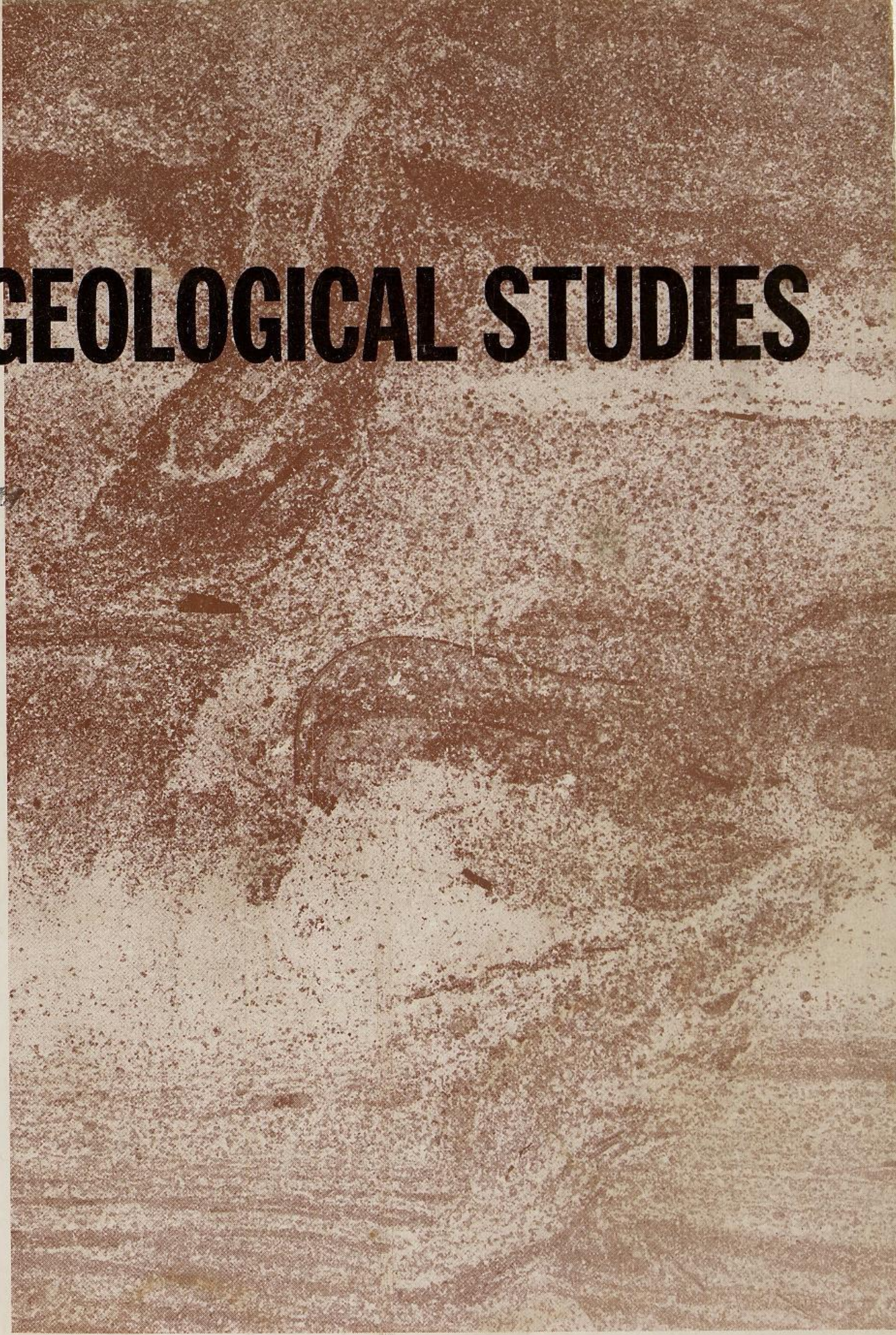
BAYLOR GEOLOGICAL STUDIES



SPRING 1963
Bulletin No. 4

BAYLOR UNIVERSITY – WACO, TEXAS
FOUNDED PRO ECCLESIA PRO TEXANA 1845

The Bluebonnet Member, Lake Waco Formation (Upper Cretaceous), Central Texas--A Lagoonal Deposit

BURR A. SILVER

"Creative thinking is more important than elaborate equipment--"

Frank Carney, Ph.D.
Professor of Geology
Baylor University
1929-1934

Objectives of Geological Training at Baylor

The training of a geologist in a university covers but a few years; his education continues throughout his active life. The purposes of training geologists at Baylor University are to provide a sound basis of understanding and to foster a truly geological point of view, both of which are essential for continued professional growth. The staff considers geology to be unique among sciences since it is primarily a field science. All geologic research including that done in laboratories must be firmly supported by field observations. The student is encouraged to develop an inquiring objective attitude and to examine critically all geological concepts and principles. The development of a mature and professional attitude toward geology and geological research is a principal concern of the department.

THE BAYLOR UNIVERSITY PRESS
WACO, TEXAS

BAYLOR GEOLOGICAL STUDIES

BULLETIN NO. 4

The Bluebonnet Member, Lake Waco Formation (Upper Cretaceous), Central Texas - - A Lagoonal Deposit

BURR A. SILVER

BAYLOR UNIVERSITY
Department of Geology
Waco, Texas
Spring, 1963

Baylor Geological Studies

The Baylor Geological Studies Bulletin is published semi-annually, Spring and Fall, by the Department of Geology at Baylor University. The Bulletin is specifically dedicated to the dissemination of geologic knowledge for the benefit of the people of Central Texas. The publication is designed to present the results of both pure and applied research which will ultimately be important in the economic and cultural growth of the Central Texas region.

Additional copies of this bulletin can be obtained from the Department of Geology, Baylor University, Waco, Texas. $1.00 postpaid.

CONTENTS

ILLUSTRATIONS

FIGURES | Page

PLATES

The Bluebonnet Member, Lake Waco Formation (Upper Cretaceous), Central Texas - - A Lagoonal Deposit

BURR A. SILVER

ABSTRACT

The geologic history of the Bluebonnet member, Lake Waco formation, Eagle Ford group (Upper Cretaceous) in central Texas is interpreted along the following lines of investigation: (1) distribution of clastic sediments, (2) depositional environments, (3) geochemical environments, (4) significance of microfaunal distribution, and (5) diagenetic effects.

The Bluebonnet depositional basin is confined to all or portions of Bell, Falls, McLennan, Limestone, and Hill counties, central Texas.

The Bluebonnet member consists of 10 to 20 feet of limestone, shale and bentonite beds. Three zones are recognized within the member, each based on lithology and microfaunal abundance. A zone is not necessarily time-equivalent throughout the area, but each represents a distinctive depositional environment.

Limestone beds (1-12 inches thick) grade upward from fine to medium-grained, well sorted, cross-bedded, ripple-marked *Inoceramus* biosparites to fine-grained, structureless Foraminifera biomicrites. Northward along the outcrop the lower limestone beds (zone 1) are *Inoceramus* biosparites in Bell and southern McLennan counties, Foraminifera biomicrites in central McLennan County, *Inoceramus* biosparites in northern McLennan County, biomicrites in southern Hill County and *Inoceramus* biosparites in central Hill County. Limestone beds in the middle and upper part of the member (zones 2 and 3) are biomicrites except in Bell and southwestern McLennan counties where locally *Inoceramus* biosparite beds occur in the middle part of the member.

Shale beds are gray to black, thinly laminated, calcareous and contain abundant planktonic foraminifers. No benthonic megafossils were observed in the shales. Shale beds are more thinly laminated in the middle part (zone 2) of the member than in the lower or upper parts (zones 1 and 3). Lamination is best developed in central McLennan and southern Hill counties. Shale is the dominant lithology in the upper two-thirds (zones 2 and 3) of the member.

Bentonite beds (⅛-10 inches thick) are more numerous and thicker in central McLennan and southern Hill counties. Bentonite beds contain calcium montmorillonite, kaolinite, sodium montomorillonite, and quartz, in relative order of abundance. Bentonite beds are commonly reworked and laterally discontinuous.

Planktonic foraminifers, *Hedbergella, Clavihedbergella,* as well as *Gümbelina,* increase in abundance upward in the shale beds. Foraminifera exceed 40,000 individuals per cubic centimeter of residue locally in central McLennan and central Hill counties. Numerous ammonites have been reported in the Bluebonnet member, and normally ammonites are restricted to limestone beds in the lower part of the member.

Mineralogy of the Bluebonnet member includes calcium montomorillonite, sodium montmorillonite, kaolinite, illite, gypsum, quartz, calcite, rhodochrosite, and carbon. Only calcium montmorillonite, kaolinite, calcite, and carbon were used for geochemical interpretations. Calcium montmorillonite reaches maximum abundance in Bell, southwestern McLennan and central Hill counties. The amount of kaolinite and carbon varies inversely with calcium montmorillonite content, whereas calcite varies directly with calcium montmorillonite content. Rhodochrosite is locally present in central McLennan and southern Hill counties.

It is concluded that the Bluebonnet member is a lagoonal deposit. Four stages of development are postulated—youth, late youth, early mature, and mature. The *youthful stage* was characterized by bay-mouth bar and inlets as suggested by subsurface and surface data. Field and petrographic data indicate cuspate and midbay bars which are characterized by limestone beds exhibiting high energy sedimentary structures, good sorting and sparry calcite cement. Values of pH were slightly alkaline and the Eh was probably positive or oxidizing.

Late youthful stage of the Bluebonnet lagoon was characterized by recession of the cuspate bar and midbay bar forming a secondary cuspate bar. Shale deposition was dominant in central and northern McLennan, and Hill counties. Marsh deposits occur in Hill County. Values of pH in the southern half of the lagoon were slightly alkaline, whereas in the northern part they were slightly acidic. Values of Eh were positive (oxidizing) near bar areas, but slightly negative (reducing) in the northern half of the lagoon.

Recession of the secondary cuspate bar and slight landward migration of the baymouth bar occurred during *early mature stage* of lagoonal development. Peripheral marsh deposits in the lagoon gradually constricted the basin. Values of pH in the basin were

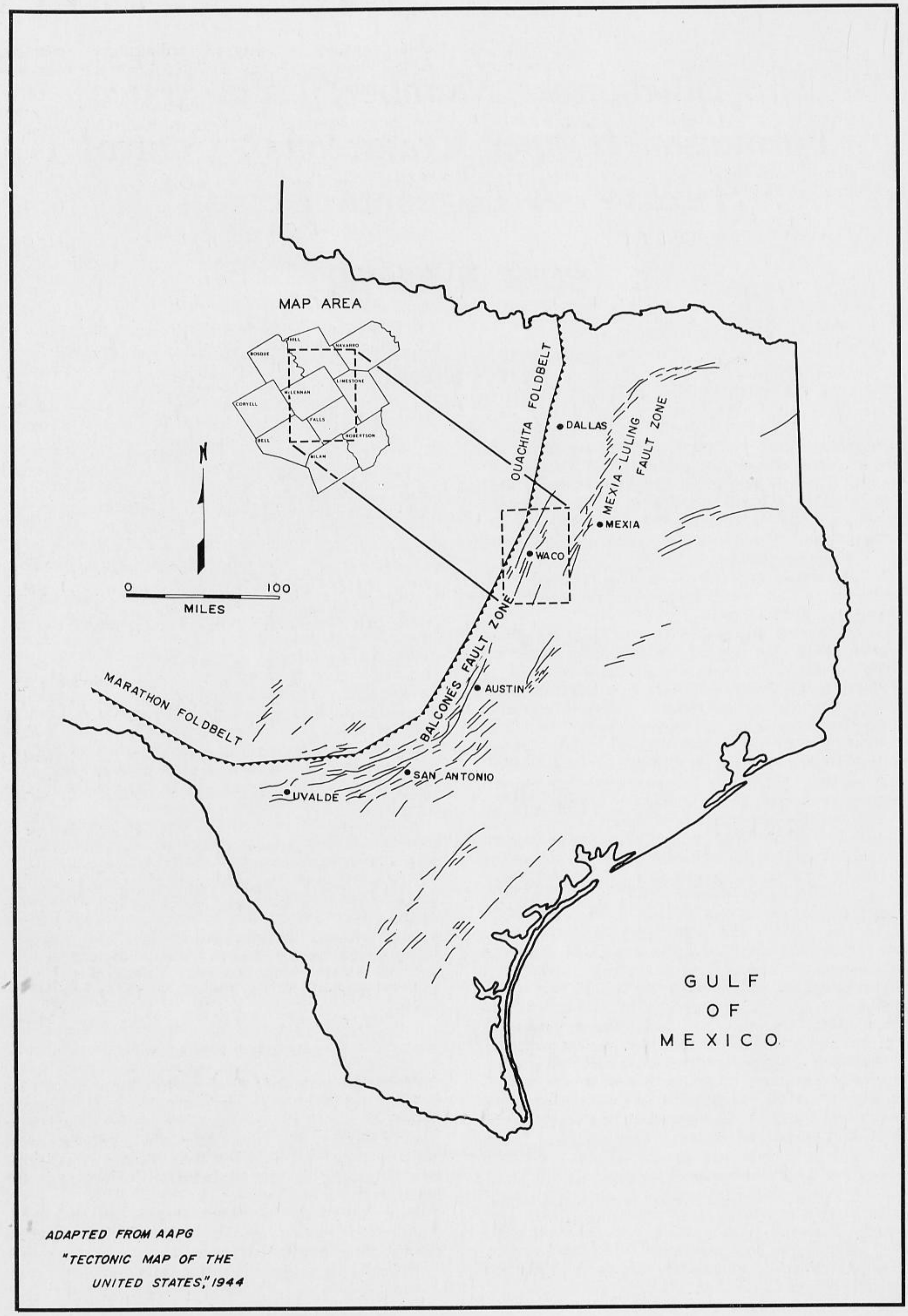


Fig. 1. Index map.

acidic, and Eh values were negative.

The Bluebonnet lagoon was filled by marsh deposits during the *mature stage* of development. Water in the lagoon was acidic; Eh was negative. Lagoonal sediments were covered and preserved by gray, thinly laminated shale deposits (Cloice member) of the transgressing sea.

Post-depositional processes exhibited in the Bluebonnet member include compaction, cementation and recrystallization. Compaction resulted in about a 45 percent decrease in original sedimentary thickness. Cementation of the bar-deposited limestone beds was due to primary precipitation of sparry calcite and later pressure solution. Recrystallization, a common diagenetic process in the member, nearly destroyed original depositional fabrics in the upper limestone beds; grain seeding and grain growth are two most prominent types of recrystallization.

INTRODUCTION[1]

PURPOSE

The Bluebonnet member of the Lake Waco formation (Upper Cretaceous) of central Texas has long been of interest to geologists because of complex lithologic relationships, sedimentary structures and paleontological variations which clearly distinguish it from other Upper Cretaceous rocks of the region.

Earlier work by Chamness (1958) and Silver (1959) considered the gross aspects of the member. Silver (*idem*) suggested that Bluebonnet sediments were deposited in a lagoonal environment, and further concluded that much of the original sediment of the postulated Bluebonnet lagoon is preserved along the present outcrop or immediately eastward in the subsurface.

The purpose of the present study was to extend the scope of the earlier investigations (*idem*) and to undertake other studies which might contribute to a more complete and accurate interpretation of Bluebonnet deposition.

This investigation considers the following major aspects in compiling and interpreting data pertaining to the geologic history of the Bluebonnet member: (1) gross configuration and lithology; (2) distribution and significance of clastic sediments; (3) significance of faunal variations; (4) postulated geochemical environments; (5) postulated sedimentary environments; and (6) diagenetic effects on the sediment.

LOCATION

The area of study includes portions of Bell, McLennan, Hill, Falls, and Limestone counties in central Texas (fig. 1).

PROCEDURES

A field study of the Bluebonnet member was completed including mapping, description, and collections for laboratory analyses. A review of the literature relating to the Bluebonnet member and lagoonal deposition was an early phase of the study. Laboratory procedures included peels and petrographic thin section studies of limestones, micropaleontological studies, mineralogic analyses by X-ray diffraction, carbon analyses, and carbonate analyses.

PREVIOUS WORK

The Eagle Ford group, which includes the Bluebonnet member, has been a formal stratigraphic unit for many years. Ferdinand Roemer (1852, p. 68) called the black Eagle Ford shales the "fish beds." In 1860, B. F. Schumard described rocks now assigned to the Eagle Ford group, following earlier studies by his brother, G. G. Schumard. B. F. Schumard applied the name "Marly Clay or Red River group" and placed the unit above the Woodbine formation, but he incorrectly considered it the base of the Cretaceous section. Marcou (1862) placed the "fish beds" of Roemer beneath the Austin chalk. J. A. Taff and S. Leverett (1893) first identified many of the Eagle Ford fossils. In 1887 R. T. Hill applied the name "Eagle Ford group" to this unit. In 1901 Hill more completely described the Eagle Ford group. Prather later (1902, p. 61) divided the Eagle Ford group into the South Bosque and Eagle Ford formations, but included within the latter, rocks now assigned to the Pepper formation.

Pace (1921) completed a reconnaissance geologic study of McLennan County. She considered the shale between the Buda formation and lowermost limestone beds of the Eagle Ford (Pepper formation) a part of the Eagle Ford group (*idem*, p. 4). Adkins (1923) mapped the Eagle Ford group in McLennan County, and later (1928; 1932, p. 434) identified fossils of the Eagle Ford, but he contributed little stratigraphic data.

Adkins and Lozo (1951, p. 120) divided the Eagle Ford into the South Bosque and Lake Waco formations. They further divided the Lake Waco formation into 3 members—Bouldin, Cloice and Bluebonnet in descending order. The type locality of the Bluebonnet member is

> ". . . along the Bosque escarpment from the old south Bosque brickyard southwest into the Moody Hills, then southward past Moody, McLennan County, Texas. The type section is opposite Bagget's Station [154-B-40[2]] east of State Highway 317, about 4.5 miles south-southwest of McGregor" (Adkins and Lozo, 1951, p. 120).

ACKNOWLEDGMENTS

Appreciation is extended to Professors O. T. Hayward, L. F. Brown, Jr., and Walter T. Huang, Department of Geology, and Professor James T. McAtee, Department of Chemistry, Baylor University, for guidance and special help during the project. Mr. Glenn McKinley, Skelly Oil Company, critically read the manuscript. The National Science Foundation sponsored the research during the summer of 1961. My wife, Linda, assisted in laboratory studies and preparation of manuscript.

[1]A thesis submitted in partial fulfillment of the requirements for the M.S. degree in Geology, Baylor University, 1963.

[2]Refer to locality on figure 2 and in Appendix II.

STRATIGRAPHY

REGIONAL GEOLOGY

The area of study (fig. 1) is near the interior boundary of the Gulf Coastal Plain of Texas. Quaternary and Cretaceous rocks crop out in the region; Quaternary rocks are unconsolidated stream deposits and Cretaceous strata consist of limestone, calcareous shale and poorly cemented sand.

The boundary between Lower and Upper Cretaceous rocks approximately coincides with the north-south trending Bosque escarpment, which also marks the western edge of the Balcones fault zone (fig. 1). In this area the Balcones fault zone is composed of down-to-the-coast normal faults of large displacement (>100 feet) and numerous smaller compensating faults. The Balcones fault zone cuts the outcropping Bluebonnet member at the surface in southern Bell, central McLennan, and central Hill counties (fig. 2). Cretaceous rocks strike northeastward, and dip southeastward; west of the Balcones fault zone Cretaceous rocks dip approximately 30 feet per mile, but east of the zone the dip increases to about 90 feet per mile. Cretaceous rocks thicken eastward into the Tyler basin.

Periodic transgression and regression of Cretaceous seas is indicated by several unconformities and sharp lithologic and faunal changes in the Cretaceous section. Lower Cretaceous rocks overlie Paleozoic strata in the western part of the area and truncated Jurassic (?) strata in the eastern part (Imlay, *in* McKee, *et al.*, 1956).

GENERAL DESCRIPTION

RELATIONSHIP TO ADJACENT UNITS

The Bluebonnet member unconformably overlies the Pepper shale in the southern half of the map area (fig. 2). The unconformity is indicated by (1) Bluebonnet limestone filling cracks in the top of the Pepper shale (Pl. VII, fig. A), (2) a thin layer of phosphate nodules and sharks teeth along the contact (Pl. V, fig. B), and (3) abrupt change in microfaunal aspect.

In northern McLennan and Hill counties, the Bluebonnet member overlies sand of the Woodbine formation. An unconformable contact is suggested by (1) sharp change in lithology, (2) thin layer of phosphate nodules and sharks teeth along the contact, and (3) distinctive faunal assemblages.

The Bluebonnet member appears to be gradational with the overlying Cloice member since there is no observable break in lithology or fauna.

GROSS LITHOLOGY

The Bluebonnet member averages 15 percent limestone, 80 percent shale and 5 percent bentonite.

Limestone beds are lenticular, black to gray, fine to medium-grained, cross-laminated, porous, fossiliferous, and weather gray to buff. They are more abundant in the lower half of the member; the limestones commonly grade upward through the Bluebonnet member from gray, medium-grained, cross-bedded, clear crystalline calcite-cemented, clastic limestone to dark gray, fine-grained, cross-laminated, chalky, foraminiferal limestone.

