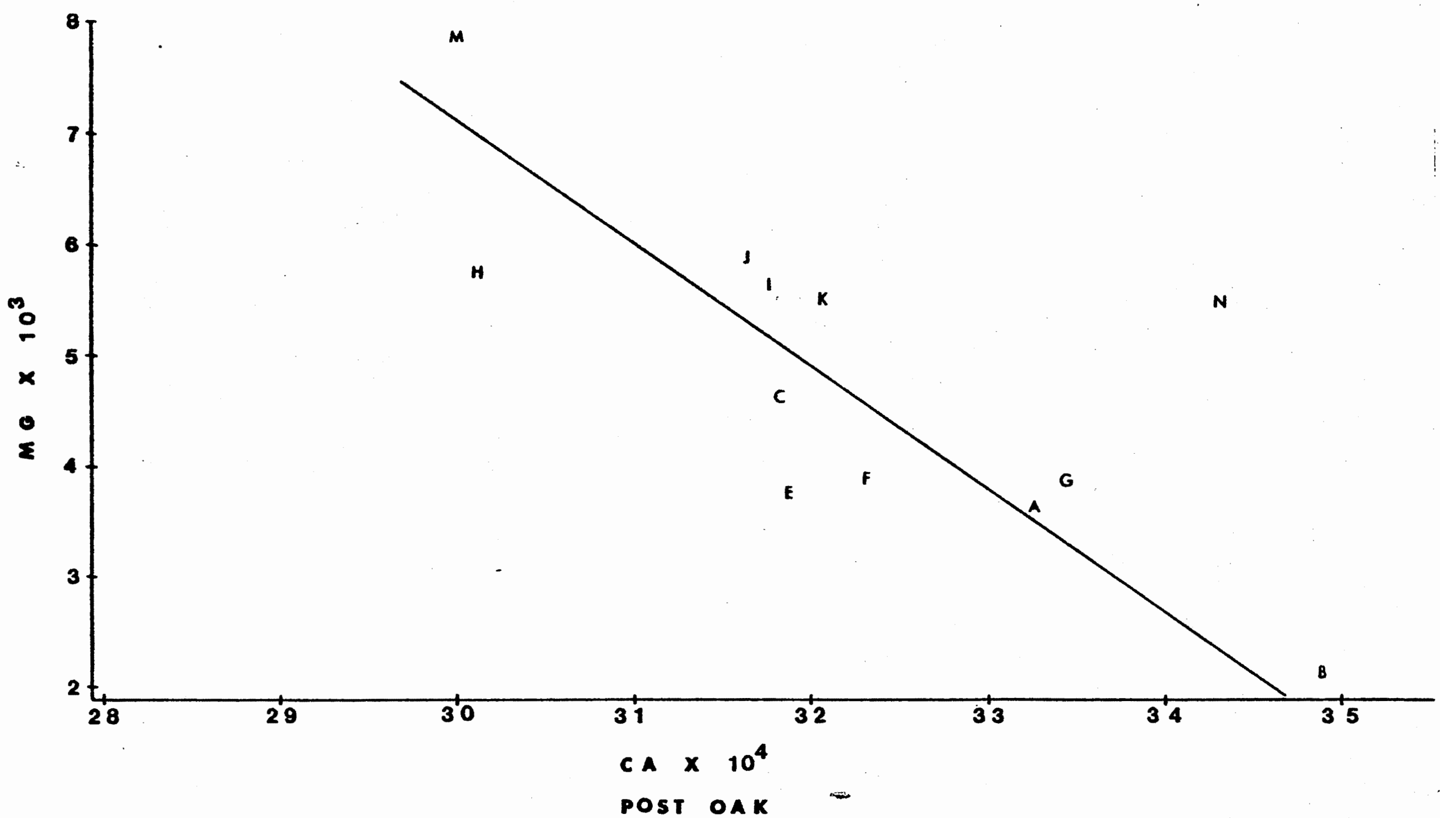


Fig. 49 Continued

lower. This may be attributed to the use of most of the available Mg in the synthesis of the dominant montmorillonitic clay assemblages. Also, due to its high cation exchange capacity, montmorillonite would very likely remove Mg from pore solutions.

Sodium and Potassium

When compared with world averages in carbonates (Table III), these cornstones except for those of the Post Oak are generally enriched in Na but are distinctly impoverished in K. Also, while samples of the Garber contain more Na, the Hennessey has a higher K content.

These variations may be related to the K and/or Na content of the solutions, and more importantly, the occurrence and relative content of clay minerals. The alteration of feldspars possibly contributed some of the ions in solution.

Clay mineral analyses (Table I) reveal locally high occurrences of illite in the Garber and Hennessey profiles. Montmorillonite is the dominant clay mineral in most of the horizons. Thus the higher K values in the Garber and Hennessey samples may be related to their illite content, while most of the Na may be associated with the occurrence of some Na-montmorillonite. On the other hand, the low Na values in the Post Oak possibly reflect the low sodic feldspar content of these arkosic sandstones and conglomerates.

Iron and Manganese

Histograms of the frequency distribution of iron (Fig. 50) show that values less than 4000 ppm are common in the Hennessey and Garber samples while the Post Oak registers a frequency spread up to 6000 ppm. The mean values for the different units are slightly greater than the values showing the highest frequency because of a few high values. Although low Mn values are prevalent, its distribution in each unit is variable, especially in the Garber which shows greater enrichment.

Table III shows that the studied samples are considerably enriched in Fe and Mn compared to Scottish and Corbin Core cornstones.

Variations in the Fe and Mn content of the respective units may be due to a number of factors: the Fe and Mn content of the solutions; precipitating mechanisms and the influence of other cations present; post-depositional effects and/or differences in their geographic distribution. Their content may be related to the observed mineral constituents. A considerable amount of haematite is observed in the samples, while some of them show dendritic growths of MnO_2 (possibly pyrolusite). Meanwhile, the higher Mn content compared to iron may be due to its lower affinity for oxygen in oxidate sediments (Rankama and Sahama, 1950) and the environment may have been more favorable for its concentration.

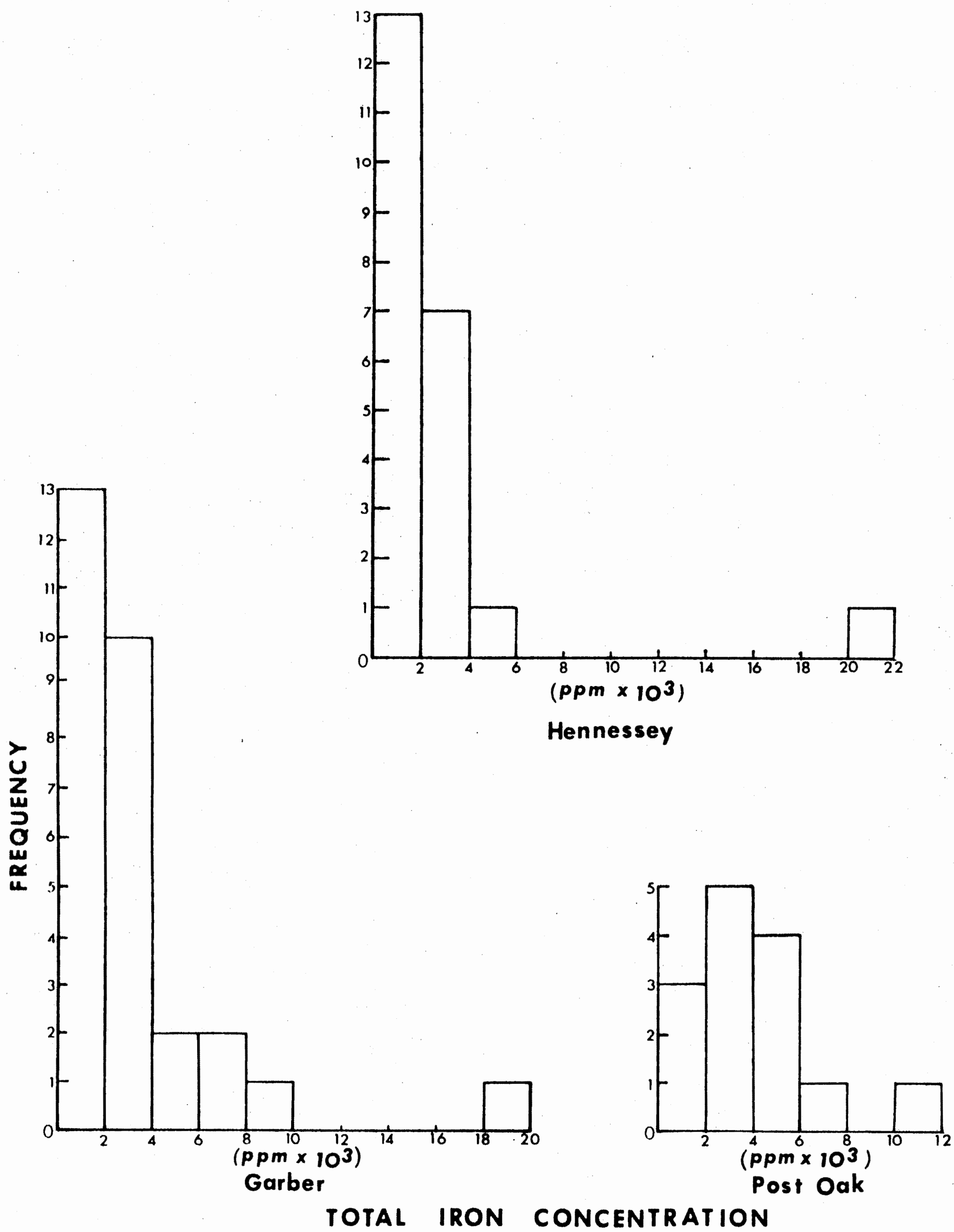


Fig. 50.-Frequency distribution of iron in cornstones of the three host horizons.

Strontium and Barium

Both elements show slight variations in their distribution (Figs. 51 and 52) and their content is higher in units of the Garber and Hennessey. The higher Ba values are primarily due to the presence of barite in many of the samples. Hence, the two environments were probably enriched in both elements.

The observed high Ba content and late barite cement suggest a late origin and dominant supply of Ba by circulating surface and interstitial waters. The solutions were enriched in sulfate ions. Although Ba is preferentially concentrated in the solid phase and Sr in the aqueous phase, some coprecipitation of Sr and Ba may have taken place. Gordon et al (1954) noted that Sr appears to be heterogeneously distributed in solution throughout Ba.

Sr enrichment in the mostly dolomitic Hennessey and Garber units may be associated with more evaporitic conditions resulting in a decrease in its solubility and hence higher concentration. While the lower content in the Post Oak may be due to the increased proportion of sparry calcite cement.

Factor Analysis

To provide further insight into the geochemistry of the 65 cornstone samples, R-mode factor analysis has been used to establish control of mineralogy and interelement relationships. Five factors were produced which together account for

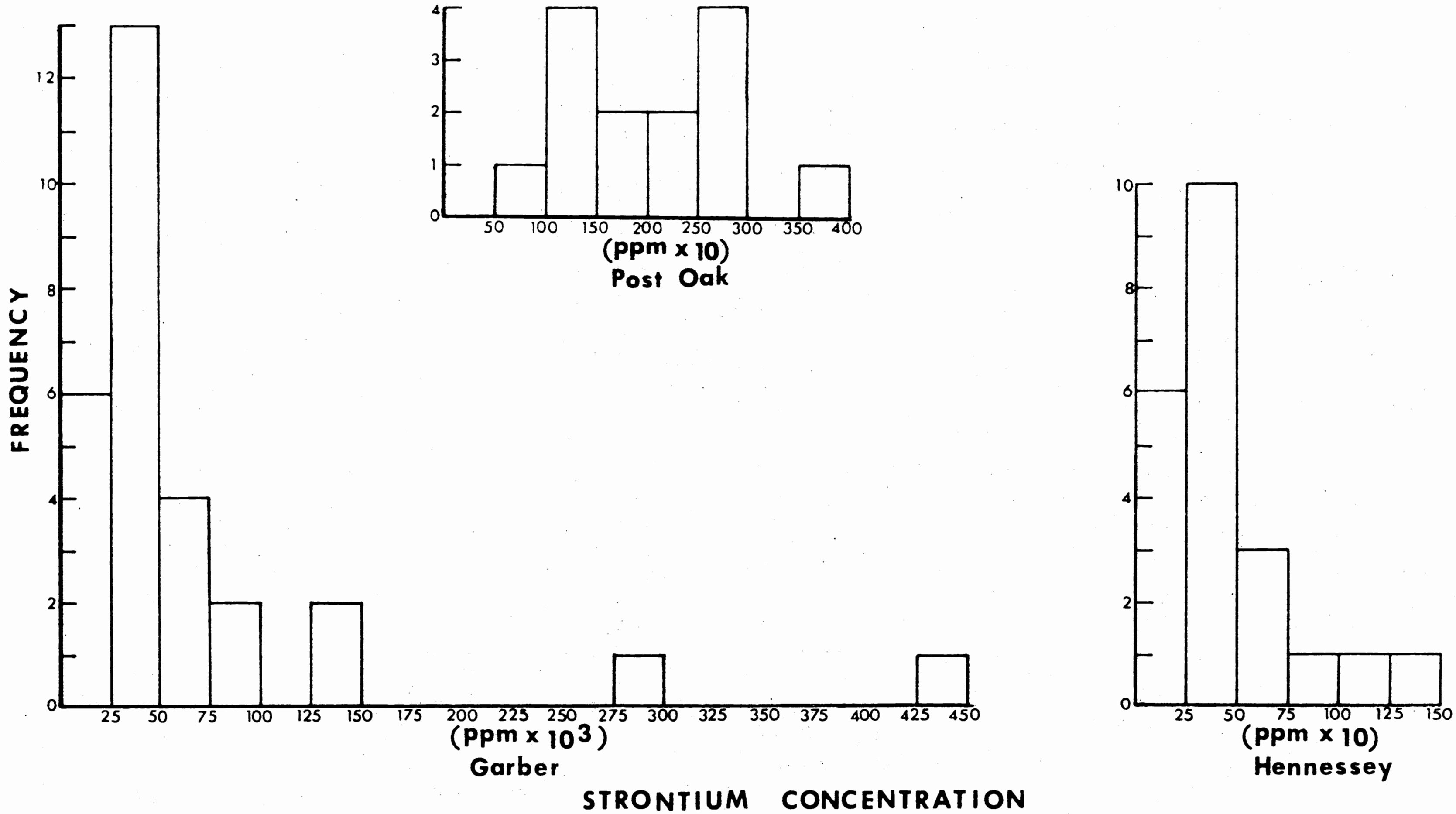


Fig. 57.-Frequency distribution of strontium in the cornstones of the three host horizons.

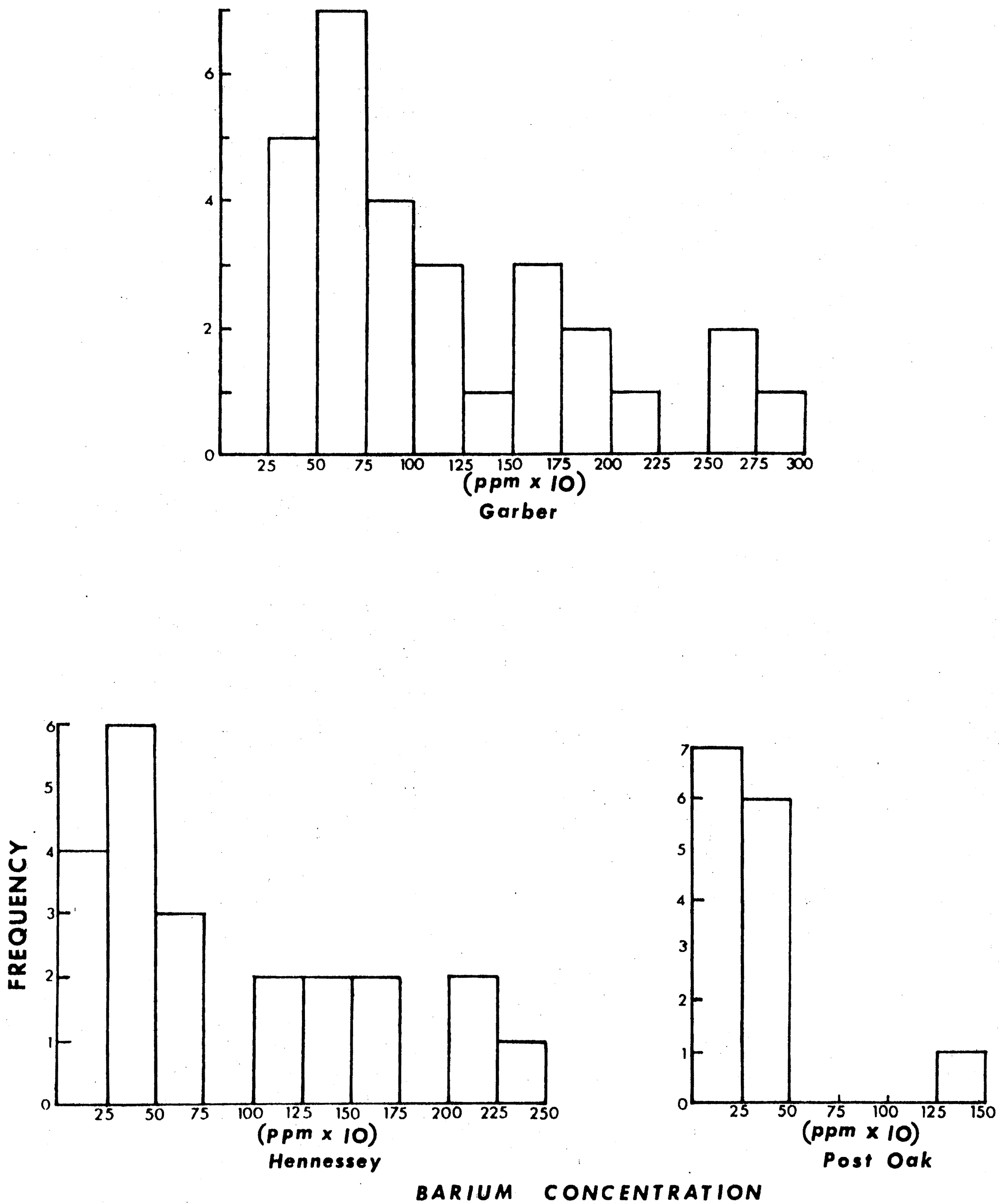


Fig. 52.-Frequency distribution of barium in cornstones of the three host horizons.

more than 60 percent of the total variance; each factor explains more than 10 percent of the variance data. Rotated variance factors have been used (Appendix C).

They show the same variance and associations of the elements with each host environment. These, according to Summerhayes (1973) are influenced by mineral provenance, physical and chemical depositional processes and degrees of geochemical coherence between certain elements.

The factor scores showed variations among the stratigraphic horizons especially in the opposing relation of Mg and Ca.

Three factors are related to depositional processes: (1) A factor with high loadings on residue and elements associated with clays (K, Mg, Na). It is related to the absorptive properties of the clays as well as a means of transport for some of the elements. (2) Bipolar factor with Mg and Ca loadings. The factor signifies the importance of the mineralogy of the cementing agent, i.e. calcite in the Post Oak and dolomite in the Garber Sandstone and the Hennessey formation. (3) A sulphate factor with high scores on Ba and some association with Sr. It is both geochemically and mineralogically induced; indicating that sulphate saturated solutions may have been brought in at a later stage of the sedimentation process.

These factors simulate and are quantitatively related to the mineralogy of the sediments. They thus add credence to the associations revealed by the correlation coefficients as well as the differences in mean contents of the elements in the stratigraphic horizons.

Chemical Environment

The chemical end-members noted in the specimens include: primary and secondary dolomite, calcite, haematite, manganese dioxide, barite and gypsum. All of these are pH- and Eh-dependent and imply alkaline oxidizing conditions although haematite may form with negative Eh at high pH.

A review of the salient aspects of their geochemistry would be a logical place to begin so as to determine if and how the chemical conditions fluctuated during their formation.