At numerous exposures limestone beds occur at similar stratigraphic positions (fig. 12). However, except for the basal limestone bed, the lenticularity of the other limestone beds is easily demonstrated since they can rarely be traced for more than 200 yards. The basal limestone bed is probably continuous in Bell and southern McLennan counties, but is absent in central McLennan County. A basal limestone bed of similar lithology is present in parts of northern McLennan and southern Hill counties.

Along the outcrop limestone beds compose approximately 50 percent of the Bluebonnet member in central Bell County, 15 percent in southwestern McLennan County, 12 percent in central McLennan County, 17 percent in northern McLennan County, 35 percent in southern Hill County and 15 percent in central Hill County (Appendix II).

Shale content in the Bluebonnet member increases northward. In central Bell County shale comprises approximately 45 percent of the Bluebonnet member, in southwestern McLennan County 75 percent, in central McLennan County 78 percent, in northern McLennan County 80 percent, in southern Hill County 85 percent, and in central Hill County 65 percent. The northward increase of shale occurs at the expense of limestone and bentonite.

Lateral changes in the amount of shale within the member also coincide with color changes in the shales. In Bell and southern McLennan counties, the shale beds of the Bluebonnet display vertical changes upward from gray to black to light gray; each color includes approximately one-third of the member. Lateral color changes occur which are similar to the vertical color variations; shale beds in southern Bell and McLennan counties are gray, whereas those in central McLennan County are black, grading into light gray shale beds in southern Hill County.

Bentonite beds of the Bluebonnet member are from ⅛ of an inch to 10 inches thick, and are most commonly composed of calcium montmorillonite. The thickest bentonite beds occur in the upper part of the member in southwestern and central McLennan County. In the map area bentonite beds increase in number and thickness northward to central McLennan County and then correspondingly decrease northward into Hill County. In Bell County bentonite comprises approximately 1 percent of the Bluebonnet member, in southwestern McLennan County 10 percent, in northern McLennan County 3 percent, and in Hill County less than 3 percent.

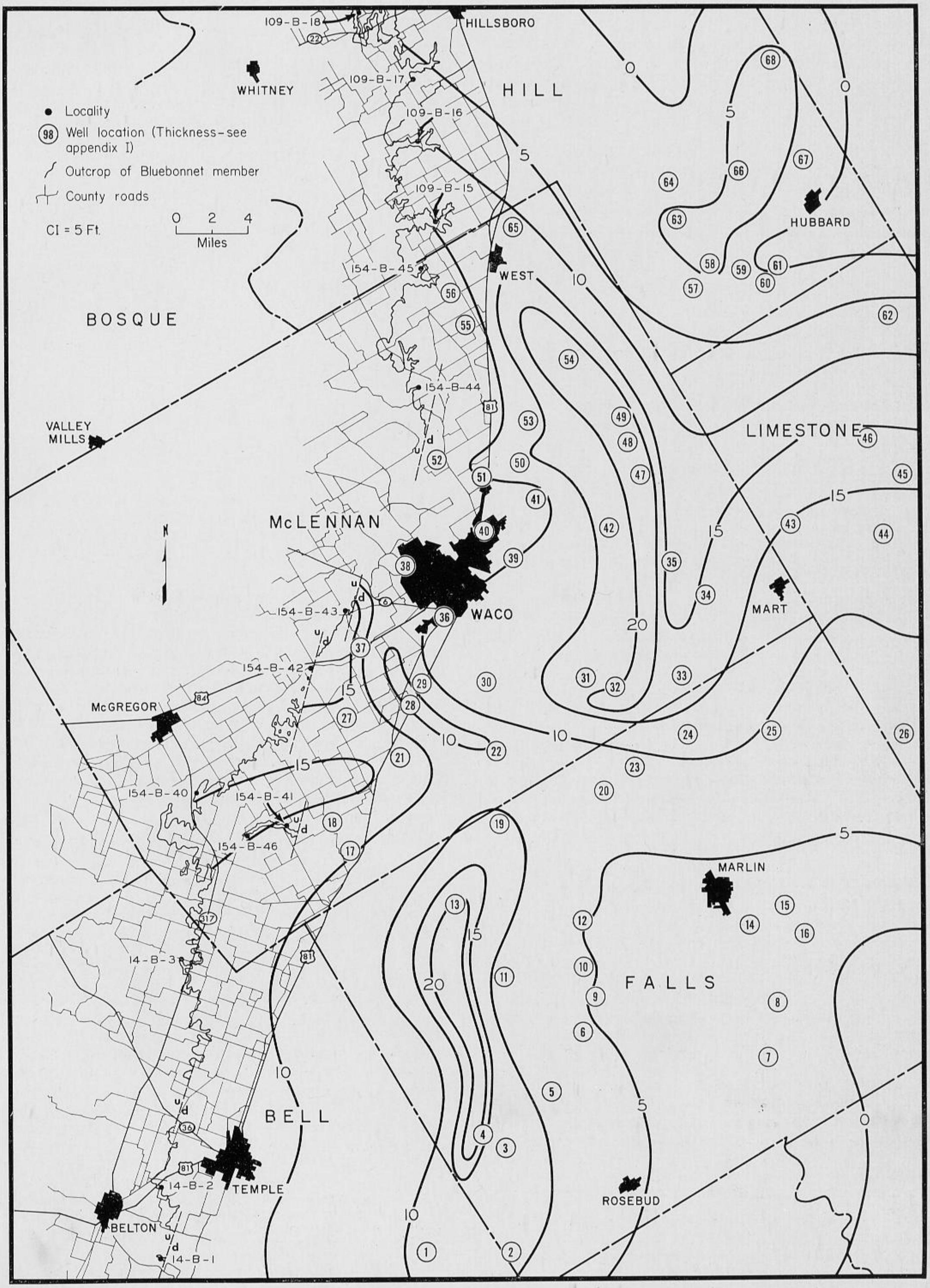


Fig. 2. Outcrop, isopach and locality map, Bluebonnet member, Lake Waco formation, central Texas.

ZONATION

Correlation of individual limestone and shale beds is not possible by either field or laboratory means. Similar lithologic sequences, however, occur throughout the area. The Bluebonnet member can tentatively be divided into 3 zones (fig. 12).

Zonation is based on lithology and microfaunal abundance. The lithology, mineralogic composition, and microfaunal population of 9 exposures of the Bluebonnet member are illustrated in figure 12. Each zone is bounded by limestone beds which are similar in thickness and almost identical in texture and mineralogy.

Shale beds in each zone are similar, including color and degree of lamination. Furthermore, shale beds in each zone have similar microfaunal abundance (fig. 12).

Zonation is not necessary to explain the environment of deposition, but it facilitates the study of vertical and lateral facies variations of the member.

A zone is not necessarily time-equivalent throughout the region, but at any locality the 3 superimposed zones represent deposition in succeeding environments. Sedimentation was most rapid near-shore in that part of the Bluebonnet basin in Bell, Coryell, and Hill counties. At any given time the shoreward perimeter of the Bluebonnet basin was being filled by prograding land-derived sediments, while lagoonal sedimentation was still in progress in the center of the basin. Therefore, the zones may be more nearly time-equivalent in an east-west direction than in a north-south direction.

SEDIMENTARY PETROLOGY

Mineralogic variations within the Bluebonnet member were determined by petrographic and X-ray diffraction methods.

LIMESTONE PETROLOGY

Polished and etched slabs, acetate peels and petrographic thin sections of limestones were studied to determine internal sedimentary features after the field relationships of the limestone beds had been determined. Types and amounts of clay minerals in each limestone bed were determined by X-ray diffraction. Petrographic terminology and concepts proposed by Folk (1959) and Bathurst (1958) are combined in a manner similar to that proposed by Stauffer (1962) in describing and interpreting carbonate thin sections.

Limestones at 2 exposures, in southwestern McLennan County (154-B-41) and in central McLennan County (154-B-43), are described to illustrate typical vertical variations. Limestone beds at other exposures are described in Appendix II, figures 3-11 and Plates I-IX.

Vertical Variations

Locality 154-B-41.—The lowermost Bluebonnet limestone bed in southwestern McLennan County (154-B-41, Pl. III, fig. B) is a 4-inch *Inoceramus* biosparite. Patches of micrite occur throughout the bed. However, larger grains in the micrite areas are in optical continuity. This suggests that the rock has undergone grain growth in diagenesis. Planktonic foraminifers are present but not abundant in this limestone. Some foraminiferal tests are filled with radiating calcite crystals, whereas tests of others are recrystallized in optical continuity with large sparry grains. Grain size and presence of abundant *Inoceramus* fragments indicate sustained, relatively high wave or current energy[3] in the depositional area.

The next overlying limestone bed (Pl. III, fig. C) is separated from the lower limestone by a 1-inch calcium montmorillonitic bentonite. This limestone bed is classified as a Foraminifera biosparite. The 6-inch bed is an alternating micrite-sparite sequence with sparite predominant in the lower half and micrite in the upper portion. This may indicate a change from relatively high energy deposition to low energy, since this is the last occurrence of a large amount of sparry calcite in this exposure. The upper 1 inch of the bed is cross-bedded micrite and sparite with foraminifers concentrated in the sparry cross-beds. Several burrows filled with crystalline calcite occur in this bed (Pl. IX, fig. E).

The third limestone bed from the base (Pl. III, fig. D) is the lowermost micrite. In the center of this 5-inch bed are several laminae composed of *Inoceramus* fragments cemented by sparry calcite. Thus, the bed grades upward from micrite to alternating laminae of sparite and micrite and back to micrite. An uneven, almost ripple-marked, micrite-sparite boundary occurs near the center of an acetate peel illustrated in Pl. III, fig. D. This bed contains the first occurrence of broken *Inoceramus* shells which do not show abrasion. This suggests lower mechanical energy than in either of the underlying limestone beds.

The upper limestone beds at locality 154-B-41 are classified as Foraminifera biomicrites. Bed 14 is the only bed which contains substantial amounts of laminated sparry calcite. Several laminae near the top of this bed are composed of *Inoceramus* prisms[4] cemented by sparry calcite. Each bed contains abundant discrete grains of hematite and magnetite. Many planktonic foraminiferal tests contain hematite grains.

Locality 154-B-43.—Bluebonnet limestones in central McLennan County are normally biomicrites. The lowermost limestone bed (154-B-43, Pl. V, fig. B) is an argillaceous fragmental limestone containing phosphate nodules and pyritized plant fragments. The overlying limestone (*idem*, fig. C) is a Foraminifera biomicrite which has undergone soft-sediment deformation (*e.g.*, Pl. IX, fig. F). Such structures as load-casting, contorted bedding, and flow structures are common. The

[3]Refers to mechanical energy, such as winnowing current, and/or wave action.

[4]*Inoceramus* prisms are disaggregated, wedge-shaped or needle-like, calcite crystals (pseudomorph after aragonite) which originally composed the inner layer of *Inoceramus* shells. Original aragonite crystals were oriented at right angles to the shell surface. The crystallographic C-axis is parallel to the long dimension of the crystals.

planktonic foraminifer *Hedbergella* is abundant in this bed; a few *Gümbelina* are present.

The remaining limestone beds (Pl. V, figs. D, E) contain no benthonic fauna. The ripple-marked texture and the presence of anhydrite are unique in limestone beds at this exposure.

Other localities.—Numerous limestone beds are laminated. Three possible origins of laminae are (1) periodic variations in mechanical energy (Pl. II, fig. A), (2) chemical variations in the depositional area which resulted in alternating orthochemical constituents (Pl. VIII, fig. B), and (3) influx of different kinds of clastic material (Pl. III, fig. C).

Another prominent feature of many limestone beds is a layer of fossil detritus embedded in a micrite matrix (Pl. IV, fig. D; Pl. VIII, fig. B). In most beds that exhibit this characteristic, the detrital fossil layer is approximately ½ to ¾ of an inch thick and bordering micro-crystalline calcite ranges from 2 to 4 inches thick. Fossil fragments appear to have been dumped into a lime mud area during a short period of increased agitation. In this case a micrite matrix does not necessarily indicate a low energy environment because *Inoceramus* fragments display abrasion (Pl. VI, fig. C).

Lateral Variations

It was concluded (p. 10) that limestone beds of the Bluebonnet member are not laterally continuous even though similar beds and similar sequences occur at several localities. However, it was noted (p. 8) that the basal limestone bed of the member is continuous over certain parts of the mapped area.

Southeast of Belton, Bell County (14-B-1), the basal limestone bed (Pl. I, fig. A) is a 7-inch thick Foraminifera biosparite which has undergone grain growth during diagenesis. It exhibits, therefore, the coarsest texture of any limestone of the Bluebonnet member. Recrystallization and grain growth occurred in 2 stages —parallel to bedding and approximately 30° to bedding. Recrystallization is evidenced by (1) patches of original micro-crystalline calcite, (2) optical continuity of larger grains, (3) gradational contact between coarse and fine grains, and (4) relic foraminifers composed of sparry calcite, which is in optical continuity with some of the surrounding grains. The relative sequence of recrystallization can be determined, since the second phase of grain growth (30° to bedding) truncates the phase parallel to bedding.

West of Temple, Bell County, approximately 4 miles north of the exposure described above, the basal limestone (14-B-2, Pl. I, fig. D) is composed predominantly of *Inoceramus* prisms cemented by sparry calcite. These prisms are widely dispersed, but where in contact, pressure solution has occurred. This may be a source of sparry cement and also suggests cementation after deep burial. The paucity of planktonic foraminifers in this limestone bed suggests that either depositional energy removed the tests, or that they simply were not abundant.

In northern Bell County (14-B-3, Pl. IX, fig. A) the basal limestone bed is a 4-inch thick biopelmicrite.

In southwestern McLennan County (154-B-46) the basal limestone bed (Pl. IX, fig. B) is 14 inches thick, the thickest bed of limestone observed in this study. This bed resembles the basal beds at two of the preceding localities (14-B-1, 2). Allochems (*Inoceramus* prisms) are more closely spaced, which may explain why pressure solution is common. Carbon content of the limestone bed is lower than at the preceding localities. Planktonic foraminifers are not abundant.

Approximately 2 miles east of the preceding locality (154-B-46), the basal limestone bed (154-B-41, Pl. III, fig. B) is 4 inches thick. This bed has previously been described (p. 10). A few foraminifers occur in the upper part of the bed. Hematite and magnetite occur as discrete grains; this is the southernmost occurrence of heavy minerals in the basal limestone bed.

About 4 miles south of McGregor, McLennan County, and 4 miles northwest of the previous locality, the basal limestone bed (154-B-40, Pl. II, fig. A) is a gradational micrite-sparite sequence. At this exposure the basal limestone bed is 4 inches thick. The bed is classified as a Foraminifera biomicrite-biosparite. Cross-laminae are well developed; the laminae are composed of *Inoceramus* fragments and foraminifers alternating with micro-crystalline calcite. The alternation of coarse and fine particles may represent an area between high and low energy.

Approximately 8 miles east-northeast of McGregor, McLennan County (154-B-42), the basal limestone is classified as a Foraminifera biomicrite. Very few allochems, with the exception of foraminifers, are embedded in the predominantly micro-crystalline calcite. Loadcasting, contorted bedding, and other soft-sediment deformation structures are common (Pl. IV, fig. B, and Pl. IX, fig. F). The bed was probably deposited in a sustained low energy environment as suggested by the fine-grained texture and distinctive sedimentary structures.

About 5 miles west-southwest of Waco the basal limestone bed (154-B-43, Pl. V, fig. C) is 6 inches thick and classified as a Foraminifera biomicrite. The abundance of foraminifers and heavy minerals compares closely with those of the preceding locality. The brackish-water foraminifer, *Gümbelina,* is abundant. Recrystallization of micro-crystalline calcite to microspar is common near the top of the bed.

Because of Balcones faulting the Bluebonnet member and most of the Eagle Ford group are absent at the surface for about 5 miles northeast of Waco, McLennan County. In northern McLennan County the basal bed (154-B-44, Pl. VI, fig. A) is a 6-inch thick *Inoceramus* biosparite. The predominant allochems are *Inoceramus* prisms and a few foraminifers. Hematite and quartz are more common than at the preceding locality. Higher energy (in comparison with the two previously described localities) is indicated by coarse grains, cross-bedding and ripple-marked upper surfaces. Patches of micrite matrix may have resulted from recrystallization during diagenesis, but in this case it is probably due to incomplete winnowing of finer particles by high energy currents.

Approximately 17 miles north of Waco the basal bed is similar to that near Waco (154-B-43). The basal bed (154-B-45, Pl. VII, fig. B) is a structureless biomicrite. A few allochems such as *Inoceramus* fragments and foraminiferal tests are embedded in micro-crystalline calcite. Fibrous calcite radiating from small grains of hematite is common near the top of the bed.

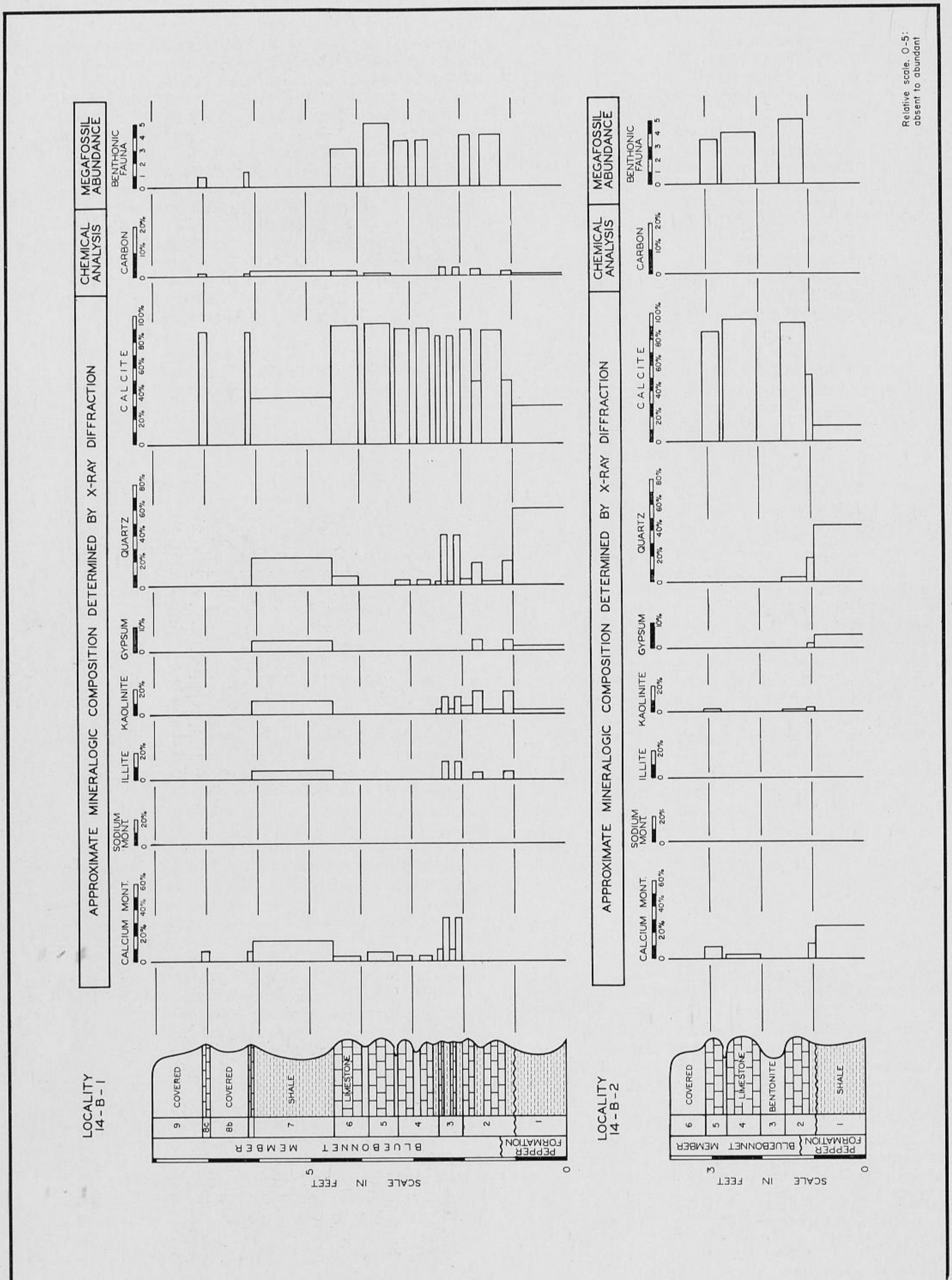


Fig. 3. Mineralogy and fauna, localities 14-B-1 and 14-B-2, Bluebonnet member, Lake Waco formation.