Dolomite ($CaMgCO_3$)

In the study area, assemblages of dolomite and calcite have been identified in the Hennessey and Garber cornstones. The dolomitization is primary (nonreplacement) with a few exceptions.

Processes resulting in the formation of primary dolomite in sediments must have also been effective in the geologic past. In Recent sediments, dolomite formation has been correlated with evaporation, high salinity, high Mg^{2+}/Ca^{2+} ratios. The solutions are periodically replenished by reflux or flooding.

Alderman (1965) presents data for the ephemeral lakes of the Coorong which show that the dolomite and calcite assemblages are confined to this area with its pH values between

8 and 10.2, high Mg^{2+}/Ca^{2+} ratio and salinity during inundation and evaporation. The Mg content is fairly constant during inundation and seems to be controlled by the Mg/Ca ratio. He also points out that these properties can be developed in evaporitic basins at higher than normal temperature. Thus evaporation serves to concentrate Mg^{2+} and raise the Mg/Ca ratio.

Dolomite is essentially formed by the reaction of carbonates in solution with Mg-rich solutions.

$Mg^{2+} + 2CaCO_3 = CaMg(CO_3)_2 + Ca^{2+}$. The pH would likely be controlled by CO_3^{2-} and HCO_3^- ions.

In the system Ca^{2+}-Mg^{2+}-CO_3^{2-}-SO_4^{2-}-Cl_2^--H_2O, with a high Mg^{2+} concentration, the recrystallization of metastable calcite is inhibited. Dodd (1965) indicated that the solubility of calcite is enhanced in the presence of Mg^{2+} and/or SO_4^{2-}. Essentially the ions are adsorbed on the $CaCO_3$ surface and substitution of Mg^{2+} for Ca^{2+} takes place. Sippel and Glover (1967) reported that this replacement increases with an increase in the Mg/Ca ratio. Dolomite has a highly ordered structure and it grows very slowly. The high hydration of Mg^{2+} and possible clustering around Ca^{2+} may hinder the arrival of Ca^{2+} and CO_3^{2-} from solution. Since the solutions are Mg-rich, inhibition of the nucleation of calcite into a stable phase probably continues until the solution is supersaturated in Mg^{2+} and dolomite is precipitated along with some calcite. If solutions are saturated with additional $CaSO_4$, gypsum or anhydrite is formed.

The dolomite of the study area was essentially generated penecontemporaneously with the formation of the cornstones. The dolomite-calcite assemblage may have formed by the process discussed above. Deposition of the matrix was probably by surface precipitation of microcrystalline dolomite from evaporating Mg-rich solutions. Clays may have enhanced the dolomite formation (Veizer, 1970). Increased permeability and dessication of the surface allowed for downward spread and floods replenished the Mg-supply.

The late diagenetic (secondary) dolomites may have formed through the reaction of Mg-rich pore solutions with the host calcites.

Calcite ($CaCO_3$)

For calcite, the most important ionic species is CO_3^{2-} which is strongly pH dependent. This with the Ca^{2+} ion are common in solution. The carbonate ions react appreciably in water to form the bicarbonate (HCO_3^-) and then carbonic acid:

$$CO_3^{2-} + H_2O = HCO_3^- + OH^-$$

$$HCO_3^- + H_2O = H_2CO_3 + OH^-$$

Thus the solution becomes alkaline.

Under alkaline conditions (pH 6.4 to 10.3), the bicarbonate ion, HCO_3^- is predominant while the carbonate ion, CO_3^{2-} is common in strongly alkaline waters (pH greater than 10.3). On the other hand, H_2CO_3 is the dominant species in weakly acid waters (pH 4 to 6.4). Thus an increase in pH tends to cause the precipitation of calcite (Fig. 53).

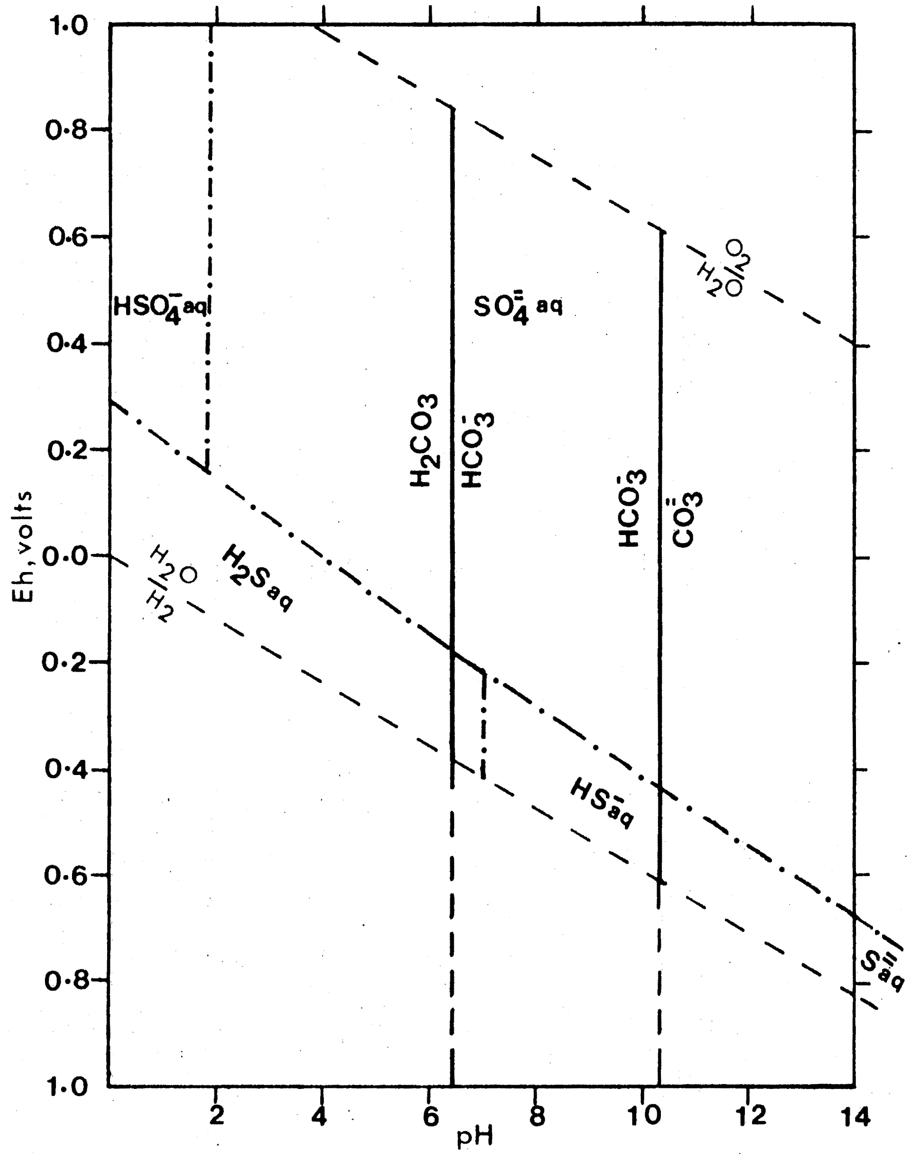


Fig. 53.-Eh-pH diagram for stable dissolved carbonate and sulphur species at 25°C and 1 atm. total pressure. Short dashed and dotted lines represent boundaries for stable sulphur species. From Garrels and Christ (1965).

Meanwhile, the removal of carbon dioxide through evaporation from the bicarbonate eventually leads to calcite precipitation from a saturated solution. Most of the CO_2 is held in HCO_3^- and a minor part in CO_3^{2-}.

$$Ca^{2+} + 2HCO_3^- = CaCO_3 + H_2O + CO_2$$

<u>Haematite (Fe_2O_3)</u>

In nature, iron occurs as ferrous and ferric ions; the species occurring depends on the Eh-pH of the solution. However, magnetite, haematite, siderite, sulfides and silicates are the forms of iron in natural environments.

Under slightly acidic conditions, larger amounts of dissolved iron are present. But in oxidizing conditions, Fe is readily converted to the ferric (Fe^{3+}) state and is precipitated as the hydroxide, $Fe(OH)_3$. With time, the latter dehydrates and forms red iron oxide.

Oxidation of iron takes place in much more alkaline conditions (Krumbein and Garrels, 1952). Under these conditions, the $\frac{Fe^{3+}}{Fe^{2+}}$ ratios and hydroxide concentration are high and the activity product of haematite is most likely to be exceeded. Hence the precipitation of haematite is Eh-pH dependent. Figure 54 also shows that haematite is the stable iron mineral, in moderately to strongly oxidizing environments.

<u>Manganese Dioxide (MnO_2)</u>

Solutions with low Eh and pH contain mainly the divalent

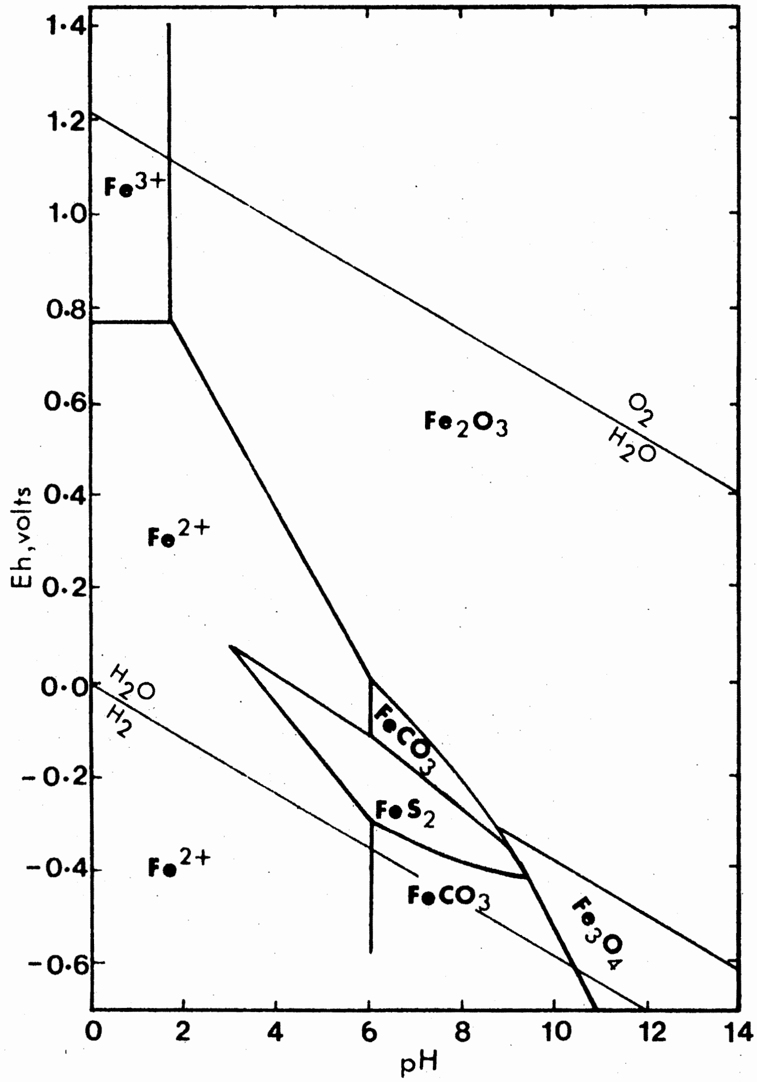


Fig. 54.-Eh-pH diagram showing stability fields for common iron minerals at total dissolved iron concentration = 10^{-6} M. From Garrels and Christ (1965).

ions. Under surface conditions, the carbonates, silicates and sulfides are readily oxidized to the oxides.

Figure 55 shows that at high redox potentials, MnO_2 is the stable manganese compound. Oxidizing and highly alkaline (high pH) conditions would, according to Rankama and Sahama (1950), readily cause the precipitation of the oxides. Meanwhile, $MnCO_3$ is stable over a wide Eh and pH range in solutions with high carbonate concentration. However, the carbonate is also convertible to oxides or hydroxides. The removal of CO_2 from the bicarbonate through evaporation also causes the precipitation of either the carbonate or hydroxides.

As a result of differential solubilities and the ready oxidation of haematite, manganese oxides are separated from haematite. Thus, the latter precipitates first.

Barite ($BaSO_4$)

Sulfate ions are formed in fairly oxidizing conditions and waters exposed to the atmosphere (Fig. 53). The precipitation of calcite and dolomite result in the high concentration of electrolytes (e.g., Ba^{2+}, Sr^{+}, Na^{+}, SO_4^{2-}, K^{+}, Ca^{2+} and Cl^{-}) and waters become increasingly sulfatic. Thus the occurrence of barite as late vein and void fillings imply the late existence of strongly sulfatic solutions. However, Ba is a weakly migrant cation in solution (Perel'man, 1967). Hence the formation of barite probably involved the mixing of previously nonsulfatic brines of Ba, Ca, Sr with

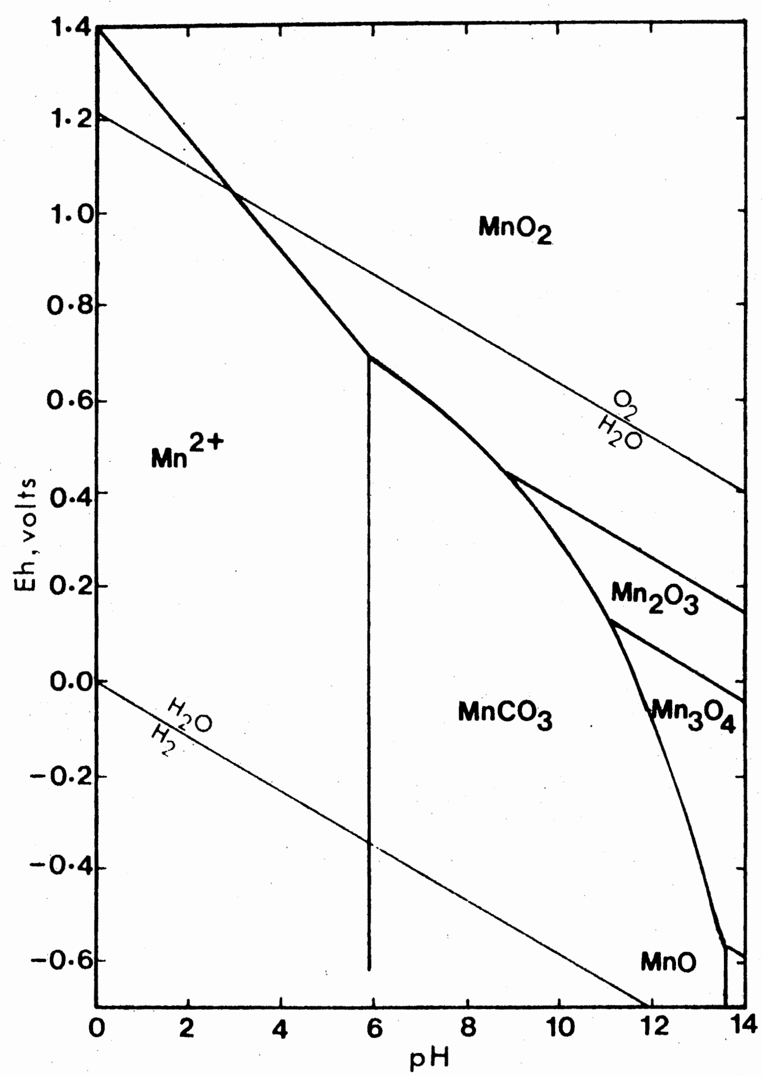


Fig. 55.-Eh-pH diagram for common manganese minerals. Total manganese = 10^{-6}M, total carbonate = 1 M, total sulfur = 10^{-6} M. From Garrels and Christ (1965).

oxygenated sulfatic ($NaSO_4$) waters which form from above (Perel'man, 1967). Gypsum and celestites will be other secondary precipitates. In these cornstones, the non-sulfatic water will mostly be held in the fractures, cracks, and voids; precipitates eventually form through evaporation.

Conclusions

The above geochemical review clearly shows that conditions were mostly evaporitic and aided in the concentration of the alkaline solution. This therefore explains the formation of the principal minerals (dolomite, calcite, manganese dioxide, haematite, and barite) in the studied cornstones. Solutions were replenished by floods during wet periods. Hence, climatic conditions were alternating.

The solutions must have been initially concentrated in Mg^{2+}, Ca^{2+}, CO_3^{2-} and small amounts of other ions. Hence the noted associations with calcite and dolomite. Changes in the ionic species and their content in solution due to precipitation, recharge by flood waters as well as the Eh-pH of the solutions may account for the differential content and precipitation stage of Fe and Mn oxides. On the other hand, barite formed late from sulphatic ions introduced into the rocks, especially fissures, by descending sulfatic waters.

CHAPTER VIII

ORIGIN

Essentially two types of cornstones are predominant in the study area: the laminated and nodular forms. Thus an explanation of the origin of the cornstones should include the formation of these two as well as the fabrics.

Earlier investigations of the origin of caliche (Bretz and Horberg, 1949; Gile et al., 1966; and others) suggest that an in-place formation by meteoric and inorganic carbonate solutions soaked into the host sediment and precipitated during dry periods. A plugged horizon develops with time and there is an eventual net downward and upward increase in the carbonate layer. This hypothesis is consistent with the studied cornstones.

However, the processes involved in the formation or deposition of these cornstones can be stated precisely by considering the role of the various aspects studied.

Thin section studies have delineated four major forms of minerals precipitated: (1) primary dolomite and/or calcite; (2) secondary calcite and/or dolomite; (3) haematite coating and (4) vein barite. These four succeed and interpenetrate each other in the order listed to produce the cornstone forms observed.

Near the surface, characteristics of the vadose environment vary (include or are) between in situ sedimentation, dessication, solution and cementation. These processes have permitted vertical and/or lateral migration and precipitation of the carbonates and cements. Thus resulting in the cornstones with their observed characteristics or features. The carbonates were very likely derived from meteoric and fluvial solutions and possibly from wind-blown deposits.

Nodules may have formed through the aid of dessication cracks which acted as depots for stagnant pockets of water. These probably also acted as conduits through which clays and solutions were flushed. Precipitation continued around and within the nodules. Later fractures and veins cutting through the matrix and host may have been retained in these voids for longer periods probably due to reduced permeability; where a slow crystallization rate resulted in the development of sparry calcite.

Pseudo-pisolitic structures according to Siesser (1973) probably formed through the precipitation of carbonate mud around incipient ooids and intraclasts. Fahraeus et al (1974) have called them pseudopellets and ascribe their origin to hydraulic forces. The writer feels that both mechanisms were probably in operation in the study area. However, growth of the structures may have been initiated in solution; aided by heterogenous nucleation. These incipient ooids (spheres) fall through the liquid, and material from flowing supersaturated water is added by diffusion and mass flow. The arcuate and/or circular voids later infilled by microspar may be attributed to water movement, solution, and reprecipitation and brecciation.

The massive cornstone of profile H-8 (Figs. 12, 14, and 15) may have formed by rapid vertical precipitation of micrite in mudcracks. The surrounding muds are displaced as the pillars grow and are flushed by solutions. Repeated brecciation would deepen the fractures and the joints connecting these cracks permit the pillars to be interconnected. Continued vertical (upward and downward) growth and precipitation eventually plugs the upper horizon and traps the muds between the pillars. This makes way for the development of the overlying massive cornstone. Periodic floods provided some of the muds and clays that continued to be entrapped between the columns. It is noteworthy that very few of the interior voids contain a small amount of clay. Later fractures developed within the carbonate are infilled with sparry calcite.

Tepee (pseudo-anticlines) structures were observed in profile Y-1 (Figs. 7 and 16). These are cusped, mutually truncating anticlinal forms. They are stripped by slickensides. Allen (1974), thinks they are probably due to "periodic compression (clay wetting and/or carbonate displacive growth) of a superficial layer".

However, visual inspection of these structures reveals the presence of fractures which are crosscut and partially infilled by secondary carbonate. These fractures may have acted as slip-planes. Hence the structures appear to be the result of small scale slump flowage of the unconsolidated upper layer over a long period. Troughs allow for the settling of material and creep seems to have been the dominant process.