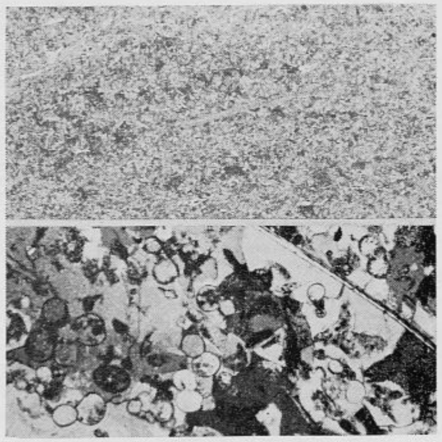


Fig. A. (14-B-1, unit 2) Foraminifera biosparite. Acetate peel, above; thin section, below. Large syntaxial calcite crystals in thin section are due to grain growth. *Hedbergella amabilis* abundant. (Peel x2; thin section x35, crossed nicols)

Fig. B. (14-B-1, unit 4) Biomicrosparite. Acetate peel. Recrystallization indicated by Foraminifera "ghosts," optical orientation of large grains, and patches of micro-crystalline calcite; shell material not recrystallized. (x1)

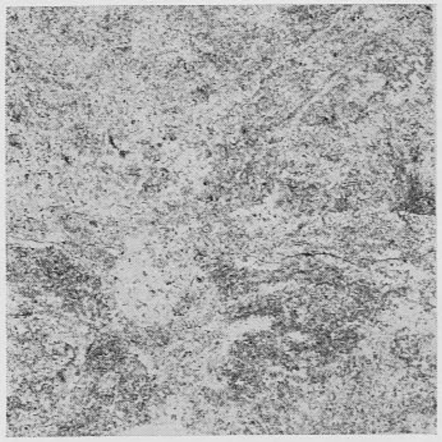


Fig. C. (14-B-1, unit 5) Biosparite. Acetate peel. Gray to black sparry calcite, white patches of micro-crystalline calcite. Calcite in Foraminifera tests is syntaxial with surrounding sparry calcite. Grain growth has destroyed bedding. (x1.5)

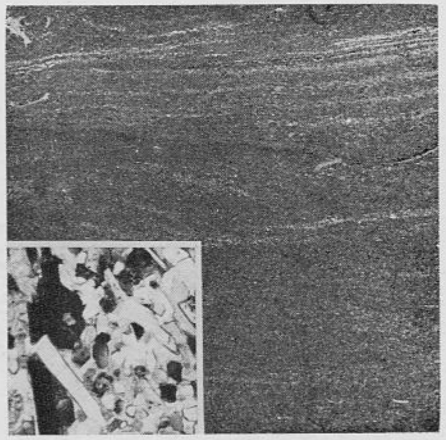


Fig. D. (14-B-2, unit 2) *Inoceramus* biosparite. Acetate peel and thin section insert. Dominant allochems are *Inoceramus* prisms cemented by sparry calcite. Thin section shows grain orientation and sparry cement. (Peel x.75; thin section insert x35, crossed nicols)

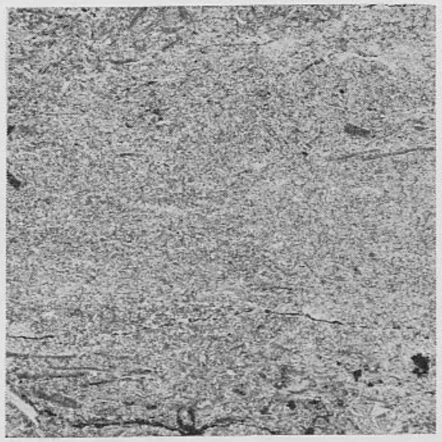


Fig. E. (14-B-2, unit 4) *Inoceramus* biosparite. Acetate peel. Same color scheme as Figure C. Bedding, coarse grains, and sparry cement indicate deposit of sustained, high energy environment. (x1.5)

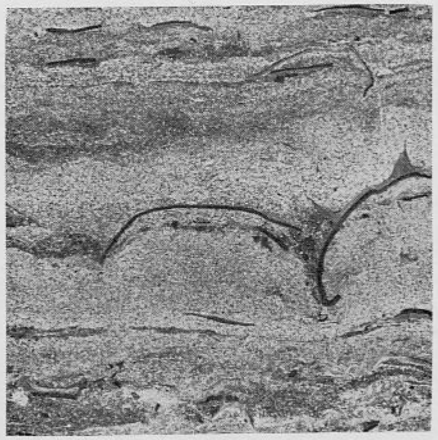


Fig. F. (14-B-2, unit 5) Foraminifera biomicrite. Acetate peel. Same color scheme as Figure C. Whole *Inoceramus* and micrite matrix indicate lower energy deposit than Figure E. (x.75)

Plate I. Micro-features, limestone beds, localities 14-B-1 and 14-B-2, Bluebonnet member, Lake Waco formation.

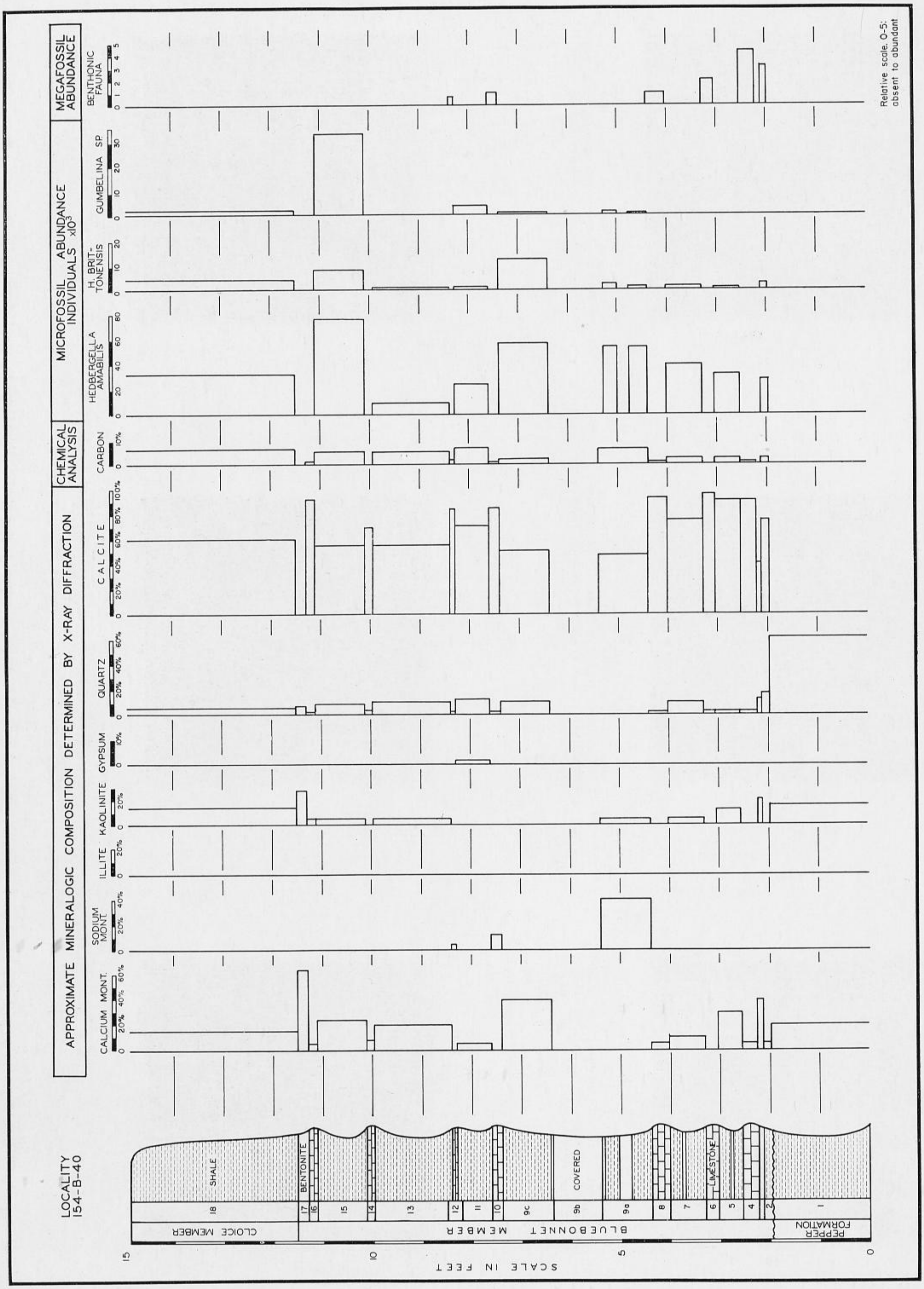


Fig. 4. Mineralogy and fauna, locality 154-B-40, Bluebonnet member, Lake Waco formation.

Fig. A. (154-B-40, unit 4) Foraminifera biomicrite-biosparite. Acetate peel. Light-gray cross-laminae are composed of Foraminifera and microcrystalline calcite; dark cross-laminae are composed of *Inoceramus* prisms and sparry cement. (x.75)

Fig. B. (154-B-40, unit 6) Biomicrite. Acetate peel. Light-gray cross-beds of concentrated Foraminifera. Cross-beds are thicker than in Figure A, suggesting more uniform energy environment. (x1)

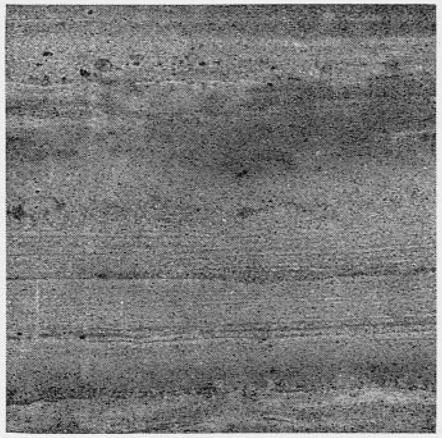


Fig. C. (154-B-40, unit 8) Foraminifera biomicrite. Acetate peel. Foraminifera have recrystallized without evident effects on remainder of rock. Contorted bedding near base. (x.5)

Fig. D. (154-B-40, unit 10) Foraminifera biomicrite. Acetate peel. Foraminifera not abundant and not recrystallized. Carbonaceous organic material and hematite concentrated near top. Note lenticular laminae. (x1)

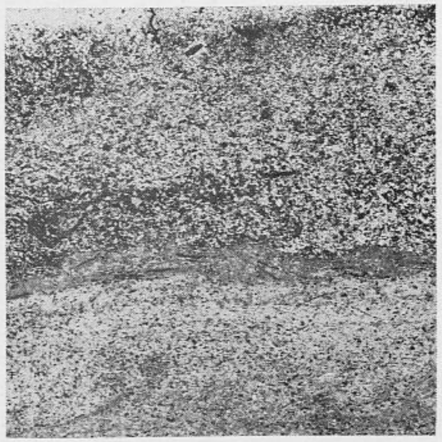


Fig. E. (154-B-40, unit 14) *Inoceramus* biomicrosparite. Acetate peel. Patches of microcrystalline calcite and recrystallized *Inoceramus* fragments suggest a recrystallized origin for microspar. (x1.5)

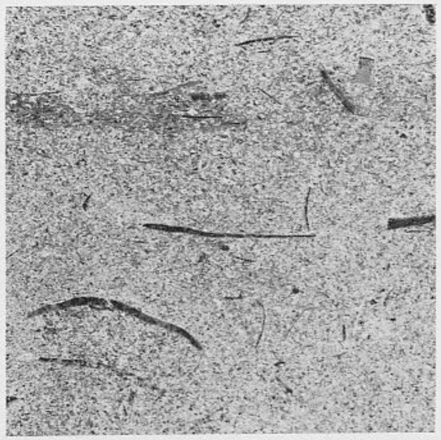


Fig. F. (154-B-40, unit 16) Biomicrite. Acetate peel. Large *Inoceramus* fragments recrystallized to calcite with no effect on remainder of rock. (x2)

Plate II. Micro-features, limestone beds, locality 154-B-40, Bluebonnet member, Lake Waco formation.

The hematite, which may have been glauconite concentrated in foraminiferal tests, may have seeded grain growth. Thus, the bed appears to be recrystallizing to microspar.

In south-central Hill County (109-B-15) the basal limestone bed (Pl. VII, fig. D) is a 7-inch Foraminifera biomicrite. Bedding planes are common but the limestone is predominantly homogeneous biomicrite. Selective recrystallization of *Inoceramus* fragments has occurred, but normally the bed appears to possess its original depositional fabric.

Approximately 24 miles north of Waco the basal limestone bed (109-B-16, Pl. VIII, fig. A) is a 4-inch *Inoceramus* biosparite. The bed contains a high concentration of moderately rounded detrital quartz which decreases upward from the base. Hematite and magnetite are common throughout the bed. The dominant allochems are closely packed *Inoceramus* prisms. Cross-bedding occurs near the top of the bed. Coarse grains and cross-bedding indicate high, sustained depositional energy.

In central Hill County (109-B-17) the basal limestone bed (Pl. VIII, fig. D) is an *Inoceramus* biosparite. The dominant allochems are *Inoceramus* prisms, whereas the dominant terrigenous constituent is quartz. The quartz is poorly rounded and fine-grained, and is texturally similar to Woodbine sand. The quartz contains overgrowths which appear to have been etched. This "etching" is probably due to incomplete overgrowth resulting from a relatively low pH environment during most of Bluebonnet time.

The northernmost exposure of the basal limestone bed is approximately 5 miles west of Hillsboro, Hill County. Here, the basal limestone bed (109-B-18, Pl. IX, fig. G) is an 8-inch thick biomicrite. Allochems are very large, including whole specimens of *Inoceramus*, ammonites and fish vertebrae. Most *Inoceramus* shells were probably macerated by shell-crushing animals rather than mechanical energy, since the *Inoceramus* fragments contained in a micrite matrix show no abrasion.

Lateral changes in the overlying limestones are more subtle than those of the basal bed. The upper limestones (zone 3) are absent in central Bell County (14-B-1, 2) and are best developed in McLennan County. The number of upper limestone beds decreases northward from Waco into Hill County. This variation is associated with a decrease in the amount of allochems and an increase in quartz and hematite content.

SHALE PETROLOGY

Shale beds were studied in terms of field relationships, mineralogic facies, and microfaunal population. Changes in color, shale-limestone ratios, and degree of lamination were observed in the field. In Bell and McLennan counties the color of shale beds changes upward from gray to black to light gray. Gray shale beds occur in zone 1 (fig. 12); black shale beds occur in zone 2; and a gradational color change from black to gray to light gray takes place in zone 3 of the Bluebonnet member. Light gray shales characterize the overlying Cloice member.

Northward along strike the shale beds grade from gray shales of southern Bell County to gray to black shales of northern Bell and McLennan counties, and finally to the light gray shales in Hill County. The black shales of northern Bell and McLennan counties contain abundant disseminated carbon, whereas the light gray shales, which weather tan in Hill County, have a ferrous iron pigment.

The northward increase in shale content in the Bluebonnet member is primarily caused by northward replacement of limestone beds by shale in the upper 2 zones of the member.

Most of the Bluebonnet shale is well laminated. Individual laminae decrease in thickness upward from zone 1 to zone 2, and become thicker and less distinct in zone 3. North along the outcrop from Bell to central McLennan County, laminae become thinner and more distinct. From central McLennan County northward, laminae increase in thickness and become less distinct.

The mineralogy of the shales was determined by X-ray diffraction and chemical analyses. Variations in clay, quartz, calcite, and carbon content were particularly useful in interpreting the depositional environment. Tabulated mineral data and procedures related to mineral analyses are described in Appendix III and V, respectively.

Calcium montmorillonite and kaolinite are the dominant clays of the Bluebonnet member; minor amounts of sodium montmorillonite and illite are present. Other constituents are gypsum, quartz, calcite, and carbon.

Vertical Mineralogic Variations

Calcium montmorillonite.—The Pepper shale at all localities, except southeast of Belton (14-B-1; fig. 3), contains a substantial amount of calcium montmorillonite, a greater percentage than normally occurs in the Bluebonnet member. At most localities calcium montmorillonite in the Bluebonnet member (fig. 12) increases upward, which may indicate a gradual change to normal marine conditions, or more likely, an increase in abundance of thin calcium montmorillonitic bentonite beds, which raises the average percent in the upper shales. Thicker bentonite beds in zone 1 were sampled individually. The calcium-sodium ratio of the calcium montmorillonite in the Bluebonnet member is approximately 4:1.

Sodium montmorillonite.—Sodium montmorillonite is a minor constituent in the Pepper shale, as well as in the Bluebonnet member. Sodium montmorillonite is present in the Bluebonnet member at only 6 of the localities studied. The calcium-sodium ratio of the dominant sodium montmorillonite in the Bluebonnet member is about 1:4. The presence of sodium montmorillonite may indicate near-shore deposition or a source area, which provided abundant calcium montmorillonite.

Illite.—The Pepper-Woodbine formation contains illite in southern Hill County (109-B-15-17; figs. 9-11). In this area the Bluebonnet member contains some illite in zone 1 (fig. 12), which may indicate that the Pepper-Woodbine formation was the clay source for the Bluebonnet member. If so, the small amount of quartz in the Bluebonnet member is interesting, since the Pepper and Woodbine formations each contain over 40 percent quartz. Illite occurs in the Bluebonnet member only where it occurs in the underlying Pepper-Woodbine formation.

Kaolinite.—At most localities similar amounts of kaolinite occur in the Pepper formation and in the Bluebonnet member. At 7 of 9 exposures illustrated in figure 12, kaolinite increases upward in the Bluebonnet member, possibly reflecting a decrease in pH during deposition. Flocculation rates may determine the site of kaolinite, illite, and montmorillonite deposition. However, flocculation is not considered a mechanism for clay mineral segregation in the Bluebonnet basin because, as will be developed later, (1) circulation was apparently poor, limiting means of transporting clastic clays, (2) Bluebonnet basin was small, reducing the effect of differential flocculation rates, and (3) the source of clastics must have been immediately west of the basin in Bosque, Coryell, and western Bell counties, yet no east-west lateral gradation of illite-kaolinite-montmorillonite was observed in the Bluebonnet member.

Gypsum.—In general gypsum content increases slightly upward in the Bluebonnet member. Gypsum is a weathering product. Crystals cutting shale laminae and a rather heterogeneous vertical variation indicate secondary occurrence.

Quartz.—Quartz is a major constituent in the Pepper-Woodbine formation, but it occurs in minor amounts in the basal part of the Bluebonnet member (fig. 12). Quartz normally increases upward in the Bluebonnet member except in central Hill County (109-B-17; fig. 11) where the quartz content is vertically uniform. This general upward increase may be due to more rapid erosion of Woodbine sand or a prograding shoreline during upper Bluebonnet time.

Calcite.—Calcite is absent in the Pepper shale, except at 2 localities near Belton, Bell County (14-B-1, 2; fig. 3). Calcite is the dominant carbonate in the Bluebonnet member (fig. 12); it gradually decreases upward, possibly reflecting decreasing pH during deposition which is also suggested by a corresponding increase in kaolinite content.

Carbon.—Carbon content increases upward in the Bluebonnet member (fig. 12) at most localities in Bell and McLennan counties; in Hill County carbon content decreases upward. Increasing carbon content may indicate decreasing Eh during deposition; this relationship suggests that the abundant hematite in the upper part of the Bluebonnet member is secondary after pyrite, since primary hematite normally would not be concentrated in a negative or reducing environment.

Lateral Mineralogic Variations

Calcium montmorillonite.—Calcium montmorillonite constitutes from 0 to 30 percent of the Pepper shale northward along the outcrop.

Laterally in zone 1 of the Bluebonnet member (fig. 12) the calcium montmorillonite content varies directly with the limestone content. No significant change occurs in zones 2, 3.

Sodium montmorillonite.—At only 2 localities, southwest of Waco, McLennan County (154-B-42; fig. 6) and in southern Hill County (109-B-15; fig. 9), sodium montmorillonite is present in the Pepper shale.

Sodium montmorillonite is a minor constituent in the Bluebonnet member (fig. 12). Sodium montmorillonite has been recognized at 5 localities in McLennan County (154-B-40-44; figs. 4-8) and 1 locality in Hill County (109-B-17; fig. 11). At 3 of these localities in McLennan County (154-B-40-42), sodium montmorillonite occurs at successively higher stratigraphic positions northward in zone 2. West-southwest of Waco (154-B-43; fig. 7), sodium montmorillonite occurs in zone 3. If this occurrence in zone 3 is time-equivalent with sodium montmorillonite of southwestern McLennan County in zone 2, it can be assumed that the zone 3 facies is progressively younger southwestward.

In central Hill County (109-B-17; fig. 11) sodium montmorillonite occurs in zone 1.

Kaolinite.—Kaolinite varies from 0 to 20 percent in the Pepper shale. Kaolinite increases northward along the outcrop to Waco, McLennan County, decreases slightly in south-central Hill County (109-B-16; fig. 10) and then increases substantially in central Hill County.

Kaolinite is the second most abundant clay in the Bluebonnet member (fig. 12). Kaolinite content varies inversely with the calcium montmorillonite content along the outcrop, which may reflect a pH control during deposition. This is further suggested by lateral variations in calcite in the Bluebonnet member.

Gypsum.—No uniform lateral variation in gypsum content was noted in the Pepper formation. Likewise, no significant distribution pattern in gypsum content occurs in the Bluebonnet member (fig. 12). Petrographic relationships suggest a secondary origin.

Quartz.—Quartz normally increases northward in the Pepper formation. An abrupt increase occurs in northern McLennan and southern Hill counties where sand of the Woodbine formation grades southward into shale of the Pepper formation.

Quartz composes from 5 to 15 percent of the Bluebonnet member (fig. 12). The most abrupt increase in quartz occurs in Hill County, where Pepper shale grades into Woodbine sand. This northward increase in quartz in the Bluebonnet member is relatively uniform throughout the section, indicating that Woodbine sand was exposed in the source area of the Bluebonnet sediments.

Calcite.—The Pepper shale contains some calcite at the two southernmost localities in Bell County (14-B-1, 2; fig. 3). In northern Bell and southern McLennan counties the Pepper shale is non-calcareous; however, it again becomes calcareous in northern McLennan and southern Hill counties as it grades into the Woodbine sand, which has calcite cement.

The amount of calcite in the shale beds of the Bluebonnet member commonly decreases northward in all 3 zones. In Bell County the Bluebonnet shales average 60 percent calcite, in McLennan County 55 percent, and in Hill County 50 percent. This northward decrease in calcite is indicative of a northward decrease in pH during deposition. This is further substantiated by a general northward decrease in calcium montmorillonite and an increase in kaolinite.

Carbon.—Carbon in zone 1 of the Bluebonnet member normally increases northward across the area from 1 to 20 percent (fig. 12).

In zone 2 carbon increases from 2 percent in Bell County to 10 percent in central McLennan County and decreases to 0 in southern Hill County (fig. 12). This same pattern is repeated in zone 3. The abnormally high carbon content in central Hill County (109-B-17; fig. 11) is due to the presence of coal beds in the section (Appendix II).

Summary

Vertical lithologic and mineralogic variations in the Bluebonnet shale beds include (1) vertical variations in iron content as denoted by a vertical color change from gray to black to light gray in zones 1, 2, and 3

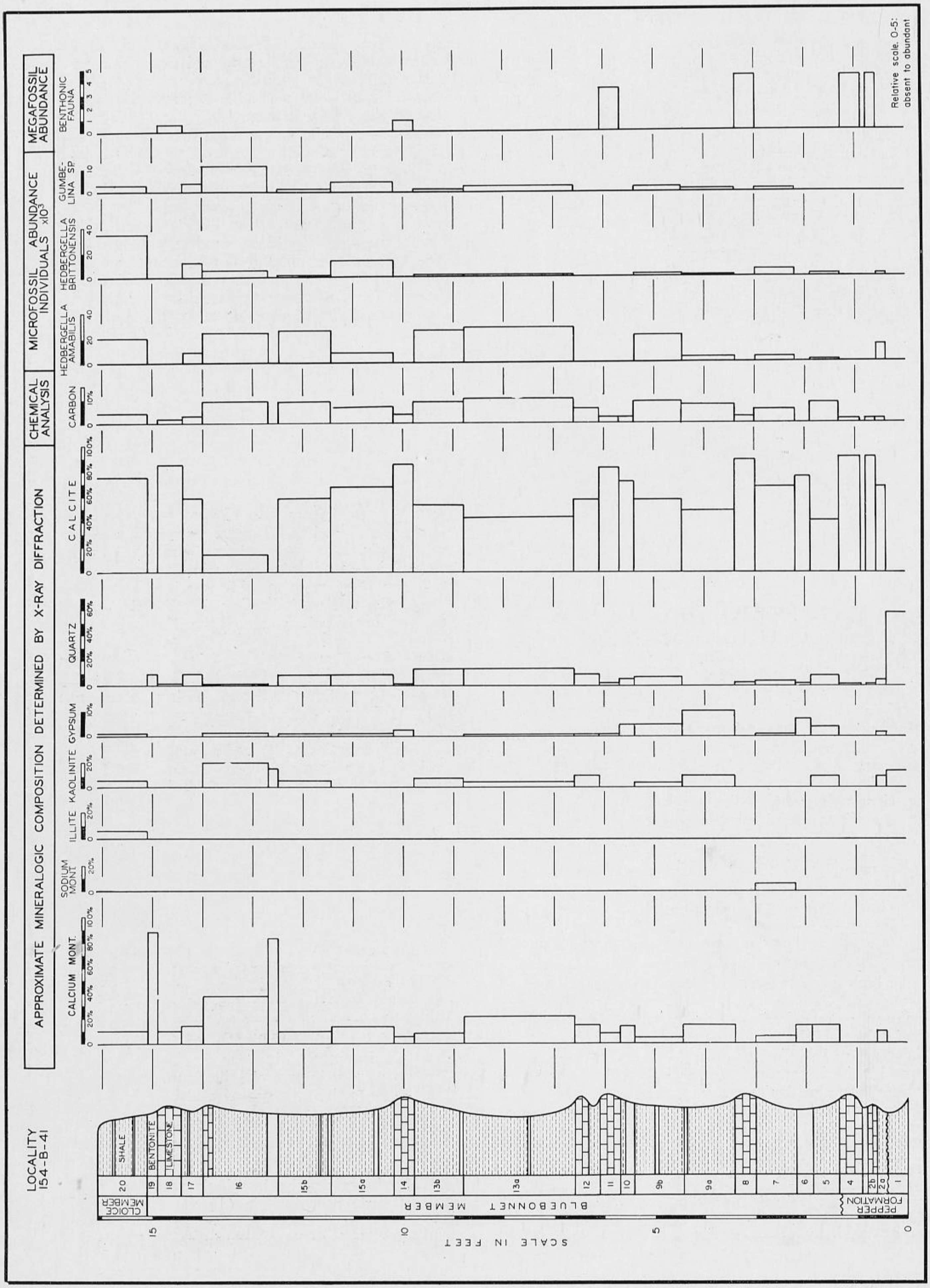


Fig. 5. Mineralogy and fauna, locality 154-B-41, Bluebonnet member, Lake Waco formation.

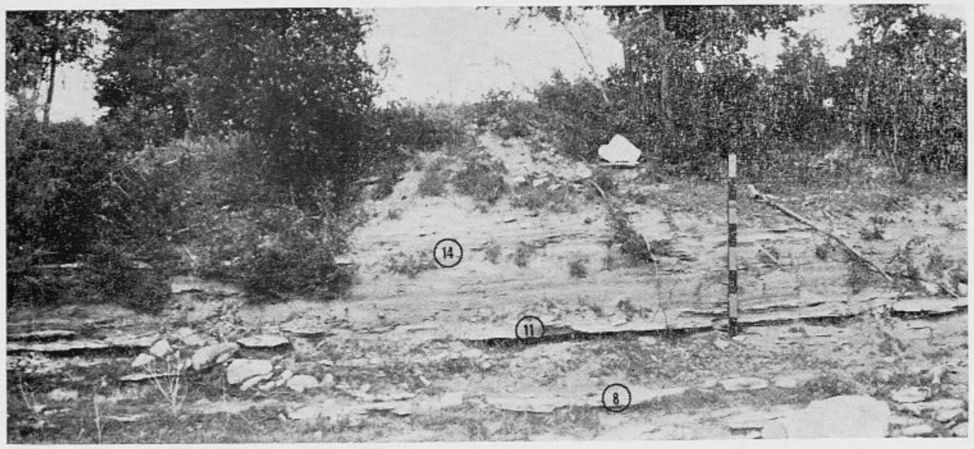


Fig. A. (154-B-41) Approximately 9 miles southeast of McGregor, McLennan County. Alternating limestone, shale and bentonite beds. Limestone beds are lenticular and normally less than 6 inches thick, shale beds average 3 feet thick, and bentonite beds are less than 4 inches thick. Numbers refer to described beds; scale unit is 1 foot.

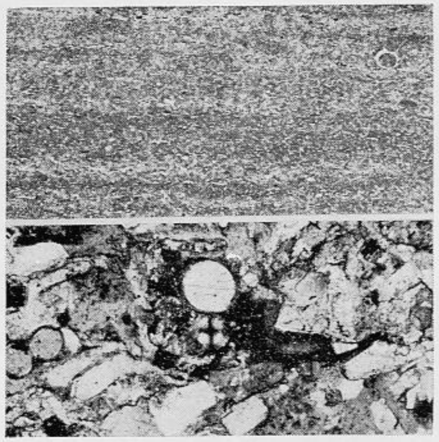


Fig. B. (154-B-41, unit 2b) *Inoceramus* biosparite. Acetate peel above; thin section below. Cross-extinction in one foraminifer indicates drusy calcite growth, whereas calcite tests of Foraminifera at extreme left are syntaxial with sparry cement. (Peel x2; thin section x90)

Fig. C. (154-B-41, unit 4) Foraminifera biomicrite-biosparite. Acetate peel. Cross-laminae at top are *Inoceramus* prisms and sparry cement. Contorted bedding occurs in areas of micrite and Foraminifera. (x.5)

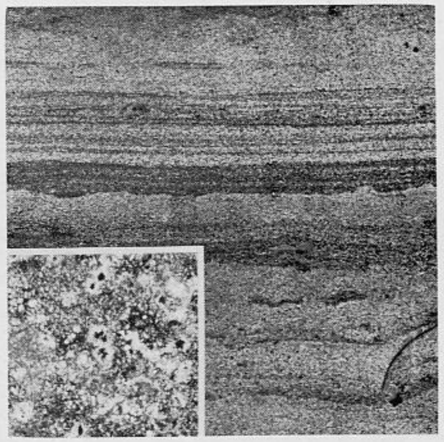


Fig. D. (154-B-41, unit 8) Biomicrite. Acetate peel and thin section insert. Note differential compaction in lower right peel and uneven contact of light and dark micrite near center. Thin section shows *Hedbergella* with hematite in center. (Peel x1; thin section x90)

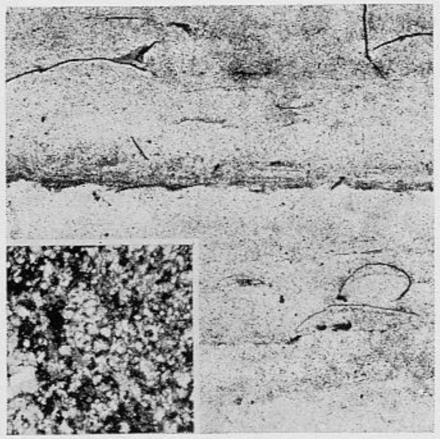


Fig. E. (154-B-41, unit 11) Foraminifera biomicrite. Acetate peel and thin section insert. Large *Inoceramus* fragments exhibit no abrasion; uneven, ripple-like surface near center of peel may be unconformity. Thin section shows microscopic texture. (Peel x1; thin section x90)

Plate III. Outcrop and micro-features of limestone beds, locality 154-B-41, Bluebonnet member, Lake Waco formation.

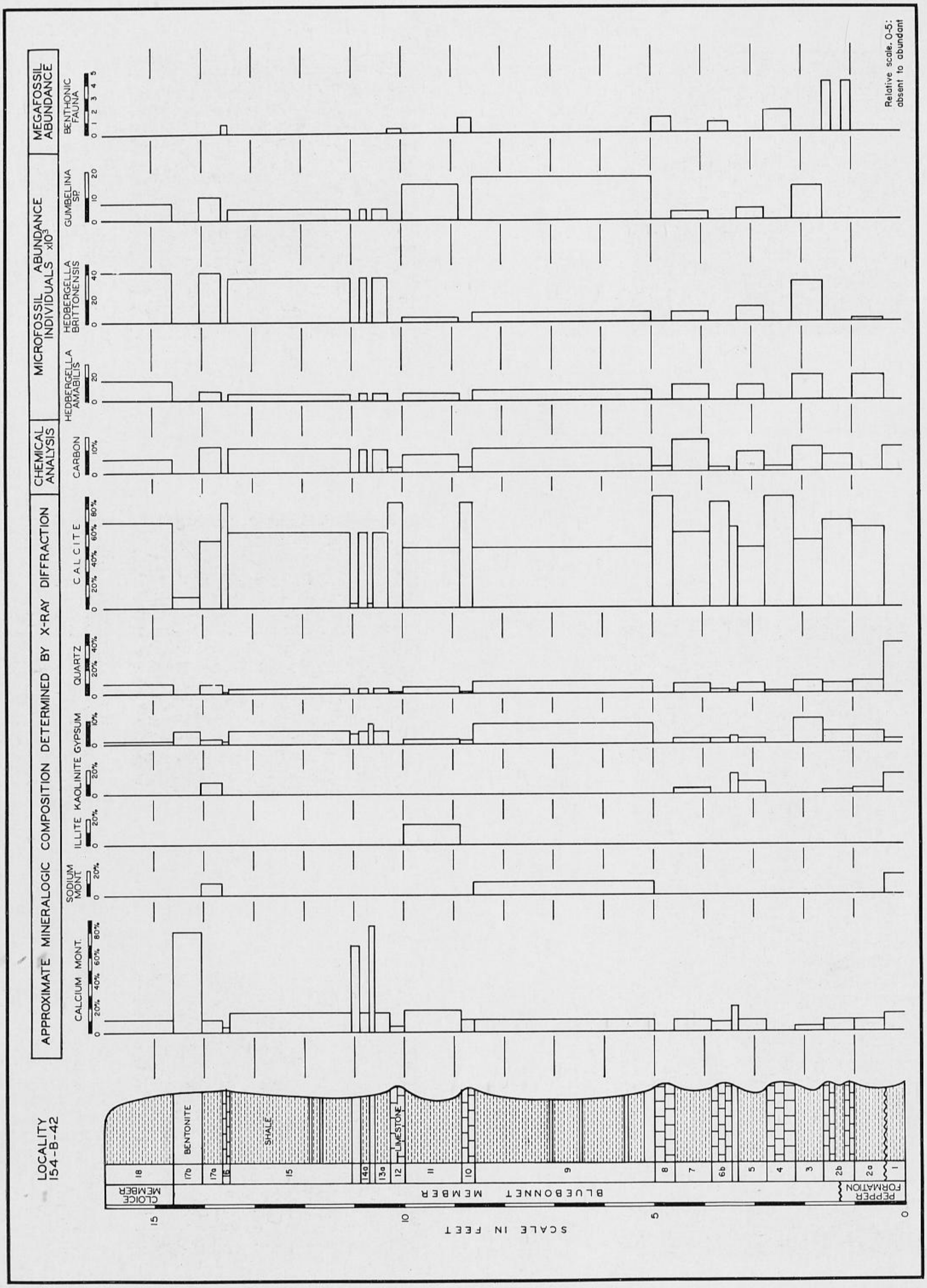


Fig. 6. Mineralogy and fauna, locality 154-B-42, Bluebonnet member, Lake Waco formation.

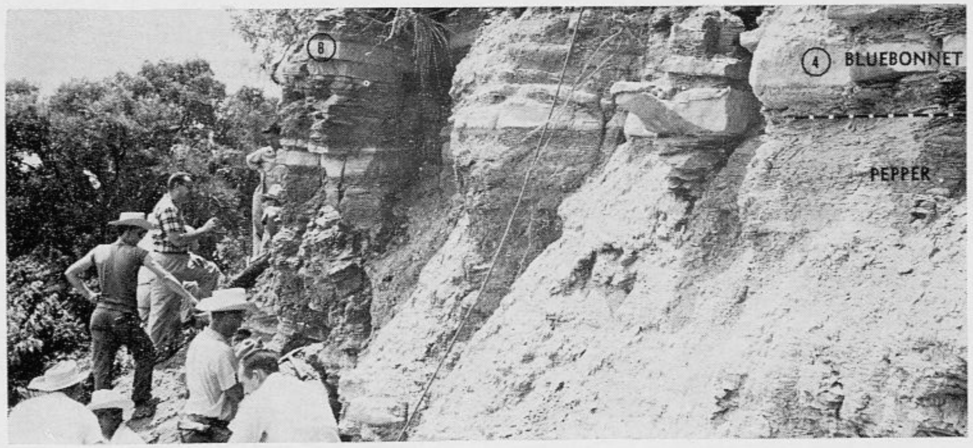


Fig. A. (154-B-42) Approximately 7 miles southwest of Waco, McLennan County. Alternating limestone and shale beds with bentonite beds most common near top. Underlying Pepper shale covered by the weathered debris. Numbers refer to described beds.

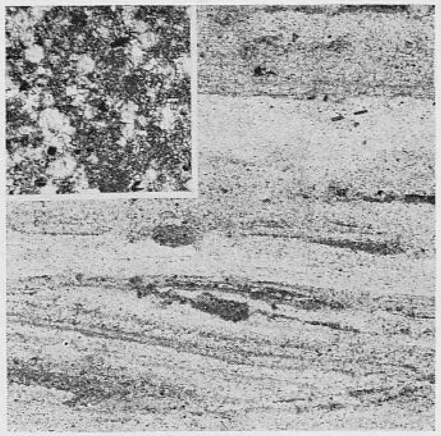


Fig. B. (154-B-42, unit 4) Foraminifera biomicrite. Acetate peel and thin section insert. Cross-laminae in peel same grain size as surrounding material. Foraminifera concentrated in the dark-colored laminae as shown in thin section. (Peel x1; thin section x35)

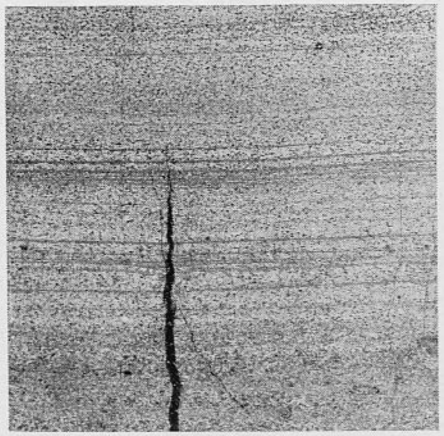


Fig. C. (154-B-42, unit 6b) Foraminifera biomicrite. Acetate peel. Dark laminae contain Foraminifera. Drusy calcite restricted to area of fracture. (x1)

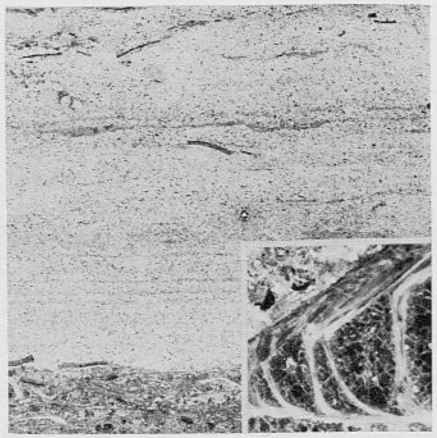


Fig. D. (154-B-42, unit 8) Foraminifera biomicrite. Acetate peel and thin section insert. Concentration of fossil fragments near base of peel embedded in micrite matrix. Heavy minerals evenly distributed suggesting uniform depositional rate in which fossils were dumped in lime mud. (Peel x1; thin section x30)

Fig. E. (154-B-42, unit 10) Foraminifera biomicrite. Acetate peel. Organic material and hematite common. Note distortion around phosphate nodule indicating soft-sediment deformation. (x1.25)

Plate IV. Outcrop and micro-features of limestone beds, locality 154-B-42, Bluebonnet member, Lake Waco formation.

respectively; (2) vertical decrease in long-term depositional energy as indicated by the upward decrease in the amount, size, and abrasion of allochems in the limestones; (3) vertical variation in laminae in the shale beds; (4) the similar distribution of illite in the Pepper-Woodbine formation and the Bluebonnet member suggesting a Pepper-Woodbine source for much of the Bluebonnet member; (5) upward increase in quartz in the Bluebonnet member indicating a prograding shoreline; and (6) gradual upward decrease in calcite and calcium montmorillonite and an upward increase in kaolinite suggesting a gradual decrease in Eh and pH during Bluebonnet deposition.

Lateral variations in lithology and mineralogy include (1) a northward decrease in the prominence of laminae in the shale beds suggesting a general northward increase in long-term depositional energy; (2) a northward increase in land-derived coarse clastics suggesting a dominant source to the north, probably of Woodbine origin; (3) a significant variation in carbon content in all 3 zones, suggesting changing sedimentary patterns; and (4) a northward decrease in calcite and calcium montmorillonite content and a northward increase in kaolinite suggesting a slight northward decrease in pH and Eh during deposition.

PALEONTOLOGY

The flora and fauna aid in interpreting the depositional environment of the Bluebonnet member. In addition, the distribution and abundance of the planktonic microfauna may indicate current directions.

MEGAFOSSILS

The stratigraphic distribution of megafossils in the Bluebonnet member has been studied by Adkins (1928), Moreman (1942), Adkins and Lozo (1951), and Stephenson (1955). Six genera and 13 species have been reported from the Bluebonnet member.

Ammonites, which have received greatest attention because of their importance in correlation, have been equated with Cenomanian ammonites of Europe. *Acanthoceras longsdalei, A. bellense, A. pepperense, A. stephensoni, A. turneri, Eucalycoceras leonense, Mantelliceras sellardi, Metacalycoceras tarrantense, Turrilites costatus,* and *Desmoceras* have been reported from the Bluebonnet member. Ammonites are most abundant in the lower part of the Bluebonnet member, although the uppermost limestone bed contains *Desmoceras.* Ammonite abundance is also related to the limestone-type; they are most common in cross-bedded, ripple-marked, fine to medium-grained limestone beds such as units 4 and 2 at localities 154-B-40, 45 respectively (figs. 4, 9). Units 16 and 18 (154-B-40, 41 respectively; figs. 4, 5) contain abundant *Desmoceras.*

Pelecypods are represented by *Inoceramus labiatus* and *I. arvanus.* They occur in most limestone beds of the Bluebonnet member. Fragments and prisms (Pl. VI, fig. B) are abundant in the lower limestone beds, whereas whole specimens occur in the upper beds (Pl. II, fig. F).