This mode of formation is favoured by, and may be the result of a number of interacting processes: (1) the inhomogenous (undulating) surface and steeply dipping, unstable slopes of the underlying laminated layer. The laminae are also potential sliding surfaces; (2) the fluid-like nature of the carbonate and the presence of ground water acting as lubricant; (3) continued precipitation of carbonates; and (4) continued expansion and contraction in the underlying laminated layer may initiate buckling through the production of vertical and lateral stresses.

Residual flood waters formed ponds, percolated vertically, flowed and diffused horizontally (laminar flow) and through evaporation became supersaturated. It may be noted that in a mudstone host, its predominant montmorillonitic assemblage and consequent poor porosity would retard vertical and horizontal diffusion. The reverse would hold true for a sandstone host. In-place dissolution of earlier precipitated carbonates and wind action may have also contributed CO_3^{2-} ions to the solutions. Intermittent floods and rainwater replenished the supply of ions and solutions. Formation of the micrite matrix (dolomite and calcite in composition) may have been by colloids nucleating on clay and sand grains.

Crystals grew by diffusion from solutions onto the colloidal surfaces. At shallow depths, illuviation was active. For the thick layers and profiles to have developed, the formation processes of these carbonates were prolonged and repetitive. Hence the cornstones are mainly synsedimentary.

Meanwhile, the type of cornstone and its lateral extent depend on a number of factors: (1) the host sediment; (2) diffusion rate and ground water flow; (3) whether distribution is homogenous or not. Heterogenous distribution results in localized precipitation of minerals (Berner, 1971). Hence nodules and layers may be apt to form; and (4) extent, volume and concentration of ponded water. The extent is controlled mainly by the surface relief.

Laminated zones probably developed from pools of stagnant carbonated water forming over the plugged horizon. With time, the latter slowly grew upward by aggradation (Steel, 1974). Solution convection currents due to evaporation of CO_2, horizontal diffusion and flow of water, and velocity of falling crystals may be responsible for the formation of the fine, undulating and truncating laminae observed in the specimens. Local conditions of greater *in situ* dissolution and brecciation than reprecipitation of microspar may have resulted in their poor development (Harrison and Steinen, 1978). The fewer laminae at the base may be attributed to the higher density of the solutions and the presence of mudstones.

CHAPTER IX

PALEOENVIRONMENT

Clay and chemical analyses, petrographic, and lithologic studies indicate that the cornstones studied are similar to recent caliche deposits. Thus, they record pedogenic or synsedimentary processes characteristic of semi-arid regions. Differences in the development stages or maturity of the profiles, clay mineralogy, chemistry, and petrography of the cornstones seem to represent the conditions that prevailed in the three stratigraphic horizons studied. Hence, they will aid in delineating differences between these environments and make it possible to postulate on how and why conditions fluctuated in the three depositional systems.

The following is a resume of the study with the differences between the stratigraphic horizons especially noted.

<u>Profiles</u>. The stratigraphic variation emerges fairly clearly when the textures of the cornstone profiles are compared. Laminated horizons (classified as old age cornstones) are found only in the Garber and Hennessey cornstones. Although their vertical positions in the profiles vary, it could be inferred that pedogenic processes were much more complete and prolonged in these

two environments than the Post Oak. Also, except for profile M-1-1, the rest of the cornstone conglomerates are in the Garber. Their locations are variably situated (Plate 1) and they represent some reworking and/or erosion of earlier formed cornstones.

Petrography. Thin section and x-ray diffraction studies reveal a marked difference in mineralogy. Garber and Hennessey cornstones are composed of dolomite and calcite while those of the Post Oak are mainly calcite. Banding of dolomite and sparry calcite as observed by cathodo-luminescence qualitatively reveals fluctuating chemical variations possibly due to the periodic supply of solutions.

Clay Mineralogy. Montmorillonite is dominant in all stratigraphic horizons, and mixed-layered clays are absent in the Post Oak.

Geochemistry. With the exception of Ca and Fe, the Garber and Hennessey specimens have higher contents of the other elements analyzed. Higher Ba and Mg are mainly due to barite and dolomite in the Garber and Hennessey samples and may be associated with prolonged ponding of solutions and evaporation. Frequency distribution plots of some of the elements show little variation in the Post Oak compared to the other hosts. Thus conditions were probably more uniform in the Post Oak.

Based on the above differences and known behavior applicable to the depositional environment, a model on the prevalent conditions is considered for each host.

Garber

Donovan (Personal Communication, 1978) thinks the Garber is a braided-stream system. Well preserved channels are randomly distributed and contain reworked nodular cornstone fragments. The depth of flow was shallow during arid conditions, during which cornstones developed on terraces and flood plains. Pedogenesis was halted during wet conditions and the Garber stream system probably underwent wide lateral shifts when the valleys were fully aggraded and during high floods. It contemporaneously combed and eroded developing cornstones and other flood plain deposits; emplacing them in channels as floods became more frequent. Also, these movements produced areas removed from sediment accumulation. Hence as a result of these lateral shifts and variations in the elemental compositions of the solutions, the frequency distribution of the elements is variable. The high dolomite and barite content may possibly indicate much more severe evaporitic conditions. Topographically low areas permitted the accumulation of ponds, resulting in laminated layers, e.g., Y-1. The erosive emplacement of cornstones explains the dominance of nodular cornstone conglomerates in the Garber.

Hennessey

Cornstones of the Hennessey were formed on tidal flats.

The fluctuations of the sea level may have been considerable and prolonged, hence the fairly thick profiles with mature horizons. Thinly laminated horizons form at the base of many of the vertical profiles. This suggests that the flats may have been level and sediment-starved, thus pedogenesis prevailed. With a rise in the base level of the tides, a major part of the flat was intermittently inundated. The climate was semi-arid and evaporatic conditions prevailed.

Post Oak

These rocks represent an alluvial fan-piedmont/braided river deposit developed under semi-arid conditions (Al-Shaieb et al., 1977). The cornstones are hosted by mostly fine conglomeratic to coarse grained arkose and a few mudstones. The depositional slope was probably gently dipping (2^{o} to 5^{o}). Semi-arid conditions are characterized by brief and infrequent periods of downpour. However, tranquil conditions may have prevailed due to lengthy periods of dryness. Hence the drainage by numerous small, shallow, ephemeral streams. During these conditions, depositional tendencies predominate and sediments remain saturated following each depositional cycle (Blissenbach, 1954). The development of the fan was slow, with slow changes; and there was probably a steady but unabundant supply and recharge of water. Pedogenesis progressed during the arid periods. Meanwhile the infrequent floods, porosity of the mostly arkosic host and gently dipping surface may have prevented the prolonged retention and ponding of waters. On the other hand, they probably aided in the fairly uniform distribution of the solutions. Thus resulting in the small scatter observed in the frequency distribution of the elements; also the lack of mature or old age profiles and mixed-layer clays. In short, equilibrium conditions probably prevailed. Nonetheless, some reworking and erosional emplacement of the cornstones took place during the infrequent floods.

These models provide alternative and possible structures in the light of the pedogenic units and explain the variations noted in the aspects covered in this study. They are dependent primarily on climatic control to determine changes in the river regime, amount of channel wandering and development stages of the cornstones. These cornstones show that parts of the Lower Permian alluvial plains and tidal flats were sediment-starved for long periods. A more complete understanding of the coarse-grade members, particularly those of the Garber and Hennessey as well as subsurface study and exploration of the sequences, would aid in the better understanding of the changes that the drainage systems underwent in addition to explaining how active and inactive areas can be juxtaposed at any one time.

CHAPTER X

CONCLUSIONS

The following are the principal observations derived from this study:

1. Cornstones within the study area are comparable to modern caliche deposits. The profiles represent and show progressive development sequences.

2. These deposits are hosted by Lower Permian fluvial/tidal flat systems and thus represent stratigraphic, sedimentologic, chemical and climatic conditions that prevailed in each host.

3. Montmorillonite is the dominant clay mineral; and although the effects of post-depositional diagenesis may be considerable, the prevalent conditions chiefly climatic and chemical, were favourable for its formation.

4. The cornstones are essentially synsedimentary; having been formed in place by the precipitation of dolomite and/or calcite from meteoric and fluvial solutions in the host material, mostly mudstones and sandstones.

5. They show features of shallow water deposition and subaerial diagenesis (dessication cracks, laminations, solution and cementation). Similar processes occur in semi-arid to arid regions today.

6. The conglomerates suggest reworking and penecontemporaneous erosion; while gypsum relicts and barite imply evaporitive conditions.

7. Variations in the clay mineralogy, maturity of profiles, distribution pattern of elements, types and mineralogy of the cornstones represent variations in sedimentation rates and environment, climate, as well as short-term (perhaps seasonal) fluctuations in Eh-pH conditions.

8. The chemical end-members noted in the samples (dolomite, calcite, haematite, barite and manganese dioxide) indicate that the solutions were variably alkaline and oxidizing.

9. Evaporation was common and also important in concentrating the major elements. The solutions were replenished by floods. Hence, conditions were alternately wet and dry. Wind action may have contributed to the supply of carbonates.

10. Cornstones of the Hennessey and Garber were developed in areas removed from active sediment accumulation due to wide lateral shifts and/or fluctuations in water levels over the tidal flats and flood plains respectively. Lateral migration was much more extensive in the Garber fluvial system. Also, mature profiles in these two hosts indicate that pedogenesis was relatively protracted and enhanced by the lack of relief.

11. Because the Post Oak is an alluvial piedmont-fan deposit, the higher depositional slope, and porosity of the host arkose possibly prevented the preservation, as well as extensive and prolonged accumulation of cornstones.

12. The equation of these cornstones with pedogenic carbonates and evidence from the aspects studied, indicate that the climate was, at least periodically, semi-arid. And due to the time span necessary for cornstone development, a prolonged period of sediment exposure and soil development between phases of major channel and tidal activity is inferred. Sediment accretion rates were thus slow and episodic.

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APPENDIXES

APPENDIX A

LOCATION, MACROSCOPIC DESCRIPTIONS AND CLASSIFICATION OF CORNSTONES

General Statement

This appendix provides detailed megascopic descriptions of all the sampled cornstone profiles (Plate I). They have been classified into their Host formations and types or development stages of the zones in vertical profiles. The latter follows the classification scheme provided under the section on "types". Havens' (1977) map is the basis for classifying the sample locations into their hosts, but some of these have been modified based on field relations.