Where whole specimens occur in lower limestone beds, they form a coquinoid layer commonly ½ to ¾ of an inch thick at the top of the limestone bed. This may indicate (1) the gradual areal restriction of favorable ecologic conditions resulting in local over-population, (2) gregarious nature of *Inoceramus,* or (3) transport of shells to the present location after death. The first 2 interpretations probably apply since specimens do not show abrasion due to transportation.

Gastropods occur in the Bluebonnet member but preservation is poor and identification is difficult. The gastropods occur mainly in the upper limestone beds in Hill County.

Vertebrates are represented by numerous genera. Such reptiles as plesiosaurs and mosasaurs have been reported in the Bluebonnet member. Several whole specimens of the fish *Septoria* were found in northern Hill County (109-B-18). Fish teeth and scales are abundant throughout the member. Teeth are concentrated along the basal contact. Preservation of vertebrates is probably due to absence of benthonic scavengers during shale deposition as indicated by the absence of benthonic fossils and the thinly laminated nature of the black shales.

MICROFOSSILS

A detailed study of Foraminifera was undertaken with the following objectives: (1) correlation of the upper shale beds, (2) delineation of the relative energies and directions of local currents, and (3) determination of sedimentary environment through ecological relationships.

The abundance of microfauna in a cubic centimeter of washed shale residue is illustrated in figures 4-11. Techniques followed in the microfaunal study are described in Appendix V; results of the analyses are recorded in Appendix IV. Microfossil studies were limited to shale beds, since it was not practical to extract microfossils from limestone; however, microfossils in the limestones were observed in thin sections (Pl. I, fig. A; Pl. III, fig. B).

Three genera and 4 species of planktonic foraminifers were identified—*Hedbergella amabilis* Loeblich and Tappan (*Globigerina cretacea* d'Orbigny), *Hedbergella brittonensis* Loeblich and Tappan, *Clavihedbergella simplex* Morrow and *Gümbelina* (Loeblich and Tappan, 1961).

In general, the planktonic microfaunal abundance increases upward in the Bluebonnet member (fig. 12). Lateral variations are not as uniform as vertical changes. The foraminifers are most abundant in all 3 zones in central McLennan (154-B-41, 43) and in north-central Hill (109-B-17) counties.

Shale beds of the Bluebonnet member contain no benthonic microfauna. It is possible that the absence of a benthonic fauna during Bluebonnet shale deposition indicates unfavorable bottom conditions for benthonic life. This may have resulted from toxic bottom muds, absence of food source, unfavorable hydrogen sulfide to oxygen ratio in water, or rapidly varying brackish to marine conditions. The various geochemical indicators previously discussed suggest that the main determining factor which prevented benthonic life was toxic bottom waters and muds caused by restricted circulation.

The vertical variation in abundance of both species of *Hedbergella* is similar (Appendix IV), which suggests that their ecology was similar. *Gümbelina* increases upward in abundance more rapidly than *Hedbergella* (*idem*), which indicates that the ecology of *Gümbelina* differed from that of *Hedbergella*.

PLANTS

The Bluebonnet member contains abundant plant material as indicated by the high amount of carbon in both limestone and shale beds. The amount of carbon in the limestone beds in zone 3 is 3 to 5 times greater than the amount of carbon in the limestones in zones 1 and 2. The amount of carbon in the Bluebonnet shale beds in zone 3 is about twice that in shales of zones 1 and 2.

The best preserved plants are cycad fragments. Fragments vary from 1 to 10 inches wide and 3 to 21 inches long, and are most commonly preserved by carbonization. The smaller and by far most common fragments of fossil cycad wood were observed in the upper limestone bed at all exposures in McLennan and Hill counties.

Well preserved spores are common throughout the member, but are most abundant in zone 3. The abundant and highly variable spore-pollen content and other floral constituents in the Eagle Ford group have been recently described by Brown and Pierce (1962). Many charophytes were observed in the shale beds of zone 3; they are most common in McLennan (154-B-42, 43) and Hill counties (109-B-16, 17).

GEOLOGIC HISTORY

BATHYMETRY AND DISTRIBUTION OF CLASTICS

The isopach map (fig. 2) shows the areal extent and topography of the floor of the Bluebonnet basin. Preserved depositional limits are indicated by the zero isopach line. The exact southern limit of deposition was not determined, either because the member was faulted out by Balcones faulting or Leon River terraces conceal the outcropping Bluebonnet member. Poor exposures of the thin member prevented mapping the exact northern limit, but it disappears on the outcrop approximately 9 miles northwest of Hillsboro, Hill County.

DEPOSITIONAL ENVIRONMENT

The Bluebonnet member is interpreted to be a lagoonal deposit. Lucke (1939) discussed the evolution of lagoons. Various stages in the development of the Bluebonnet lagoon are illustrated by the 4 paleogeographic maps (fig. 13, A-D) which represent postulated stages in the evolution of the Bluebonnet lagoon. The landward part of the paleogeographic maps is hypothetical, based on the presence of marginal lagoonal sediments in zone 3 in McLennan and Hill counties.

The *youthful stage* (fig. 13-A) of the lagoon is illustrated by the postulated paleogeography of zone 1 of the Bluebonnet member in Bell, southwestern McLennan, and central Hill counties; evidence for this stage is better than for later stages of basin history. The baymouth bar and inlet are suggested by the isopach map (fig. 2). Since the postulated baymouth bar is not exposed at the surface, only limestone beds in the cuspate and midbay bars have been studied. Abundance and distribution of planktonic microfossils suggest 2 additional inlets—in south-central Hill County near 109-B-17 and in southwestern McLennan County near 154-B-41. Shales at each of these localities contain abnormal concentrations of planktonic microfossils relative to adjacent localities, which suggests the presence of an inlet into the lagoon. Evidences for the cuspate bar at the north shore of the lagoon are features exhibited by limestone beds in north-central McLennan County (154-B-44; fig. 8). At this locality large festoon cross-beds and ripple-marks are prominent in the basal limestone bed. The limestone is an *Inoceramus* biosparite composed of approximately 80 percent allochems. Interpretation of the area immediately east of the cuspate bar within the lagoon is based on exposures in northern McLennan and southern Hill counties (154-B-45 and 109-B-15). In this area the basal limestone bed is a Foraminifera biomicrite; shales in zone 1 contain a large amount of clay and display poorly developed laminae, which suggest that deposition in this part of the lagoon was probably more rapid than in adjacent areas to the south. Some of the bentonites indicate transportation by water because of the absence of glass shards.

Conditions which existed between the cuspate bar and mid-bay bar are indicated by exposures near Waco (154-B-42, 43). The basal limestone in this area is a Foraminifera biomicrite, suggesting the absence of higher energy characteristic of cuspate and/or mid-bay bars. Sediments in zone 1 of this area are dominantly gray to black, thinly laminated, calcareous, fossiliferous (planktonic microfossils) shales. The relatively small amount of preserved plant material suggests that this area was not near a plant source. Furthermore, the amount of calcium montmorillonite is greater than in adjacent areas, suggesting more normal marine conditions. Foraminiferal content is high in this area, which further substantiates the occurrence of the ancient inlet as indicated by the isopach map (fig. 2).

The mid-bay bar is interpreted from exposures in southwestern McLennan and Bell counties (154-B-40, 41, 46; 14-B-1, 2) where basal limestone beds are cross-

Fig. 7. Mineralogy and fauna, locality 154-B-43, Bluebonnet member, Lake Waco formation.

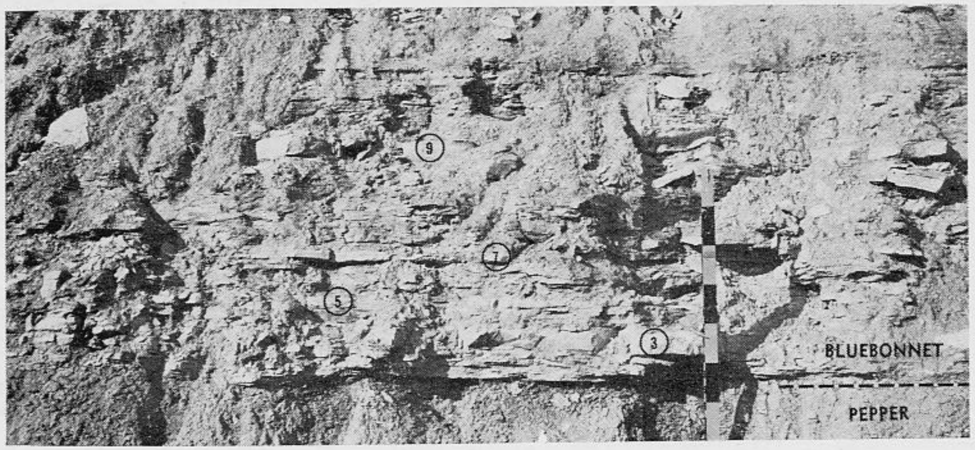


Fig. A. (154-B-43) Approximately 4.5 miles west of Waco, McLennan County. Shales of Pepper formation are blocky, whereas shales of Bluebonnet member are thinly laminated. Excavated exposure weathered 3 months before photographed. Note lenticular limestone beds, especially unit 9. Scale unit is 1 foot.

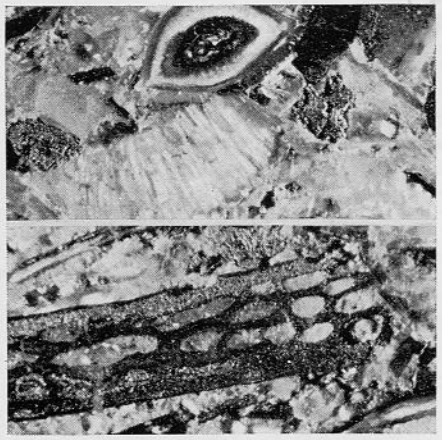


Fig. B. (154-B-43, unit 2a) Shale and limestone. Thin sections. Phosphate nodules above; pyritized plant fragment below. (x35, reflected light)

Fig. C. (154-B-43, unit 3) Foraminifera biomicrite. Acetate peel. Slightly cross-laminated. Load casting in lower right center of peel; little variation in grain size. (x1)

Fig. D. (154-B-43, unit 5) Biomicrite. Photograph. Thinly bedded with faint ripple-marked or uneven bedding in upper part of print. Hematite abundant in dark bands at top of print. (x.75)

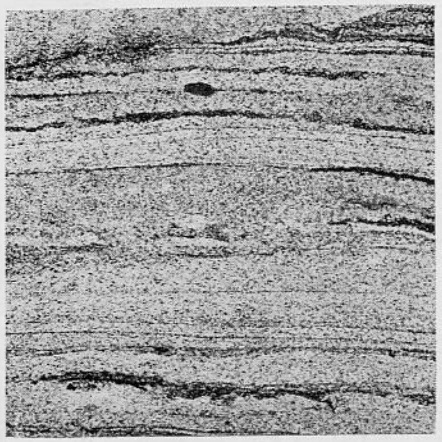


Fig. E. (154-B-43, unit 9) Foraminifera biomicrite. Acetate peel. Soft-sediment deformation in upper part of peel. (x1)

Plate V. Outcrop and micro-features of limestone beds, locality 154-B-43, Bluebonnet member, Lake Waco formation.

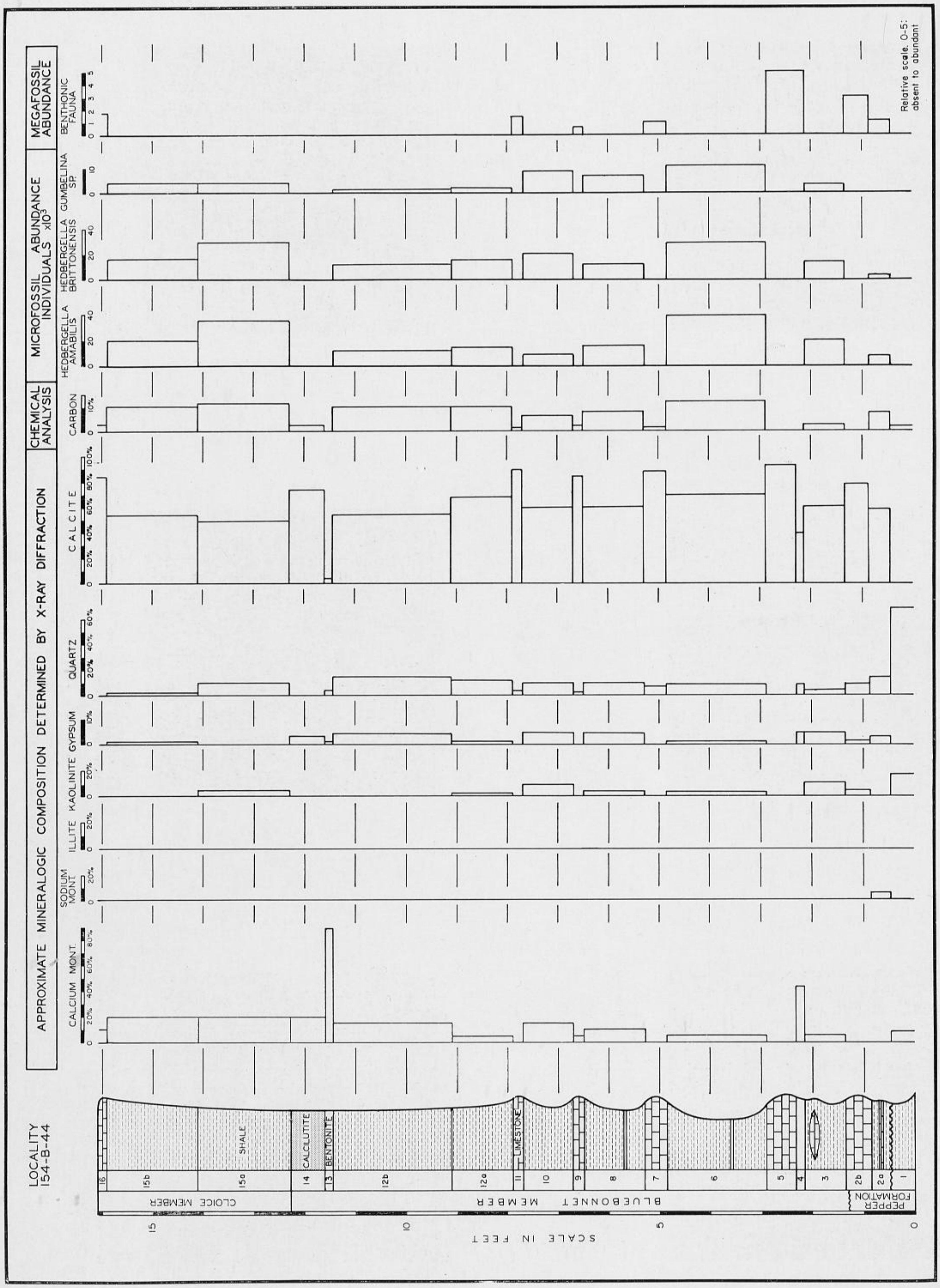


Fig. 8. Mineralogy and fauna, locality 154-B-44, Bluebonnet member, Lake Waco formation.

Fig. A. (154-B-44, unit 2b) *Inoceramus* biosparite. Acetate peel. Cross-beds are developed in upper part of peel. An increase in grain size and decrease in sorting is associated with the cross-bedding. (x1)

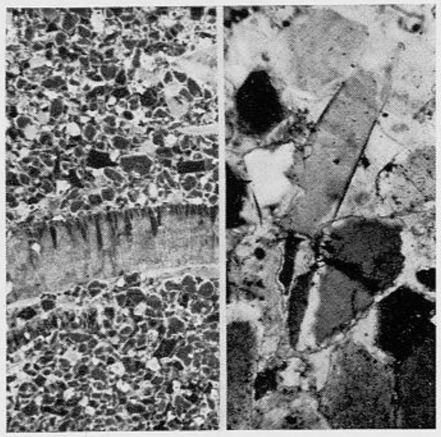


Fig. B. (154-B-44, unit 2b) *Inoceramus* biosparite. Acetate peel, left; thin section, right. Note orientation of *Inoceramus* prisms which are cut perpendicular to the C-axis in peel. Pressure solution is well displayed in thin section. (Peel x30; thin section x90, crossed nicols)

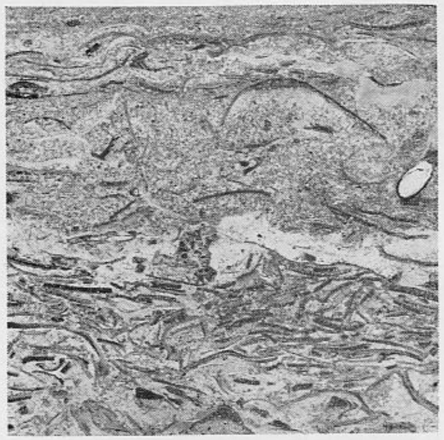


Fig. C. (154-B-44, unit 5) *Inoceramus* biomicrite. Acetate peel. *Inoceramus* fragments were dumped into lime mud. Maceration was probably result of shell crushers rather than wave energy. White elongate object at right center of peel is a phosphate nodule. (x1)

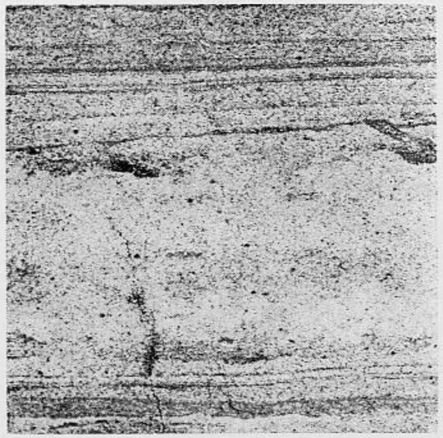


Fig. D. (154-B-44, unit 7) Foraminifera biomicrite. Acetate peel. Uniform grain size suggests that irregular laminae are of depositional rather than post-depositional origin. (x1)

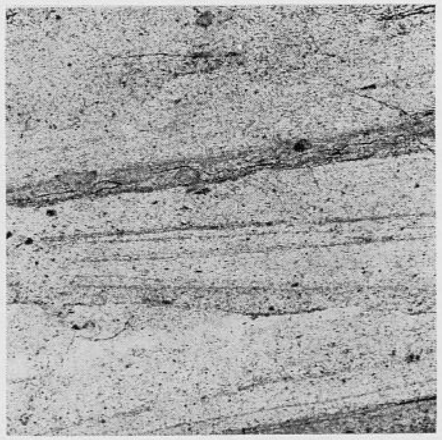


Fig. E. (154-B-44, unit 11) Foraminifera biomicrite. Acetate peel. Severely weathered. Cross-laminae are uniform in grain size. Gypsum is common and probably secondary; hematite is common near top of peel. (x1.25)

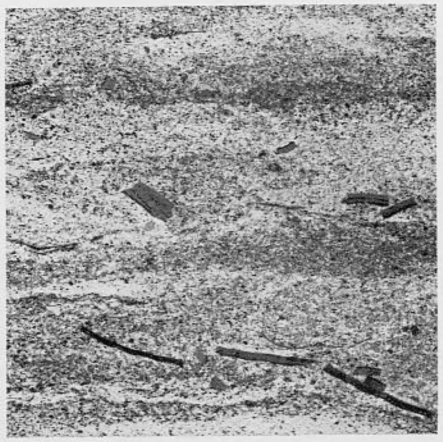


Fig. F. (154-B-44, unit 16) Foraminifera biomicrite. Acetate peel. Large recrystallized calcite fragments of *Inoceramus* are common; dark-gray areas contain clay. (x2)

Plate VI. Micro-features, limestone beds, locality 154-B-44, Bluebonnet member, Lake Waco formation.

bedded and ripple-marked. Each limestone is an *Inoceramus* biosparite. The basal limestone bed in southwestern McLennan County (154-B-40, Pl. II, fig. A) is also cross-laminated, which may indicate that the locality is on the western side of the mid-bay bar as indicated in figure 13-A.

The cuspate and mid-bay bars were not laterally persistent and were frequently above base level of wave and current agitation, as suggested by the ripple-marked and cross-bedded limestones in southwestern and northern McLennan County. Climatic changes, as well as the width and number of inlets, would have greatly affected the turbulence of water in the lagoon. The two bars were, therefore, continuously built and destroyed as shown by the varying thickness of the basal limestone bed.

Reworking of sediments in the Bluebonnet member by benthonic organisms was limited to the bar-deposited limestone beds. Boring organisms thoroughly reworked portions of the basal limestone (Pl. IX, fig. E). The presence of undisturbed thin laminae and absence of filled borings in limestone beds deposited in postulated marsh environments may indicate toxic conditions (and/or lower pH) in the mud areas. In addition boring organisms perhaps could not migrate from the bars to the isolated areas of limestone deposition in the marshes.

The shale and limestone beds in zone 2 reflect deposition during the *late youthful stage* (fig. 13-B) of the Bluebonnet lagoon. The absence of a cuspate bar along the northern coast is suggested by the texture and composition of the limestone beds in zone 2. Zone 2 limestone beds in northern McLennan and southern Hill counties are Foraminifera biomicrites. Dominant allochems are planktonic foraminifers with a few poorly rounded, poorly sorted *Inoceramus* fragments. The allochems and matrix suggest a long-term, low energy environment.