All the zones in a profile are numbered and described from the top of the base. These numbers also correspond to those shown on diagrams of measured sections.

HOST FORMATION: GARBER SANDSTONE

D-1-: SW Sec. 33, T1N, R16W; Comanche County

1. Gray, massive basal nodular cornstone conglomerate, 2-4 inches thick. Nodules are white and 0.1-0.5 inches in diameter. Grades upward into a coarse-grained, calcareous sandstone with a corresponding decrease in size and content of nodules. The layer is ledge-forming, 4-5 ft thick. Nodules represent type one cornstones.

2. Shale intermixed with white nodular cornstones; 4-5 inches thick. Nodules are white, oval in shape and content decreases downward. Horizon contains a thin layer of non-nodular shale, about 1" thick. Grades into a basal shaly layer with very few, white carbonate nodules.

D-2: SW SE Sec. 32, T1N, R16W; along Tillman-Comanche County Line.

1. Gray, massive, coarse-grained calcareous sandstone interbedded with shale. Contains a 4-10 inch thick nodular cornstone conglomerate. Nodules are white and <1.0" in diameter. The conglomerate thickens at the base of a channel-fill sandstone (Fig. 19). Nodules are type one cornstone.

2. White cornstone nodules, 0.2-0.5" in diameter, intermixed with a grayish shale. Are concentrated at the top and base of the channel-fill. Layer is about 4" thick.

3. Interbedded grayish mudstone and small-scale crossbedded fine-grained sandstone.

E-1-: SW SW Sec. 14, T1S, R15W; Tillman County (Fig.20).

1. Massive, coarse-grained, brownish-yellow calcareous sandstone. Immediately grades into a basal cornstone conglomerate; 4-10" thick, containing irregular, yellow-brown nodules, <1.0" in diameter. Nodules are dolomitic and contain several black dendritic pyrolusite streaks.

2. Zone of greenish-yellow shale mixed with nodules similar to those in the overlying conglomerate. Veins or fractures in the nodules are infilled with barite. Nodules represent type 2 cornstones.

3. Fine-grained grayish sandstone. Contains small-scale cross-bedding.

E-3-: SW SE Sec. 15, T1S, R15W; Tillman County (Fig.21).

Coarse-grained, yellowish-brown sandstone marks the top of the profile. Contains a basal nodular cornstone conglomerate, 2-3" thick, underlain by alternating zones of nodules and greenish clays. The nodules (including those in the conglomerate) are generally <5" in diameter and are compositionally and characteristically similar to those of profile E-1. Voids are infilled by secondary carbonate and powdery white barite. The profile is about 3 ft 6 inches thick. Type 2 cornstone.

G-1-: SE SE Sec. 35, T1N, R14W; Comanche County.

Reddish, brecciated and nodular cornstones scattered on the ground surface. Slightly vuggy; some of which are infilled with secondary calcite, others by a reddish clay. Type 2 cornstone.

G-2-: NE Sec. 26, T1N, R14W; Comanche County.

This profile consists of two main zones (Figs. 18, 22-24):

1. Irregular to botryoidal nodules, 0.2-5" in diameter. Reddish-brown, with greenish mottles. Vuggy interior, partially filled with clear and dark-gray secondary calcite. Equivalent to type 3 cornstones.

2. Reddish, fine-grained, thinly laminated channel sandstone. Also show small scale crossbedding. Few small calcareous nodules up to 1/2 inch in diameter are embedded between the laminae. To the south, this top horizon grades laterally into a laminated, grayish-green, very fine-grained sandstone.

   The base of this sandstone is a nodular cornstone conglomerate, 4-18" thick. It also contains a reddish clay. The conglomerate thickens at the base of a channel-fill. In places, it is intruded by thin channels of the overlying sandstone. Nodules represent type one cornstones.

   A non-nodular, reddish-purple shale underlies this horizon.

G-3 : NW, Sec. 35, T1N, R14W; Comanche County.

Reddish-brown carbonate nodules, 2-5" in diameter, scattered on slopes. Hollow and vuggy interior is infilled by clear to dark gray secondary calcite. Barite also occurs as a late vug-filling mineral. Type 3 cornstones.

G-4 : SW SE Sec. 30, T1S, R14W; Tillman County.

Irregular cornstone nodules, 0.5-2" in diameter. Overlie a red, fine-grained, thinly laminated calcareous sandstone. Some of the basal nodules are embedded in the sandstone. Nodules are reddish in color and contain bifurcating vugs which are connected to its outer part by dessication cracks. These are infilled by clear secondary calcite. Type 2 cornstones.

G-5 : SE SW Sec. 29, T1S, R15W; Tillman County.

Mainly a basal nodular cornstone conglomerate which grades upward into a reddish, fine-grained, crossbedded sandstone. In places, channels of this sandstone, 1-2" thick, intrude into the conglomerate.

The nodules are 1-2 1/2" in diameter, and grayish-green to reddish purple. Irregularly shaped and interior bifurcating vugs are partly to completely infilled with secondary calcite.

G-6 : NE NW Sec. 4, T2S, R16W; Tillman County.

Gray, fairly indurated and brecciated carbonate crust. Poorly laminated and slightly banded and contain several small infilled irregular voids. Type 4a cornstones.

V-1 : NE SE Sec. 4, T2S, R16W; Tillman County.

Brecciated and nodular dolomitic cornstone. Show variegated colors: reddish-brown with grayish-green blotches and greenish-gray with purple streaks. Contain small and large irregular voids which are completely to partially infilled with a reddish clay and some calcite and/or barite respectively. Walls of a few small vugs are coated with secondary calcite crystals. The large voids are probably a result of solution enlargement.

One of the nodular sample contains a clot of radiating, tabular barite crystals. Type 3 cornstones.

A thinly bedded, grayish-green, very fine-grained sandstone underlies the cornstone.

G-7 : SW SW Sec. 23, T1S, R16W; Tillman County.

Slope-forming, gray, brecciated, non-compact carbonate crust, about 2-1/2 ft thick. Most vugs are partially infilled with a clear crystalline secondary calcite and a later generation of friable white, greenish stained calcite. Type 2 cornstone.

Purple mudstone underlies this horizon and grades downward into a reddish-brown clay. The latter is further underlain by a very fine-grained, grayish-green sandstone.

G-8-: NW NE Sec. 35, T1N, R17W; Comanche County.

1. Brecciated carbonate with variegated reddish-brown color and mottled gray and grayish-green. Generally scattered on the ground surface. Both the surface and interior are coated with white streaks of barite(?) Type 2 cornstones.

G-9-: NE NE Sec. 13, T1N, R17W; Comanche County.

The cornstones of this profile are generally red with mottles of green coloring and are coated with white streaks of barite(?). They are immediately associated with a greenish mudstone. Four main zones can be delineated (Figs. 5,8):

1. Brecciated carbonates, forming about 50% of the zone. About 1 ft thick. Type 3 cornstone.

2. Cylindrical and slightly inclined nodules intermixed with a reddish clay. Most of the nodules are horizontally inclined; others are variably inclined in a southwest to southeast direction. The layer is about 2.5 ft thick and the nodules make up 10-20% of the rock. Type 2 cornstones.

3. Thin zone of brecciated carbonate; about 6 inches thick. Compose about 50% of the rock. Type 3 cornstone.

4. Irregularly shaped, inclined cylindrical nodules intermixed with a red mudstone. Most of them slope to the southwest and form 10-20% of the rock. Type 2 cornstones.

I-3 : SW Sec. 21, T1N, R15W; Comanche County.

Gray carbonate crust, with a cracked appearance. Contains small, irregular and bifurcating vugs infilled with secondary calcite. Type 4 cornstone.

J-3 : NW NE Sec. 11, T1S, R15W; Tillman County.

Gray, brecciated nodular carbonate. The nodules are irregular, 2-3" in diameter, and contain small irregular vugs mostly filled with a greenish clay. Type 2 cornstones.

Y-1-: SW SW Sec. 9, T1S, R16W; Tillman County (Figs. 6, 7 & 16).

1B. Gray, brecciated and nodular and dolomitic cornstone. Most voids are partially to completely infilled with clear secondary calcite and a later generation of white, crumbly calcite.

1L. Massive, indurated, reddish gray, thinly laminated dolomitic cornstone. Laminae are gently undulating and truncating. At the top are tepee (pseudo-anticlinal) structures, 4-5" across. Interior voids are channel-like and are partially to completely infilled with a white and clear secondary calcite. Infilled hexagonal dessication cracks mark the base of this layer. Type 4a cornstone.

This zone (1B and 1L) has an overall thickness of 12-15" and is underlain by a reddish mudstone (Zone 2), about 21" thick.

3. Thin, reddish-gray, compact and finely laminated dolomitic cornstone. Ledge-forming and 2-4" thick. Horizontal voids (veins) contain a white and clear secondary calcite infilling. Walls of small irregular voids are coated with a clear calcite and also contain white, powdery calcite. The layer represents type 4a cornstones and is also underlain by a reddish mudstone.

HOST: HENNESSEY GROUP

H-1: SW SW Sec. 30, T1N, R16W; Comanche County.

Reddish, irregularly shaped calcite nodules (Horizon HN-1) of variable size (a few are up to 7" in diameter). Contain calcite- and clay-filled veins and vugs respectively. Overlie a grayish thin, poorly laminated dolomitic crust about 2" thick. Fractures are infilled with calcite. Type 4 cornstones.

H-2: 0.2 mile from H-1.

Reddish-brown, brecciated and finely laminated dolomitic cornstone. Interior voids are small,irregular and randomly distributed, and partly to completely infilled secondary calcite. Type 4a cornstones.

This horizon is respectively underlain by a purple mudstone and a purplish-red, fine-grained sandstone.

H-3: SE SE Sec. 15, T1S, R15W; Tillman County.

Gray, compact, slightly vuggy carbonate layer, 8-12" thick. Overlies a thin, grayish shale. The latter is underlain by a siltstone which grades downward into a grayish, fine-grained sandstone. Type 4 cornstones.

H-4-: SW NW Sec. 25, T1N, R17W; Comanche County.

1. Light gray to grayish-gray brecciated and nodular cornstone. Nodules are irregular, with red blotches and 2-3" in diameter. The interior contains some detrital quartz grains and the vugs are bifurcating with clear to white secondary calcite infilling. Barite also infills vugs in some of the nodules. Type 3 cornstones.

2. Fine- to medium-scaled laminated grayish-red cornstone, 3-6" thick. Respectively underlain by a reddish-gray mudstone and very fine-grained sandstone.

   The carbonate contains two systems of voids: Small, irregular and horizontal interior vugs mostly infilled with a red clay; vertical shrinkage cracks pinch upward into the carbonate. These are infilled by secondary calcite.

   This horizon represents type 4a cornstones.

H-5-: NW NE Sec. 25, T1N, R17W; Comanche County (Fig. 12).

1. Reddish-brown, compact, poorly laminated carbonate, 1-2" thick. Slightly vuggy with secondary calcite infilling. Contains dessication cracks at the base. A thin, nodular crust forms on the top surface with some nodular pedestals protruding upward. These nodules are <0.5" in diameter. Type 4a cornstones.

This horizon is underlain by a red mudstone (Zone 2) about 2 ft thick.

3. Greenish-gray mudstone containing small, white carbonate nodules, <0.3" in diameter. The nodules are type 1 cornstones. This layer is about 1.5 ft thick and is underlain by a red mudstone (Zone 4) about 1 ft thick.

5. Irregularly shaped nodules, 3-4" in diameter. Vugs are irregular and most are infilled with a red clay; few of them contain secondary calcite. This zone is about 2 ft thick and is underlain by a reddish mudstone, (Zone 6) about 1 ft thick. These nodules are type 3 cornstones.

7. Gray, massive, poorly laminated and banded cornstone. Bands are green and red. Shrinkage cracks are widespread at the top and basal surfaces. Secondary calcite infills interior vugs and veins. This zone is 6-8" thick and represents type 4a cornstones. It is underlain by a dark grayish-green mudstone (Zone 8).

H-6-: NW NW Sec. 29, T1N, R16W; Comanche County.

1. The horizon consists of pale red nodular and light gray brecciated cornstones. The nodules are irregular, 1-1/2-3" in diameter and contain alternating bands of pale red and light greenish colors. Bifurcating shrinkage cracks with secondary calcite infilling are common. Some small irregular vugs contain a reddish mudstone. Meanwhile, few vugs in the brecciated carbonates are infilled with a white crumbly calcite. Type 2 cornstones.

2. Banded carbonate horizon, 2-3" thick. A light greenish-gray band, 1/2-3/4" thick overlies a pale reddish band. The latter contains light green blotches. Interior vugs are irregular and infilled with some secondary calcite and a reddish clay. Type 4a cornstone.

H-7-: NW NW Sec. 8, T1N, R16W; Comanche County.

Moderate red, brecciated and concretionary carbonate, 2-3" in diameter, intermixed with a reddish mudstone. Contains irregular vugs, infilled with clear secondary calcite. Type 3 cornstones.

H-8-: NE NE Sec. 4, T1N, R16W, Comanche County (Figs. 13-15).

1. Light greenish-gray brecciated and nodular carbonate. Overlies a reddish mudstone (Zone 2). Type 2 cornstones.

3. Pale red, massive carbonate with pisolitic structures. Is also internally brecciated. Interior vugs are irregular and bifurcating and are infilled with a red and green clay as well as a clear secondary calcite.

Grades downward into a massive, pale red, discontinuous carbonate zone (Zone 4) consisting of vertical pillars. The interior also contains a few pisolitic structures and the vugs are irregular with a secondary calcite infilling. The layer is also brecciated and the vugs at the base contain a red clay. Both zones are type 4a cornstones.

5. Thin greenish and red mudstone band about 5-7" thick. Overlies a zone (Zone 6) consisting of a red mudstone hosting irregular to botryoidal reddish-brown nodules. Vugs within the nodules are bifurcating and partially to completely infilled with clear to white secondary calcite scalenohedrons and a red clay. Nodules are type 3 cornstones.

R-1-: Sec. 7 & 8, T5N, R18W; Kiowa County

Two thin, grayish and chalky carbonate layers separated by a red and green mudstone about 6" thick. The top carbonate crust (about 2" thick) has a hackly and cracked appearance, while the lower one (<1" thick) is fairly compact. Type 4 cornstones.

This zone grades (in descending order) into a red mudstone (4-6" thick) with light greenish blotches and a dense, compact, reddish clay (about 4" thick).

A compact reddish clay (4-5 ft thick) and a green, thinly laminated, fissile calcareous shale (6-8" thick) overlie the cornstone profile.

X-2-: SE SE Sec. 31, T1N, R16W; along Comanche-Tillman County Line.

1. Reddish nodular dolomite and clays. The nodules are 1-5" in diameter and the interior is mottled green and vuggy. The vugs are irregular, some of which are infilled with a white powdery barite and red clay. This greenish interior consists mainly of detrital quartz grains and carbonate while the outer reddish part consists of a red clay and carbonate. Thiz zone is about 2 ft thick. Type 3 cornstones.

2. Reddish mudstone; contains few cornstone nodules at the upper section. The contact with the overlying nodular horizon is gradational.

X-3-: SW SW Sec. 31, T1N, R16W; along Comanche-Tillman County Line.

Reddish cornstone nodules and mudstone. Interior vugs are mostly infilled with a red clay and are partially coated with clear secondary calcite and some barite. Type 2 cornstones.

The profile overlies a grayish-green, fine-grained sandstone.

HOST FORMATION: POST OAK

P-1: SE SE Sec. 21, T2N, R13W; Comanche County.

Reddish, irregular cornstone nodules with botryoidal terminations; 5-8" in diameter. Interior vugs are bifurcating and partly to completely infilled with clear to white secondary calcite scalenohedrons and a red clay. Type 3 cornstones.

This nodular zone is underlain by an indurated or carbonate impregnated horizon (3-5" thick) which grades downward into a fine-grained, arkosic sandstone.

P-2: SW Sec. 20, T2N, R14W; Comanche County.

Reddish-brown, irregular carbonate nodules, 2-3" in diameter. Contain small, irregular vugs infilled with a red and light-green clay and secondary calcite. Exterior of nodules are coated with grains of quartz and orthoclase. These nodules overlie a medium-grained arkose. They represent type 2 cornstones.

P-3-: SW SE Sec. 23, T2N, R15W; Comanche County.

1. Zone of irregular to botryoidal carbonate nodules, 1-3" in diameter. Interior vugs are hexagonal and bifurcating with a secondary calcite infilling. Type 3 cornstones.

2. A very thin, white, discontinuous, porous and friable carbonate, about 0.2" thick. Generally overlie thick, medium-grained, massively crossbedded arkosic sandstone. The contacts are erosional.

P-4-: SE NE Sec. 10, T1N, R15W; Comanche County.

1. Small, red and gray nodular and brecciated carbonates. Vugs are bifurcating and irregular and with clear secondary carbonate and red clay infilling. Some nodules contain pisolitic structures. Quartz and orthoclase grains are present within and on the exterior surfaces of the cornstones. Type 2 cornstones and overlie a:

2. Gray, indurated, sandy carbonate layer, 4-5" thick which grades downward into a coarse-grained arkose. Voids are filled with fine sand grains. Amount of carbonate in the layer increases upward.

P-5-: NE SE Sec. 35, T2N, R14W; Comanche County

1. Red, irregular to botryoidal nodules, 2-4" in diameter. Their interior contains several bifurcating shrinkage cracks. Most are completely infilled with a clear to green calcite and some red clay. Others are partly lined with isopachous calcite crystals. Type 2 cornstones and overlie a:

2. Gray carbonate crust, 8-10" thick. The latter grades downward into a coarse-grained, crossbedded, arkosic sandstone. Contact with the sandstone is gradational.

I-1-: NE SE Sec. 3, T1N, R15W; Comanche County.

Profile consists of three zones (Figs. 9&11):

1. Non-compact zone consisting of irregular to botryoidal cornstone nodules; 0.5-7" in diameter, intermixed with a greenish clay. Grades upward into smaller nodules. Interior voids are bifurcating and are partly to completely filled with secondary calcite and a greenish-red clay. Drusy calcite crystals line the walls of some voids. These nodules form over 50% of the zone, and their amount decreases downward. The zone is about 3 ft. thick. Type 3 cornstones.

2. A fairly compact, mixed red and green clay zone, about 2 ft thick. Contains few carbonate nodules (about 20%) at the top. Contact with the overlying zone is gradational. Type 2 cornstones.

3. Compact greenish clay, 1-1 1/2 ft thick. Overlies an arkosic conglomerate.

I-2: SE SE Sec. 22, T1N, R15W; Comanche County.

Slope forming, gray, blocky carbonate horizon. Contains small, bifurcating vugs filled with clear and crumbly secondary carbonate. A few voids contain a small amount of grayish clay with which the cornstones are associated. The exposed portion of this profile is over 4 ft thick and represents type 4 cornstones.

M-1: SE SE Sec. 31, T1N, R15W; along Tillman-Comanche County line. (Fig. 10).

A thin, grayish nodular cornstone conglomerate; grades upward into an arkosic conglomerate. Nodules are irregular and contain bifurcating vugs filled with secondary calcite. Pores between the nodules are filled with quartz, and potash feldspar grains and a greenish clay. The cornstone is 0.5-1 ft thick. The overlying arkosic conglomerate also contains green clays which also underlie the nodular conglomerate. Type one cornstones.