The recession of the mid-bay bar (which was a prominent feature during youth) is evidenced by shale and limestone beds in zone 2 in southwestern McLennan County (154-B-40, 41). Limestone beds in zone 2 in this area are Foraminifera biomicrites, which are similar to limestone beds of zone 2 in southern Hill County. Shale beds of zone 2 in southwestern McLennan County contain more kaolinite and less calcium montmorillonite and calcite than shale beds of zone 1 in the same area. This suggests that the pH in this area during deposition of zone 2 was slightly lower than for zone 1.

The cuspate bar at the southern coast of the Bluebonnet lagoon during late youth was the remnant of the earlier mid-bay bar. This cuspate bar is indicated by limestone beds of zone 2 in central Bell County (14-B-1, 2). These limestone beds are *Inoceramus* biosparites and biomicrosparites. Allochems, which constitute more than 80 percent of the limestone, are moderately rounded and well sorted. Cross-beds and ripple-marked surfaces are common in these limestones.

Sedimentation was slower in zone 2 than in zone 1 as indicated by thinner laminae in both shales and limestones in zone 2; by limestone beds of micrite in zone 2 and sparite in zone 1; and by a greater abundance of carbon in zone 2, except in the area of the cuspate bar. This evidence suggests that marsh deposition was more common during deposition of zone 2 than during zone 1.

The *early mature stage* (fig. 13-C) of the Bluebonnet lagoon was characterized by absence of mid-bay and cuspate bars, and accumulation of marsh sediments in zone 3. The absence of mid-bay and cuspate bars is suggested by the dominance of shale in zone 3, as well as by Foraminifera biomicrites and micrites. Limestone beds of this zone contain a smaller amount of allochems and crystalline calcite compared to limestone beds in zone 1; in addition, zone 3 limestones do not contain cross-bedding, ripple marks or other high energy indicators suggesting bar deposition.

Decreased circulation in the Bluebonnet lagoon, due to gradual restriction of the main inlet, is suggested by texture and mineralogy of limestone and shale beds in zone 3. Limestone beds in this zone are very fine-grained, structureless Foraminifera biomicrites. Limestone beds contain a high carbon content, suggesting heavy plant growth in surrounding marshes and subsequent accumulation in the lagoon. The uppermost limestone bed contains well preserved cycad fragments and charophytes. The shale beds of zone 3 contain a high amount of kaolinite and carbon, but no benthonic foraminifers, suggesting a low pH environment. Laminae are poorly developed indicating rapid deposition in zone 3, relative to zones 1 and 2. Restricted circulation (low energy) is further indicated by a thick bentonite bed containing glass shards in the upper part of zone 3 in McLennan County (fig. 12).

Kaolinite and carbon content reached maximum abundance during this stage of sedimentation, whereas the overall calcium montmorillonite and calcite contents are at a minimum (fig. 12), which denotes a lower pH and Eh in the depositional environment of zone 3 than in zones 1 and 2. This is expected since decaying plants should have resulted in sub-normal pH and Eh values. Deposition was more rapid along the perimeter of the lagoon than in the open water near the center of the basin.

Interpretation of the *mature stage* (fig. 13-D) of the Bluebonnet lagoon is based on less evidence than the other stages. During this final stage, the lagoon was completely filled with marsh deposits and covered by the transgressing Cloice sea.

The overlying Cloice member of the Lake Waco formation is probably a restricted shallow-water deposit. A low energy, long-term depositional environment for the lower part of the Cloice member is indicated by wide-spread thinly laminated shale beds, uniformly distributed microfauna, and relatively uniform mineralogic composition in Bell, McLennan, and Hill counties. A low energy depositional environment permitted the preservation of the soft unconsolidated marsh deposits of zone 3 of the underlying Bluebonnet member.

GEOCHEMICAL ENVIRONMENT

It is difficult to determine whether a given suite of minerals reflects sedimentary or diagenetic processes. Ranges of pH and Eh values of ancient depositional environments, as inferred from contained minerals, are of questionable value unless the minerals can be verified to be primary in origin. In order to verify the origin of contained minerals it is necessary to expand the number of lines of evidence to include physical and organic indicators, such as field relationships, sedimentary structures, and fossils.

The Bluebonnet member was probably deposited in a dominantly low energy, anaerobic environment as demonstrated by (1) thinly laminated shale beds, (2) lack of benthonic fossils in shale beds, (3) abundance of well preserved fish scales, (4) carbonized plant fragments, (5) thin lenticular coal seams, (6) predominance of structureless biomicrite limestone beds, and (7) low energy soft sediment deformation structures. Low energy, anaerobic environments are associated with negative Eh values. Values of Eh were negative both above and below the depositional interface during deposition of the Bluebonnet shales, but positive in the bar areas (fig. 13). It has been demonstrated (Krumbein and Garrels, 1952) that diagenesis does not normally alter primary minerals in a negative Eh environment. Garrels (1960) has demonstrated that pressure and temperature ranges in nature are not sufficient to cause a loss of pH-Eh control of mineral stability. It is, therefore, concluded that the mineralogic composition of the Bluebonnet member is primary and reflects pH and Eh values during deposition.

Several geochemical indicators occur in the Bluebonnet member; these are kaolinite, calcium montmorillonite, calcite, rhodochrosite, and carbonaceous material. Kaolinite and calcium montmorillonite are not independently good geochemical indicators, but the ratio of kaolinite to calcium montmorillonite may be important.

Kaolinite-calcium montmorillonite ratio cannot be used as a pH indicator, unless it can be demonstrated that the clay minerals reflect the environment of deposition and were not later altered. Clay minerals in the Bluebonnet member are interpreted to reflect depositional environments because little similarity occurs between the clay mineral suites of the Bluebonnet member and underlying Pepper and Woodbine formations, probable source of the sediments.

Normally an increase in pH precipitates calcite, whereas saturation will not be reached in a low pH environment. Therefore, abundant calcite suggests a pH above 7.8 during deposition; when calcite is an accessary mineral, a pH of 7.0-7.8 is indicated (Krumbein and Garrels, 1952). Calcite precipitation is not affected by oxidation-reduction potential, and is, therefore, not an indicator of Eh in paleo-environments.

Rhodochrosite, which occurs at localities 154-B-40, 43 (Appendix III), can be precipitated at a $pH>7.0$ and at an $Eh<0.0$ (*idem*).

The pH and Eh values were high during the *youthful stage* (fig. 13-A) of the Bluebonnet lagoon. Water surrounding the cuspate and mid-bay bars had a pH above 7.8 as indicated by the abundant calcite (zone 1). The Eh must have been positive since the water adjacent to the bars was oxygenated by agitation as evidenced by well sorted, cross-bedded, ripple-marked, bar-deposited limestone beds composed of shell fragments (Pl. I, figs. A, D).

Values of pH and Eh were slightly lower between the cuspate and baymouth bars (Hill County) than in areas adjacent to the bars. This is suggested by a slight decrease in the amount of calcite and calcium montmorillonite and an increase in kaolinite in the interbar area in zone 1.

The *late youthful stage* (fig. 13-B) of the Bluebonnet lagoon was characterized by lower pH and Eh values than was the youthful stage. The only area of relatively high pH and positive Eh was near the cuspate bar along the southern coast of the lagoon. These high pH and positive Eh values are suggested by limestone beds of zone 2 in central Bell County (154-B-1, 2; Pl. I, figs. B, F), which are moderately sorted and slightly cross-bedded *Inoceramus* biosparites, indicating moderately agitated waters.

The remaining sediments of the Bluebonnet lagoon during the late youthful stage were deposited at a neutral to slightly alkaline pH and negative to slightly positive Eh. These conditions are indicated by a decrease in the amount of calcium montmorillonite and calcite, and an increase in the amount of kaolinite in zone 2 shales, relative to zone 1. Furthermore, in zone 2 the increase of well preserved fish scales and a slight trace of rhodochrosite are indicative of an approximately neutral (0.0) Eh environment.

During the *early mature stage* (fig. 13-C) of the Bluebonnet lagoon (zone 3) calcium montmorillonite and calcite deposition was low, whereas kaolinite deposition was at a maximum. This suggests that the pH was also probably slightly acid during the *mature stage*. The Eh values were commonly negative as evidenced by abundant well preserved plant fragments in shales and rare benthonic fossils in the limestones in zone 3.

BORDERLAND FEATURES

The absence of coarse, land-derived sediments in the limestone and shale beds suggests a land area of low relief adjacent to the Bluebonnet lagoon. The Pepper and Woodbine formations were apparently exposed in areas adjacent to the lagoon, as denoted by texturally similar quartz grains in the basal Bluebonnet limestone bed (Pl. VIII, fig. D) and in the Woodbine formation (Pl. IX, fig. D) of Hill County.

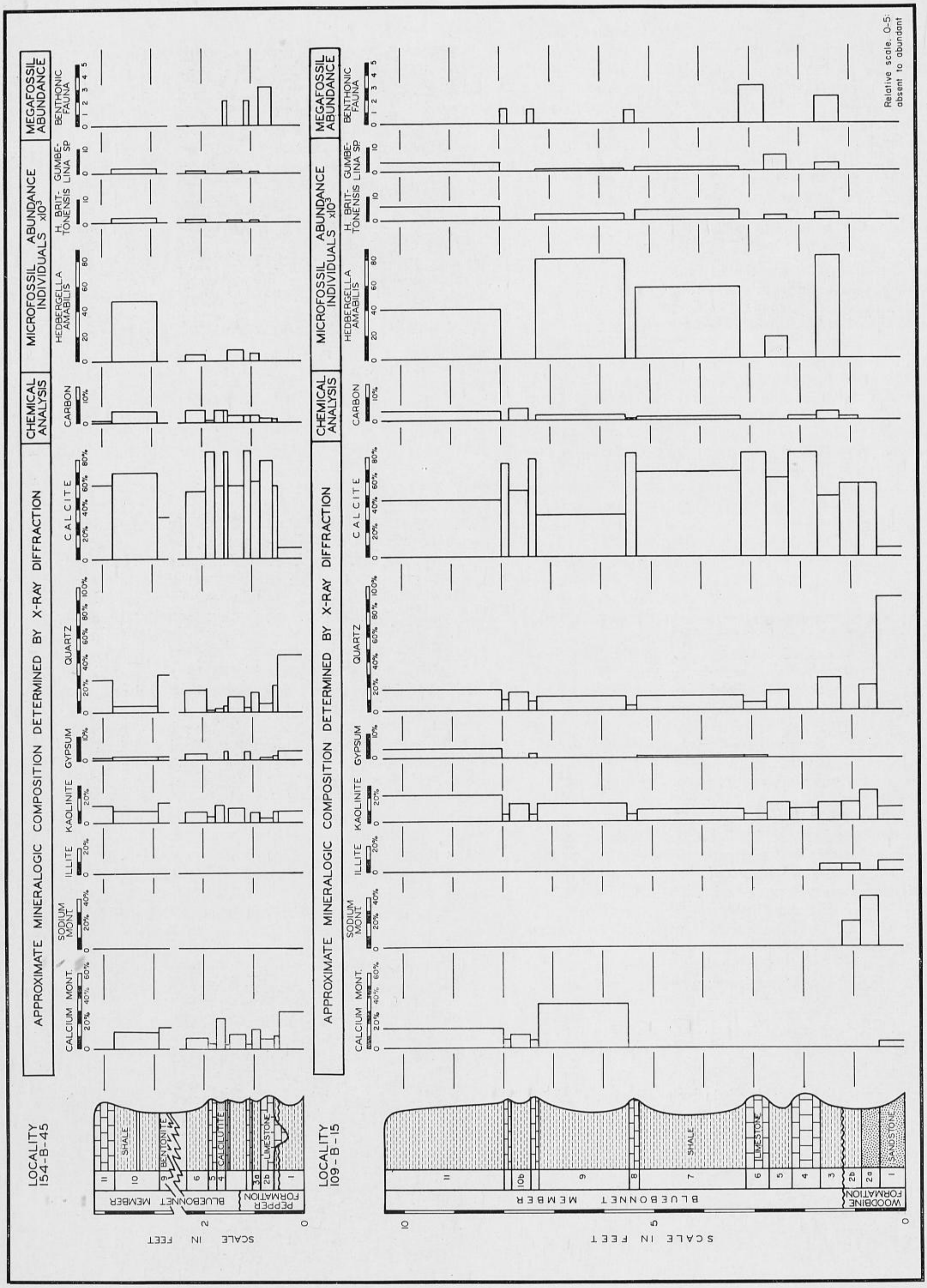


Fig. 9. Mineralogy and fauna, localities 154-B-45 and 109-B-15, Bluebonnet member, Lake Waco formation.

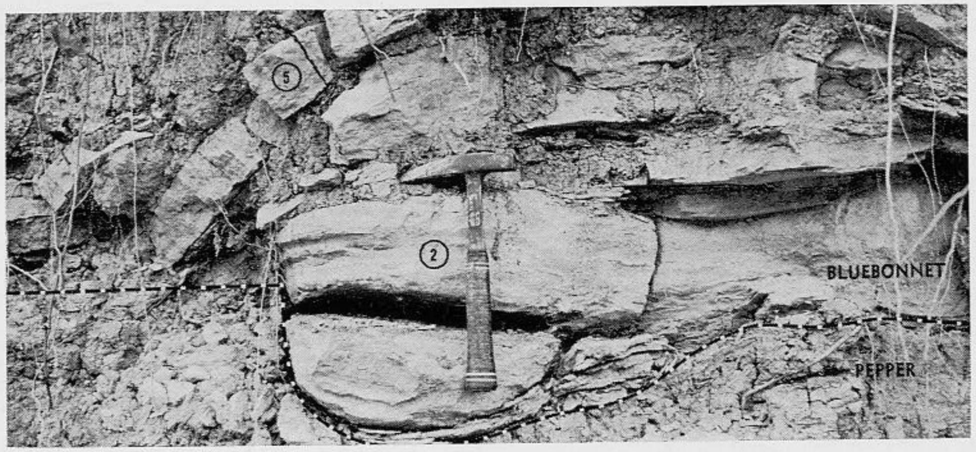


Fig. A. (154-B-45) Approximately 17 miles north of Waco, McLennan County. Blocky shales of the Pepper formation are in contact with limestone bed of the Bluebonnet member. Limestone of unit 2 was deposited on an uneven depositional surface. Shank of hammer is 1 foot.

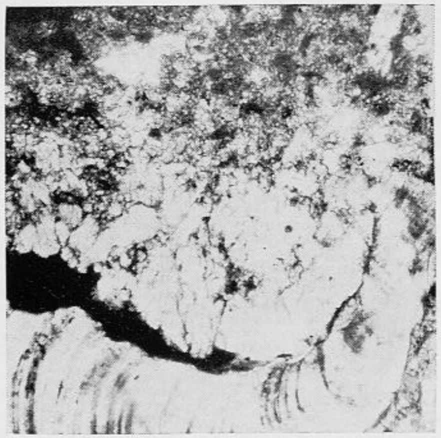


Fig. B. (154-B-45, unit 2b) *Inoceramus* biomicrite. Thin section. Allochems are dominantly poorly rounded and poorly sorted *Inoceramus* fragments. (x30, crossed nicols)

Fig. C. (154-B-45, unit 3b) Biomicrite. Acetate peel. Higher magnification shows grain seeding in early stage of development near base of peel; hematite abundant near base. (x1)

Fig. D. (109-B-15, unit 4) Foraminifera biomicrite. Acetate peel. Cross-laminae near base contain some allochems in micrite matrix. Lenticular dark-gray area at upper right is pyrite. (x.75)

Fig. E. (109-B-15, unit 6) Foraminifera biomicrite. Acetate peel. Light colored local areas at center of peel are zones of *Inoceramus* prisms cemented with sparry calcite. Soft sediment deformation is displayed at lower right of peel. (x.5)

Plate VII. Outcrop and micro-features of limestone beds, localities 154-B-45 and 109-B-15, Bluebonnet member, Lake Waco formation.

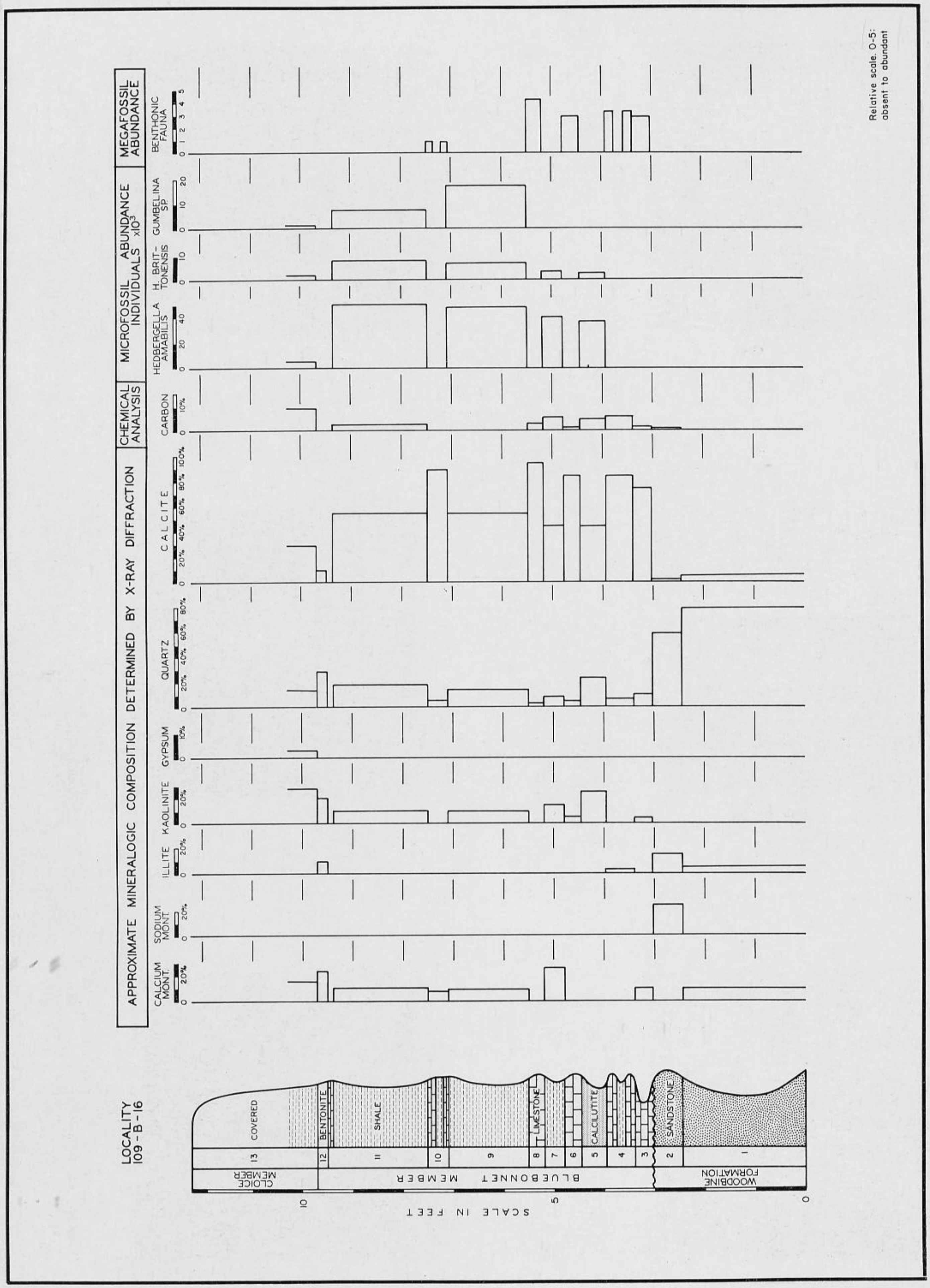


Fig. 10. Mineralogy and fauna, locality 109-B-16, Bluebonnet member, Lake Waco formation.