APPENDIX B

CHEMICAL ANALYSES OF LOWER PERMIAN CORNSTONES IN SOUTHWESTERN OKLAHOMA

HOST = GARBER

SAMPLE	SAMPLET	RESIDUE	MG	NA	K	SR	BA	MN	FE	CA	INSOL	MG/CA
D-1-1T	A	0.330	5597	142	97	224	2537	11940	1851	283582	0.670	0.0032
D-1-1B	B	0.161	8790	268	155	262	894	10310	2062	303933	0.839	0.0047
D-1-2	C	0.478	7299	881	546	316	2874	2586	3898	320881	0.522	0.0037
D-2-1T	D	0.651	4914	845	458	186	573	6877	6862	293696	0.349	0.0027
D-2-1B	E	0.483	4720	909	474	261	290	4836	3752	283365	0.517	0.0027
D-2-2	F	0.313	4658	146	553	182	364	2038	4607	315866	0.687	0.0024
E-1	G	0.416	66781	856	317	1404	1712	6935	6926	232877	0.584	0.0472
E-1-2N	H	0.211	113752	963	190	2915	2091	1838	4068	178073	0.789	0.1053
E-3N	I	0.345	14397	481	618	344	382	6183	19618	264122	0.655	0.0089
G-1	J	0.190	27160	296	241	957	2593	2222	1043	280864	0.810	0.0159
G-2-1	K	0.294	31160	382	425	588	1062	6445	1884	297450	0.706	0.0172
G-2-2C	L	0.380	6210	565	790	419	1855	4677	3113	330645	0.620	0.0031
G-2-2NC	M	0.184	7089	551	392	521	735	2206	1134	294118	0.816	0.0039
G-3	N	0.231	4779	481	410	267	1300	4291	2061	295839	0.769	0.0027
G-4	A	0.479	13340	144	288	720	1536	11132	2514	261036	0.521	0.0084
G-5C	B	0.253	6070	67	261	321	1941	4618	770	274431	0.747	0.0036
G-5NC	C	0.238	5348	72	269	328	1706	3281	1129	314960	0.762	0.0028
G-6	D	0.181	119658	647	452	360	855	2503	946	198413	0.819	0.0994
G-7	E	0.176	100120	686	485	388	728	5522	1487	197209	0.824	0.0837
G-8	F	0.253	107095	622	207	1473	602	2142	1573	174029	0.747	0.1014
G-9	G	0.291	117772	458	282	4372	705	2257	1897	198166	0.709	0.0979
I-3-1	G	0.051	4226	47	0	174	369	1159	843	316122	0.949	0.0022
J-3	H	0.341	7086	53	395	190	531	2200	10395	295903	0.659	0.0039
Y-1-1BN	I	0.357	115086	956	840	599	1011	6998	1991	202177	0.643	0.0938
Y-1-1L	J	0.274	104339	944	758	399	551	2273	2438	187328	0.726	0.0918
Y-1-3	K	0.241	112978	534	632	296	1054	2964	2009	193017	0.759	0.0965
Y-2	L	0.115	6864	322	215	169	395	6497	593	327684	0.885	0.0034
V-1N	M	0.289	112518	872	450	338	985	19409	2918	168776	0.711	0.1099
V-1B	N	0.684	122627	1060	1060	870	791	5854	2927	245253	0.316	0.0824

HOST = HENNESSEY

SAMPLE	SAMPLET	RESIDUE	MG	NA	K	SR	BA	MN	FE	CA	INSOL	MG/CA
H-1	O	0.197	93400	691	604	255	1245	6663	1663	195517	0.803	0.0787
HN-1N	P	0.148	6737	141	346	604	411	10035	1162	274648	0.852	0.0040
H-2	Q	0.280	88542	743	528	326	139	7222	2069	240278	0.720	0.0607
H-3	R	0.669	18505	227	1057	559	453	4381	20695	309668	0.331	0.0098
H-4-1	S	0.408	76000	625	802	439	2027	3801	1985	247466	0.592	0.0506
H-4-2	T	0.237	53700	819	550	446	1507	5046	2661	249017	0.763	0.0355
H-5-1	U	0.205	7830	283	465	962	566	4277	2044	286164	0.795	0.0045
H-5-3	V	0.322	12131	1143	516	317	369	1549	1696	287611	0.678	0.0069
H-5-6	W	0.281	7997	1022	779	278	1460	6745	2399	292072	0.719	0.0045
H-6-1	X	0.193	4511	285	508	198	248	2602	1487	289963	0.807	0.0026
H-6-2	Y	0.196	3794	255	485	386	684	3731	1461	291045	0.804	0.0021
H-7	Z	0.225	10065	32	129	394	194	1742	884	322581	0.775	0.0051
H-8-1	P	0.147	3429	0	12	240	352	1641	551	287221	0.853	0.0019
H-8-3	Q	0.189	3465	0	18	216	308	986	795	308261	0.811	0.0018
H-8-4T	R	0.206	3552	82	0	264	1008	1889	869	365239	0.794	0.0016
H-8-4B	S	0.128	3423	23	17	189	287	1319	625	306766	0.872	0.0018
H-8-6	T	0.165	2737	12	96	180	2096	1198	1066	314371	0.835	0.0014
R-1-1	U	0.393	135900	906	1301	157	659	2801	3377	184514	0.607	0.1214
X-2B	V	0.330	114900	739	739	1254	2388	5075	3619	167164	0.670	0.1133
X-2N	W	0.166	118400	1067	665	348	240	2878	2092	188249	0.834	0.1037
X-2-2	X	0.215	90446	650	369	1032	1656	3185	1210	221019	0.785	0.0675
X-3	Y	0.250	120000	673	467	673	1400	4600	4787	167333	0.750	0.1182
HOST = POST OAK												
P-1	A	0.162	3669	0	54	131	239	2566	1772	332637	0.838	0.0018
P-2	B	0.298	2151	121	228	192	214	1496	7842	349003	0.702	0.0010
P-3-1	C	0.264	4687	0	177	224	204	6522	11685	317935	0.736	0.0024
P-3-2	D	0.307	3117	14	209	216	289	51	5519	281385	0.693	0.0018
P-4-1	E	0.216	3699	0	108	172	383	2360	2117	318878	0.784	0.0019
P-4-2	F	0.366	3825	32	213	118	315	2524	4416	323344	0.634	0.0019
P-5	G	0.150	3894	0	41	129	294	5294	1735	334118	0.850	0.0019
I-1-1T	H	0.170	5771	301	108	253	181	3313	2982	301205	0.830	0.0031
I-1-1B	I	0.138	5568	186	99	273	232	1450	2517	317285	0.862	0.0029

I-1-2	J	0.194	5881	81	136	267	1365	4777	2636	316377	0,806	0,0031
I-1-3	K	0.182	5471	238	171	275	245	1773	3564	320905	0.818	0.0028
I-2-1	L	0.080	2174	0	22	82	109	1902	1120	285326	0.920	0.0012
M-1-1T	M	0.160	7914	228	174	354	360	7614	4526	299760	0.834	0.0043
M-1-1B	N	0.301	5458	64	64	150	358	3004	4470	343348	0.699	0.0026

APPENDIX C

FACTOR ANALYSES OF LOWER PERMIAN
CORNSTONES IN SOUTHWESTERN
OKLAHOMA

*FACTOR ANALYSIS OF LOWER PERMIAN CORNSTONES IN S W OKLAHOMA

ROTATION METHOD: VARIMAX

ROTATED FACTOR PATTERN HOST=GARBER

	FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
RESIDUE	-0.06366	-0.26536	0.05595	0.13067	0.18140
MG	0.90234	-0.21472	-0.07639	-0.00301	-0.13261
NA	0.41271	-0.28008	-0.00863	0.02721	0.02386
K	0.17397	-0.88315	-0.09567	-0.05688	0.10367
SR	0.33201	0.12910	0.07072	-0.14258	-0.01101
BA	-0.08359	0.06878	0.98478	0.04265	-0.10785
MN	0.05983	0.03844	0.04303	0.98416	0.01577
FE	-0.07467	-0.07837	-0.11167	0.01581	0.97601
CA	-0.95943	0.00683	0.05457	-0.07988	-0.00553

	1	2	3	4	5
EIGENVALUES	2.887297	1.964847	1.195600	1.032307	0.901547

PROPORTIONAL CONTRIBUTIONS TO COMMON VARIANCES BY ROTATED FACTORS

FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
2.065738	1.003981	1.010281	1.018414	1.026447

APPENDIX C (Continued)

*FACTOR ANALYSIS OF LOWER PERMIAN CORNSTONES IN S W OKLAHOMA

ROTATION METHOD: VARIMAX

ROTATED FACTOR PATTERN HOST=HENNESSEY

	FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
RESIDUE	0.06111	0.94485	0.08425	-0.00013	-0.04518
MG	0.93989	0.10220	0.14077	0.05763	-0.09514
NA	0.45761	0.09257	0.09083	0.13374	-0.00646
K	0.40486	0.59995	0.05331	0.21702	0.01509
SR	0.18467	0.10150	0.20556	0.14485	-0.94463
BA	0.17538	0.01299	0.96138	0.03633	-0.19537
MN	0.14241	0.07259	0.03566	0.97021	-0.13646
FE	-0.00522	0.96404	-0.06223	0.07213	-0.09340
CA	-0.91151	0.00186	-0.12248	-0.16569	0.18729
	1	2	3	4	5
EIGENVALUES	3.807217	1.898089	1.163950	0.883295	0.598819

PROPORTIONAL CONTRIBUTIONS TO COMMON VARIANCES BY ROTATED FACTORS

FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
2.176459	2.216813	1.024652	1.064560	1.004280

APPENDIX C (Continued)

*FACTOR ANALYSIS OF LOWER PERMIAN CORNSTONES IN S W OKLAHOMA

ROTATION METHOD: VARIMAX

ROTATED FACTOR PATTERN HOST=POST OAK

	FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
RESIDUE	-0.20576	0.89837	-0.12232	-0.03779	0.21610
MG	0.74357	-0.05292	0.48254	-0.20597	-0.02803
NA	0.97310	-0.02446	-0.03275	0.10601	-0.01289
K	0.26222	0.89775	-0.04848	-0.05397	-0.07976
SR	0.85428	0.13830	0.19802	-0.20283	-0.17817
BA	0.06160	0.02866	0.13538	-0.98533	0.02769
MN	0.13910	-0.06615	0.97156	-0.12982	0.03725
FE	-0.00146	0.61940	0.22393	0.15632	0.07394
CA	-0.08588	0.08402	0.03268	-0.02623	0.99122

	1	2	3	4	5
EIGENVALUES	2.899461	2.362165	1.323580	0.943377	0.879996

PROPORTIONAL CONTRIBUTIONS TO COMMON VARIANCES BY ROTATED FACTORS

FACTOR1	FACTOR2	FACTOR3	FACTOR4	FACTOR5
2.371238	2.031478	1.303919	1.112007	1.075899

*Factors less than 0.2 have been disregarded.

VITA

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