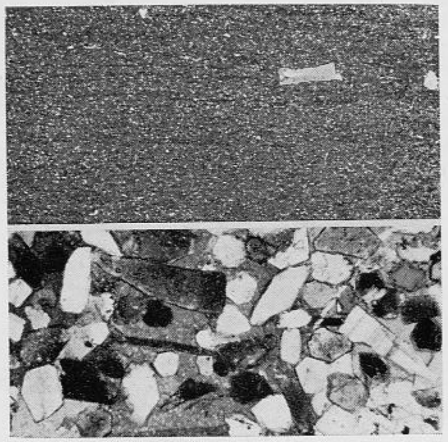


Fig. A. (109-B-16, unit 3) *Inoceramus* biosparite. Acetate peel, above; thin section, below. Note large crystals of sparry cement; some quartz grains were etched. Grains are loosely packed and unevenly distributed. (Peel x1.5; thin section x90, crossed nicols)

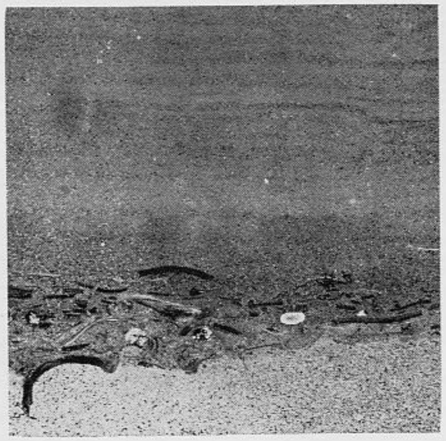


Fig. B. (109-B-16, unit 6) Foraminifera biomicrite. Acetate peel. Some drusy calcite occurs below some large *Inoceramus* fragments. Organic material and hematite are abundant; hematite is concentrated in Foraminifera which have been partially recrystallized. (x1)

Fig. C. (109-B-16, unit 8) Recrystallized biomicrite. Acetate peel. Recrystallization progressed from bottom to top. Concentration of hematite along upper surfaces of laminae may indicate brief periods of non-deposition. (x.5)

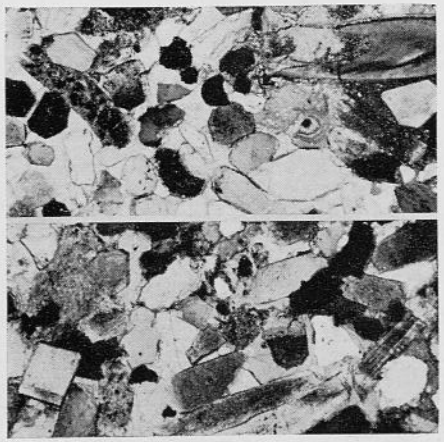


Fig. D. (109-B-17, unit 2) *Inoceramus* biosparite. Thin sections. Dominant allochems are *Inoceramus* prisms; dominant clastic component is quartz. Grains are closely packed, poorly rounded, and poorly sorted. (x90, crossed nicols)

Fig. E. (109-B-17, unit 6) Biomicrite. Acetate peel. Note lenticular cross-laminae and uneven bedding planes. Allochems are fine-grained, moderately rounded, and moderately sorted. (x1)

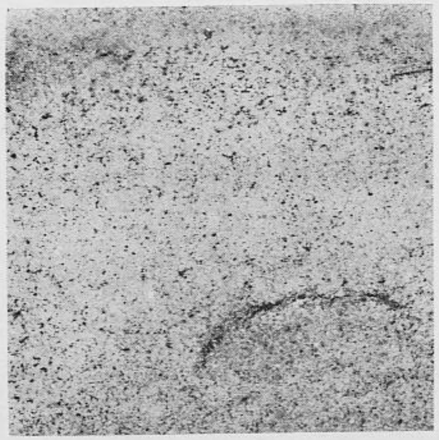


Fig. F. (109-B-17, unit 8) Biomicrite. Acetate peel. Allochems are fine-grained, poorly rounded and sorted. Hematite is abundant; entire bed is stained by limonite. (x1.5)

Plate VIII. Micro-features, limestone beds, localities 109-B-16 and 109-B-17, Bluebonnet member, Lake Waco formation.

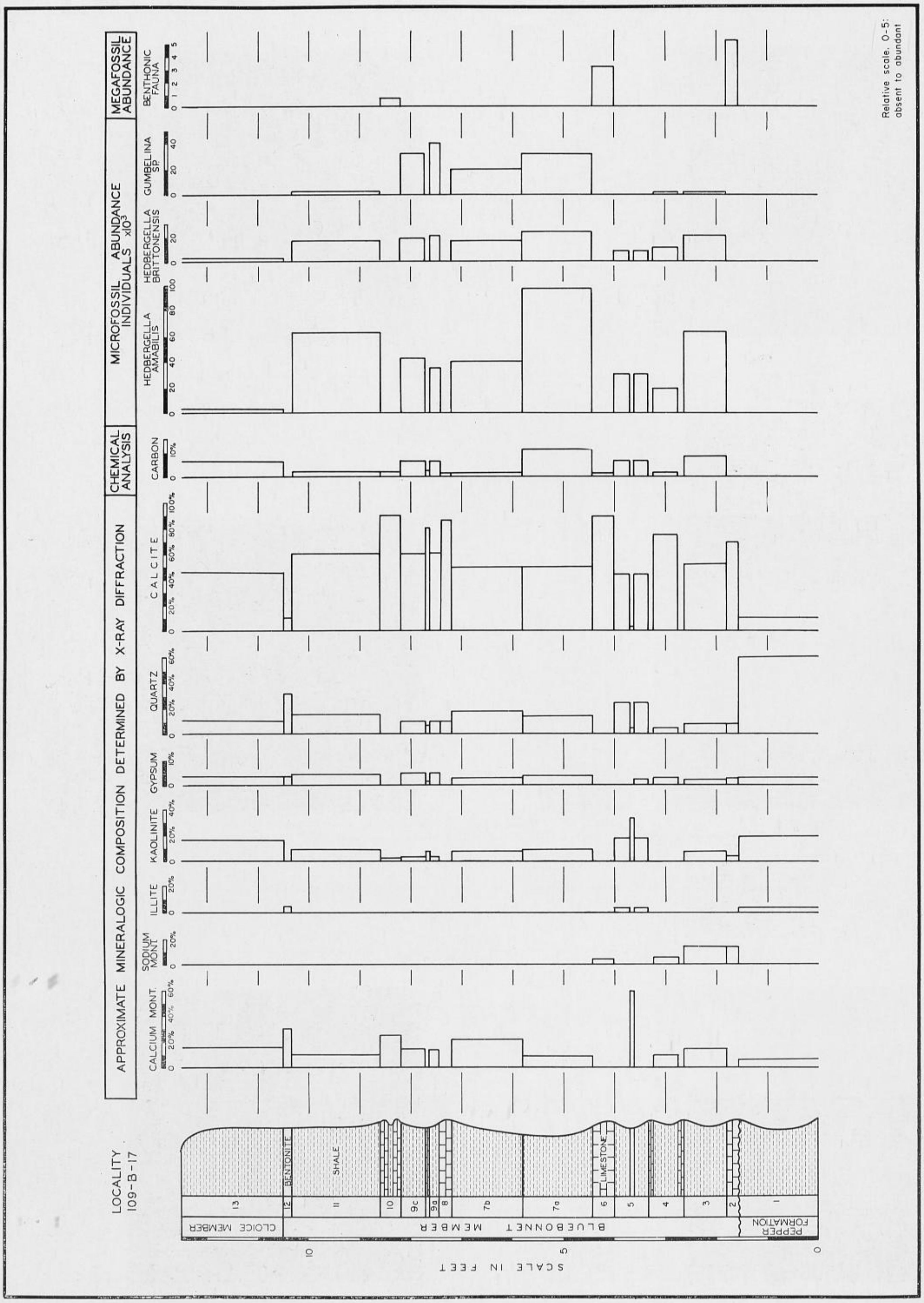


Fig. 11. Mineralogy and fauna, locality 109-B-17, Bluebonnet member, Lake Waco formation.

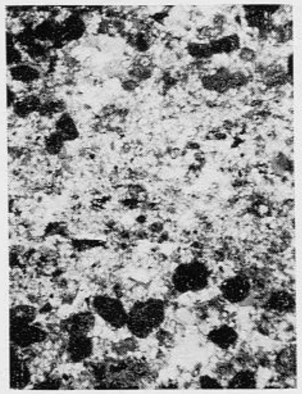


Fig. A. (14-B-3, unit 2) Biopelmicrite. Thin section. Dominant allochems are Foraminifera and pellets. Pelletal laminae are interlaminated with microspar which may be result of recrystallization. (x30)

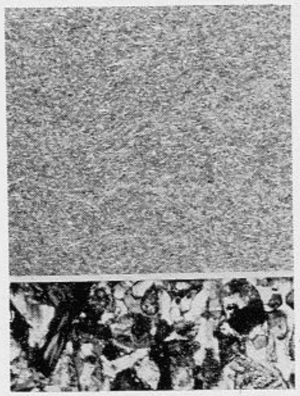


Fig. B. (154-B-46, unit 2) *Inoceramus* biosparite. Acetate peel, above; thin section, below. *Inoceramus* prisms are closely packed; some pressure solution occurs in the upper part of bed. (Peel x1; thin section x30, crossed nicols)

Fig. C. (109-B-18, unit 2) Fragmental biomicrite. Thin section. Fish vertebra in micrite matrix. (x30)

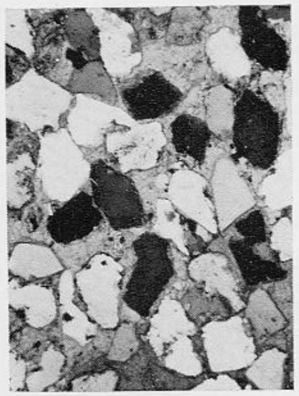


Fig. D. (109-B-19, unit 1) Woodbine sand, orthoquartzite. Thin section. Quartz etched; overgrowths give grains rounded appearance. Calcareous cement is syntaxial over large areas. (x90, crossed nicols)

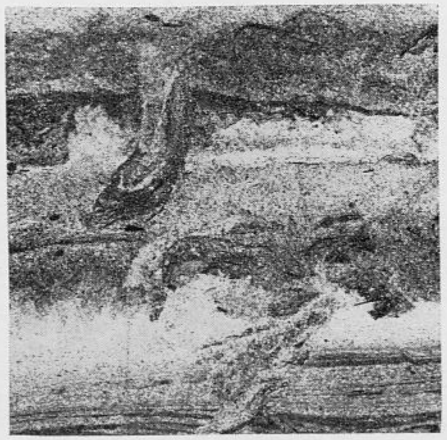


Fig. E. (154-B-41, unit 4) *Inoceramus* biosparite-biomicrite. Acetate peel. Uppermost structure is a burrow containing similar sediment within and above burrow. Lower part of peel displays soft-sediment deformation. (x.75)

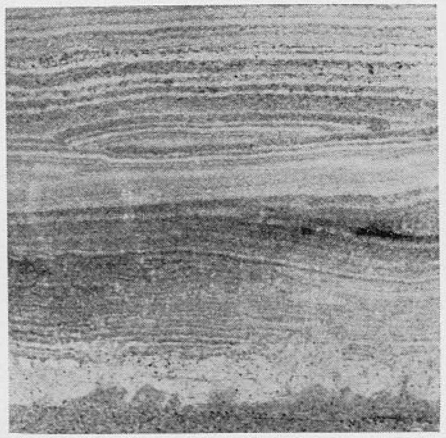


Fig. F. (154-B-42, unit 4) Micrite. Photograph. Allochems are silt size. Contorted bedding near base of photograph; gravity flowage from right to left is suggested. (x.75)

Fig. G. (109-B-18, unit 2) Fragmental biomicrite. Acetate peel. Oval structure in upper center is an ammonite filled with drusy calcite. Large fragments of *Inoceramus* are recrystallized. (x.75)

Plate IX. Selected micro-features, limestone beds, Bluebonnet member, Lake Waco formation.

POST-DEPOSITIONAL HISTORY

COMPACTION

It is estimated that a limestone specimen from locality 109-B-15 displays 45 percent reduction due to vertical compaction. Pressures required to accomplish this reduction would approximate 1,000 feet of overburden (Weller, 1959, p. 286). If this estimate is valid, nearly 1,000 feet of overlying strata have been removed, which suggests that the Lake Waco, South Bosque, and Austin formations, and part of the Taylor formation originally overlay the Bluebonnet member in the map area. The lithologic character of these formations in the area also indicates a distant westward shoreline, and, therefore, a greater areal extent than occurs today.

CEMENTATION

Cementation is a major post-depositional process in the bar-deposited limestone beds, but the process is much less important in shale. Cement in the bar-deposited limestone beds is sparry calcite, which may have formed as primary chemical cement by pressure solution or by recrystallization of microcrystalline calcite to microspar and/or sparry cement. Sparry cement in the Bluebonnet member is interpreted to be dominantly a cement precipitated from solution onto free surfaces of *Inoceramus* prisms (Pl. VIII, fig. D). Crystals of calcite cement grew by precipitation of calcium carbonate in lattice continuity with pre-existing free crystals (Pl.I, fig. A). Growth of some crystals ceased as they became enclosed by crystals with more favorable orientation. This process led to a reduction in the number, as well as an increase in the size of crystals. The presence of sparry cement indicates original porosity, which resulted from winnowing of fine particles during deposition of the bar-deposited limestone beds.

In the bar-deposited limestone beds the *Inoceramus* prisms (grains) were elastically strained at the intergranular boundaries (Pl. VI, fig. B) resulting in pressure solution and reprecipitation.

The occurrence of pressure solution in the limestones suggests that cementation by chemical precipitation was not completed early in diagenesis. This may indicate a depletion of calcium carbonate in the depositional area; the gradual lowering of pH within the water, increasing the solubility of calcium carbonate; and/or rapid sedimentation during late youth and early maturity, which did not permit sufficient time for complete cementation. A combination of the above factors probably occurred.

RECRYSTALLIZATION

Recrystallization, which was an important factor during diagenesis of the Bluebonnet member, has been observed throughout the limestone beds. Bar-deposited limestone beds are composed of *Inoceramus* prisms, which were cemented dominantly by sparry calcite. Two phases of recrystallization are evident in several of the bar-deposited limestones (Pl. I, fig. A). The first phase is grain growth parallel to the bedding. The second phase truncates the bedding and the first phase at a 30° angle. The first phase of recrystallization may have occurred contemporaneously with cementation as denoted by the large (1-2mm) crystals of sparry cement. The second phase at 30° to the bedding may have resulted from forces associated with Balcones faulting.

Several of the Foraminifera biomicrites, deposited in zones 2 and 3 of the Bluebonnet member, have been recrystallized by the process of grain seeding (Bathurst, 1958). Grain seeding is indicated by fibrous calcite crystals radiating from a grain of hematite in a foraminiferal test (Pl. III, fig. D). The hematite may be altered glauconite deposited in the test. Alteration of glauconite to hematite would have resulted in expansion, which is suggested by microscopic fractures radiating from hematite in the center of the test. The microscopic fractures would increase porosity which would lead to recrystallization of micro-crystalline calcite to fibrous calcite.

EROSIONAL HISTORY

In general erosion was probably not an important process in the Bluebonnet lagoon. The youth, late youth and early mature stages of the lagoon are well preserved in the outcrop belt. The mature stage is partially destroyed in Hill County as a result of Recent erosion.

CONCLUSIONS

(1) The Bluebonnet member of the Upper Cretaceous Lake Waco formation occurs in parts of Bell, Falls, McLennan, Limestone, Hill, Robertson, Milam, and Navarro counties, central Texas. The maximum thickness of the member is 22 feet. The member strikes north-northeast and dips 40 to 80 feet per mile east-southeast.

(2) The Bluebonnet member is a sequence of limestone, shale, and bentonite beds. Limestone beds are dominantly Foraminifera biomicrites; however, the basal limestone bed at several localities is an *Inoceramus* biosparite that contains abundant closely packed allochems. The allochems are well sorted *Inoceramus* prisms with long axes parallel. Shale beds are gray, fissile, thinly laminated, calcareous, and weather buff. Bentonite beds are composed of calcium montmorillonite, which is free of glass shards, indicating the detrital nature of the bentonites.

(3) The depositional environment was a shallow lagoon. Four general stages of lagoonal evolution can

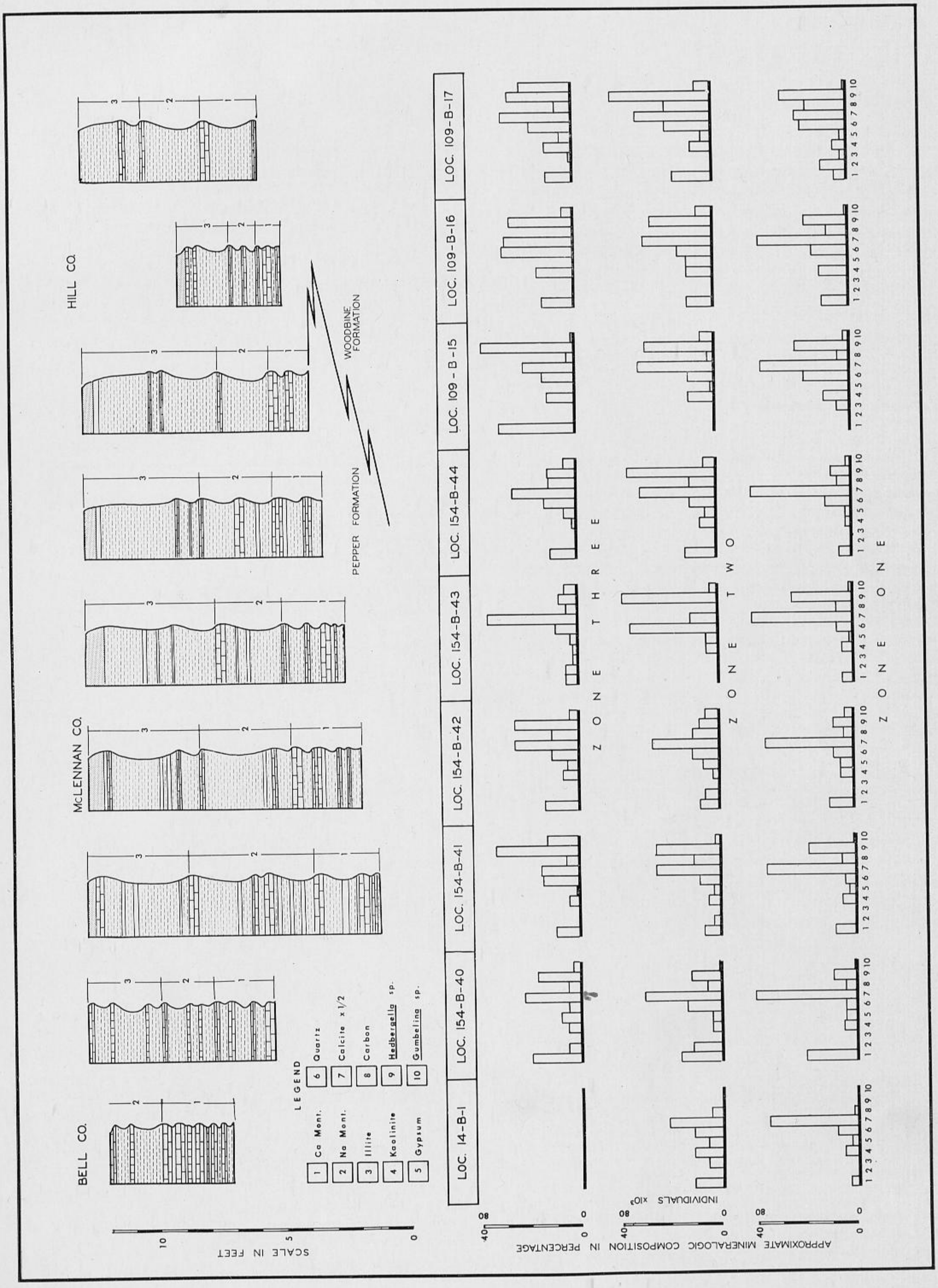
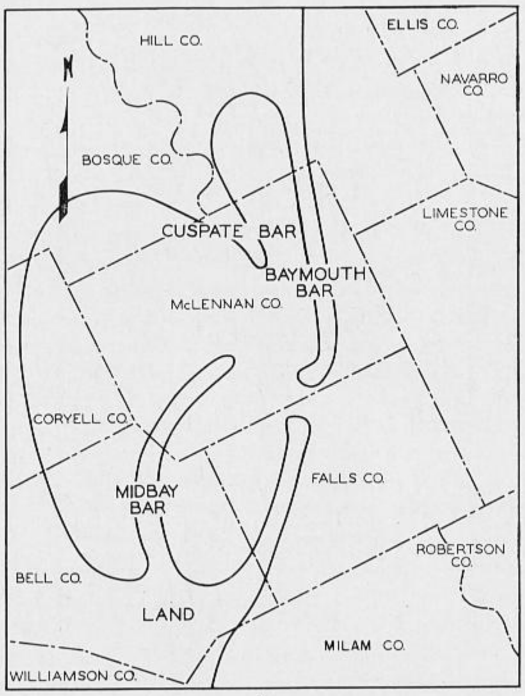
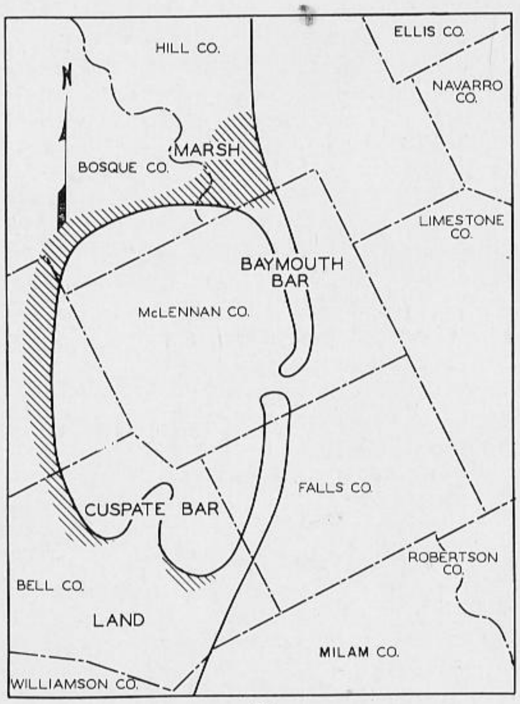


Fig. 12. Summary of mineralogy and fauna, zones 1, 2 and 3, Bluebonnet member, Lake Waco formation, central Texas.



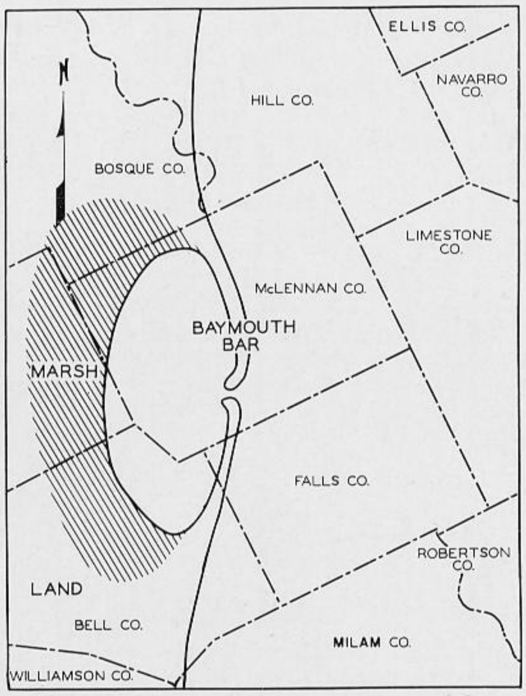
A

Youth. The baymouth bar is interpreted from subsurface data. Midbay and cuspate bars are represented by ripple-marked, cross-bedded, clastic limestone on the outcrop. Intervening shales are black, thinly laminated and carbonaceous. Planktonic microfossils are concentrated in shale beds adjacent to the inlet. Values of pH and Eh were probably between 7.8-8.6 and —0.1-0+ respectively with lower values restricted to marsh areas.



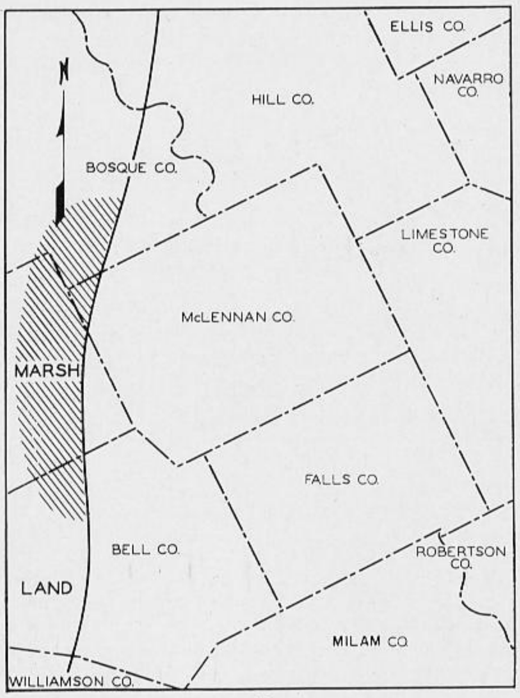
B

Late Youth. The midbay and cuspate bars of the youth stage receded. Clastic limestones are limited to the cuspate bar. Thinly laminated, highly carbonaceous black shale is the dominant lithology. Shale beds contain no benthonic fauna. Bentonite beds are common and widely distributed. Planktonic microfossils are more abundant and evenly distributed than in the youth stage. Values of pH and Eh were probably lower than those of youth, especially in marsh areas.



C

Early Mature. The lagoon was characterized by marsh deposition. Limestone beds are low energy biochemical deposits. Shale is the dominant rock type. Carbon, kaolinite, rhodochrosite, and planktonic microfossils reach maximum abundance. Calcite and calcium montmorillonite concentrations are minimum. Microfossils are in general evenly distributed. Values of pH were probably between 7.0-7.8; Eh was probably negative.



D

Mature. The lagoon was filled with marsh deposits and in part covered by the transgressing Cloice Sea. Depositional energy during early Cloice time was low, as suggested by widespread, thinly laminated shales of the lower Cloice member (Lake Waco formation). Low depositional energy resulted in preservation of unconsolidated marsh deposits of the lagoon. Transgression is evidenced by the gradation from Bluebonnet to Cloice deposition.

Fig. 13. Postulated evolution of Bluebonnet lagoon, central Texas.

be demonstrated—youth, late youth, early mature, and mature. The youthful stage is characterized by cuspate and mid-bay bars which are delineated by field relationships, sedimentary structures, composition, and fabric of the basal limestone bed. The late youthful stage is marked by marsh sedimentation and recession of cuspate and mid-bay bars. Planktonic foraminifers are concentrated in the shale beds near the lagoonal inlet. By early maturity the cuspate and mid-bay bars were covered by marsh deposits as a result of reduced circulation due to nearly complete closure of the lagoonal inlet. Marsh deposits were the predominant sediments during early maturity, while bentonite beds reached maximum thickness and areal distribution. In the mature stage of development, the lagoon was completely filled with marsh sediments and buried by deposits of the overlying Cloice member of the Lake Waco formation. Erosional energy during Cloice transgression was inadequate to remove unconsolidated marsh deposits in the upper Bluebonnet member.

(4) Bed by bed correlation is impossible, but the Bluebonnet member was divided into 3 distinct lithologic sequences or zones. Each zone is approximately time-equivalent in an east-west direction, but not necessarily in a north-south direction. Each zone represents a distinctive depositional and geochemical environment throughout the basin, with local variations such as bar, lagoon, and marsh areas.

(5) The geochemical environment of the Bluebonnet member is interpreted from the ratio of calcium montmorillonite to kaolinite, calcite, and rhodochrosite, as well as by fossil assemblage and sedimentary structures. During the youthful stage of the Bluebonnet lagoon the pH was slightly alkaline and Eh values were positive for both limestone and shale areas. The bar-deposited limestone beds in the late youthful stage of the Bluebonnet lagoon were deposited in an environment similar to that of the youthful stage; the shale beds were deposited at a pH near neutrality and at a negative Eh. Most of the shale beds in the early mature and mature stages of the Bluebonnet lagoon were deposited at a slightly acidic pH and a negative Eh.

(6) Post-depositional history of the Bluebonnet member is characterized by compaction, cementation, and recrystallization. Compaction resulted in approximately 45 percent decrease in original sedimentary thickness. Cementation of the bar-deposited limestone beds was due to contemporaneous precipitation of sparry calcite, and later pressure solution and reprecipitation. This may indicate rapid sedimentation and/or depletion of calcium carbonate from the depositional area due to a lowering of pH.

Recrystallization, which was a common diagenetic process in the Bluebonnet member, has commonly destroyed original depositional fabric. Grain seeding and grain growth, contemporaneous with cementation, are two of the most prominent types of recrystallization.

(7) Bluebonnet rock types are not unique to the map area (fig. 2). Similar rocks in the basal Eagle Ford group (often referred to as basal Eagle Ford flags) were observed as far south as the Del Rio area and as far north as Dallas (fig. 1). If these basal Eagle Ford flags are environmentally similar to the rocks of the Bluebonnet member, lagoonal deposition was common along the slowly transgressing Eagle Ford shoreline.

REFERENCES

ADKINS, W. S. (1923) Geology and mineral resources of McLennan County: Univ. Texas Bull. 2340, 202 pp.

ADKINS, W. S. (1928) Handbook of Texas Cretaceous fossils: Univ. Texas Bull. 2838, 385 pp.

ADKINS, W. S. (1932) The Mesozoic system in Texas *in* The Geology of Texas: Univ. Texas Bull. 3232, pp. 289-518.

ADKINS, W. S. and LOZO, F. E. (1951) Stratigraphy of the Woodbine and Eagle Ford, Waco area *in* The Woodbine and adjacent strata of the Waco area of central Texas: South. Meth. Univ., Fondren Sci. Ser. no. 4, pp. 105-164.

BATHURST, R. G. C. (1958) Diagenetic fabrics in some British Dinantian limestones: Liverpool and Manchester Geol. Jour., vol. 2, pp. 11-36.

BROWN, C. W. and PIERCE, R. L. (1962) Palynologic correlations in Cretaceous Eagle Ford group, northeast Texas: Bull. Am. Assoc. Petrol. Geol., vol. 46, pp. 2133-2147.

CHAMNESS, RALPH S. (1958) The Eagle Ford group *in* Guide to the mid-Cretaceous geology of central Texas: Baylor Geological Society guidebook, pp. 70-74.

FOLK, R. L. (1959) Practical petrographic classification of limestones: Bull. Am. Assoc. Petrol. Geol., vol. 43, pp. 1-38.

GARRELLS, R. M. (1960) Mineral equilibria at low temperature and pressure: Harper and Brothers, New York, 254 pp.

HILL, R. T. (1887) The Texas section of the American Cretaceous: Am. Jour. Sci., ser. 3, vol. 34, pp. 287-309.

———— (1901) Geography and geology of the Black and Grand Prairies, Texas: U. S. Geol. Survey, 21st Ann. Rept., pp. 323-328.

KRUMBEIN, W. C. and GARRELS, R. M. (1952) Origin and classification of chemical sediments in terms of pH and oxidation-reduction potentials: Jour. Geol., vol. 60, pp. 1-33.

LOEBLICH, A. R. and TAPPAN, H. (1961) Cretaceous planktonic Foraminifera, Part I, Cenomanian: Micropaleontology, vol. 7, no. 3, pp. 256-305.

LUCKE, J. B. (1939) A theory of evolution of lagoonal deposits on shorelines of emergence: Jour. Geol., vol. 42, pp. 561-584.

MARCOU, JULES (1862) Notes on the Cretaceous and Carboniferous rocks of Texas: Proc. Boston Soc. Nat. Hist., vol. 8, pp. 86-97.

MASON, BRIAN (1960) Principles of geochemistry: McGraw-Hill, New York, 385 pp.

MCKEE, EDWIN D., *et al.* (1956) Paleotectonic maps, Jurassic system: U. S. Geol. Survey, Miscel. Geol. Inv. map I-175. Paleogeography by Ralph W. Imlay.

MOREMAN, W. H. (1942) Paleontology of the Eagle Ford of north and central Texas: Jour. Paleontology, vol. 16, pp. 192-220.

PACE, LULA (1921) Geology of McLennan County, Texas: The Baylor Bulletin, Baylor University, vol. 24, no. 1, 25 pp.

PRATHER, J. K. (1902) South Bosque marl: Trans. Texas Acad. Sci., vol. 4, Pt. II, no. 8.

ROEMER, FERDINAND (1852) Die Kreidebildungen von Texas und ihre organischen Einschlüsse: Bonn (Germany), Adolph Marcus, 100 pp.

SHUMARD, B. F. (1860) Observations upon the Cretaceous strata of Texas: Trans. St. Louis Acad. Sci., vol. 1, pp. 582-590.

SILVER, BURR A. (1959) The stratigraphy of the Bluebonnet member, McLennan County, Texas: Baylor Univ. unpublished student geology paper no. 266.

STAUFFER, KARL W. (1962) Quantitative petrographic study of Paleozoic carbonate rocks, Caballo Mountains, New Mexico: Jour. Sed. Petrology, vol. 32, pp. 357-396.

STEPHENSON, L. W. (1955) Basal Eagle Ford fauna in Johnson and Tarrant counties, Texas: U. S. Geol. Survey, Prof. Paper no. 274-C, pp. 53-67.

TAFF, J. A. and LEVERETT, S. (1893) Report on the Cretaceous area north of the Colorado River: Texas Geol. Survey, 4th Ann. Rept., Pt. 1, pp. 239-354.

WELLER, J. M. (1959) Compaction of sediments: Bull. Am. Assoc. Petrol. Geol., vol. 43, pp. 273-310.

APPENDIX I

SUBSURFACE CONTROL[1]

Well No.		Bluebonnet Thickness (in feet)
1.	A. R. P. Oil Company, John P. Mascheck No. 1, Bell County. (31°01' N; 97°06' W)	13
2.	W. P. Luse, Voltin No. 1, Falls County. (31°01' N; 97°06' W)	13
3.	Humble Oil & Refining Company, Eleanor Carrol No. 1, Falls County. (31°06' N; 97°05' W)	11
4.	A. Delcambre, D. V. Doskocil No. 1, Falls County. (31°07' N; 97°07' W)	14
5.	Max Cohen, E. C. Stuart No. 1, Falls County. (31°09' N; 97°03' W)	9
6.	L. E. Lockhart, Silva No. 2, Falls County. (31°11' N; 97°01' W)	8
7.	Marlin Petroleum Company, Joe LaBarbeca No. 1, Falls County. (31°10' N; 96°51' W)	3
8.	Dail Goodson, J. B. Barganier No. 1, Falls County. (31°13' N; 96°50' W)	6
9.	Maury Hughes, Trustee, A. H. Bell, C. L. Trice No. 1, Falls County. (31°13' N; 97°01' W)	4
10.	W. P. Luse, Jones No. 4, Falls County. (31°14' N; 97°02' W)	16
11.	Jenkins & Perkins, Porter No. 1, Falls County. (31°14' N; 97°11' W)	1
12.	Ace Oil Company & Ray Holbert, Harrison No. 1, Falls County. (31°16' N; 97°01' W)	5
13.	P. W. Curry, Newman No. 1, Falls County. (31°17' N; 97°09' W)	22
14.	Bailey and Obermeyer, Warren Allen No. 1, Falls County. (31°16' N; 96°53' W)	4
15.	L. E. Miers and Dr. C. A. Greenwalt, O. R. Gilliam No. 1, Falls County. (31°17' N; 96°50' W)	3
16.	H. C. Pockburn and Zephyr Oil Company, N. D. Buie No. 1, Falls County. (31°16' N; 96°49' W)	3
17.	Paine, Eubank, No. 1, McLennan County. (31°20' N; 97°13' W)	10
18.	Jet Oil Company, Wills No. 1, McLennan County. (31°22' N; 97°15' W)	16
19.	Hamilton and Torrance, Guderian Est. No. 1, Falls County. (31°21' N; 97°06' W)	11
20.	Midstates Oil Corporation, B. E. Mitchell No. 1, Falls County. (31°23' N; 97°00' W)	8
21.	Gray Oil Company, Warren No. 1, McLennan County. (31°24' N; 97°12' W)	12
22.	Rosental Water Company, O'Dowd No. 1, McLennan County. (31°25'N; 97°06' W)	9
23.	J. E. Banks, Kerr No. 1, Falls County. (31°24' N; 96°58' W)	4
24.	A. R. Sheaf, Pavelka No. 1, Falls County. (31°25' N; 96°54' W)	12
25.	F. R. Jackson, Samuel B. Landrum No. 1, Falls County. (31°26' N; 97°50' W)	7
26.	Lone Star Gas Production Company, Criswell No. 1, Limestone County. (31°25' N; 96°42' W)	10
27.	Beacon Oil Company, Trice No. 1, McLennan County. (31°26' N; 97°14' W)	12
28.	Chapel Hill Water Company, Water Well No. 1, McLennan County. (31°27' N; 97°10' W)	13
29.	J. L. Myers, Waco Memorial Park No. 1, McLennan County. (31°28' N; 97°09' W)	9
30.	J. L. Myers, Youngblood No. 1, McLennan County. (31°28' N; 97°06' W)	12
31.	Max McCotter, Wardlaw No. 1, McLennan County. (31°29' N; 97°00' W)	19
32.	Layne Texas Company, Texas Power and Light Company No. 2, McLennan County. (31°28' N; 96°59' W)	20
33.	Riesel Ind. School Corporation, Riesel Ind. School Water Well No. 1, McLennan County. (31°28' N; 96°56' W)	17
34.	R. J. Caraway, Slaughter No. 1, McLennan County. (31°32' N; 96°53' W)	17
35.	J. L. Myers, City of Mart No. 1, McLennan County. (31°34' N; 96°55' W)	14
36.	Joe Thompson, Paul Shelby No. 1, McLennan County. (31°31' N; 97°09' W)	12
37.	J. L. Myers, Midway Ind. School District No. 1, McLennan County. (31°29' N; 97°13' W)	8
38.	Texas Water Company, Texas Water Company No. 3, McLennan County. (31°33' N; 97°10' W)	8
39.	J. L. Myers, Waco Water District 4, Well No. 1, McLennan County. (31°34' N; 97°05' W)	10
40.	Layne Texas Company, Texas Power and Light Company No. 1, McLennan County. (31°35' N; 97°07' W)	5
41.	J. L. Myers, Tiery No. 1, McLennan County. (31°36' N; 97°04' W)	6
42.	Mt. Carmel Center, Mt. Carmel Center No. 1, McLennan County. (31°35' N; 96°59' W)	16
43.	Balcones Oil Company, Jackson No. 1, Limestone County. (31°35' N; 96°49' W)	14
44.	M. M. Miller, J. C. Rogers No. 1, Limestone County. (31°34' N; 96°43' W)	12
45.	O. W. Killier, Stone No. 1, Limestone County. (31°37' N; 96°42' W)	18
46.	Hunt Oil Company, Union Central Life Ins. Company No. 1, Limestone County. (31°40' N; 96°45' W)	16
47.	William H. Winn, James L. Morrow No. 1, McLennan County. (31°39' N; 96°57' W)	20
48.	J. H. Snowden et al., Eubanks No. 1, McLennan County. (31°40' N; 96°58' W)	20
49.	Simon Korshoj, R. W. Ferguson No. 1, McLennan County. (31°41' N; 96°58' W)	22
50.	Layne-Texas Company, Connally Air Base No. 3. McLennan County. (31°39' N; 97°05' W)	14
51.	Lake-View Water Company, J. E. Passmore No. 1, McLennan County. (31°39' N; 97°07' W)	10
52.	Chalk Bluff Water Supply, Chalk Bluff No. 1, McLennan County. (31°40' N; 97°08' W)	9
53.	C. R. Porter, Kophal No. 1, McLennan County. (31°41' N; 97°04' W)	13
54.	Layne-Texas, Leroy-Tours-Gerald No. 1, McLennan County. (31°44' N; 97°01' W)	20
55.	Baylor University Geology Department, J. L. McCain No. 1, McLennan County. (31°45' N; 97°08' W)	6
56.	C. P. Quinlan, Prause No. 1, McLennan County. (31°47' N; 97°07' W)	8
57.	Camtex Oil Corporation, Cartwright No. 1, Hill County. (31°47' N; 96°54' W)	4
58.	Joe Thompson, Easter Doherty No. 2, Hill County. 31°48' N; 96°53' W)	7
59.	Eureka Tool Company, Daugherty No. 1, Hill County. (31°48' N; 96°51' W)	4
60.	Davidson and Fitzpatrick, Grant No. 1, Hill County. (31°47' N; 96°51' W)	6
61.	U. J. Hester et al., Beard No. 1, Hill County. (31°48' N; 96°50' W)	0
62.	St. Anthony Oil Corporation, Allen No. 1, Limestone County. (31°46' N; 96°42' W)	8
63.	A. O. Phillips and American Liberty, Vosburg No. 1, Hill County. (31°50' N; 96°55' W)	7
64.	J. L. Myers, Penelope Water Well No. 1, Hill County. (31°52' N; 96°55' W)	4
65.	C. R. Porter, E. D. Mazanec No. 1, McLennan County. (31°50' N; 97°05' W)	12
66.	R. J. McMurrey, Joe F. Janek No. 1, Hill County. (31°52' N; 96°52' W)	6
67.	C. A. Lee, Hight No. A-1, Hill County. (31°53' N; 96°48' W)	3
68.	George Rahal, Lewis Martin No. 1, Hill County. (31°58' N; 96°50' W)	6

[1]Refer to figure 2 for location of wells.

APPENDIX II

MEASURED SECTIONS[1]

Unit	Lithology	Thickness (feet)

LOCALITY 14-B-1 (Fig. 3)

In south bank of Leon River approximately 800 yards north of Farm Road 496, about 3.8 miles southeast of intersection of State Highway 317 and U. S. Highway 190, and approximately 7 miles southwest of intersection of State Highway 36 and U. S. Highway 81, Bell County, Texas (31°01' N; 97°25' W). Limestone 56%; shale 44%.

Unit	Lithology	Thickness (feet)
	Bluebonnet Member (Lake Waco formation)	
9	Shale, tan, severely weathered, weathers buff	1.0
8c	Limestone, tan, micro-crystalline calcite matrix, thinly bedded, moderate porosity, weathers buff	0.3
8b	Shale, covered	0.6
8a	Limestone, tan, micro-crystalline calcite matrix, thinly bedded, moderate porosity, weathers buff	0.1
7	Shale, gray, fissile, thinly laminated, calcareous, severely weathered, weathers tan	1.7
6	Limestone, tan to brown, medium-bedded, micro-crystalline calcite matrix, porous, ripple-marked on upper surface, wavy-bedded, 2-inch bentonite separating unit from underlying limestone, weathers tan	0.7
5	Limestone, tan to brown, medium-bedded, fine-grained, moderate porosity, opposing ripple marks on upper surface, wavy-bedded, ½-inch bentonite seam separating unit from underlying limestone, weathers tan	0.6
4	Limestone, tan to brown, fine-grained, moderate porosity, ripple-marked on upper surface, wavy-bedded, 1-inch bentonite seam in middle, weathers tan	0.7
3	Shale, gray to black, fissile, thinly laminated, calcareous, weathers tan; intercalated with two limestone beds	0.5
2	Limestone and shale. Limestone, tan to brown, fine-grained, well sorted and poorly rounded grains, thinly laminated, well cemented, **Inoceramus** fragments, moderate porosity, cross-bedded, wavy-bedded, weathers brown; two intercalated shale beds, gray, fissile, thinly laminated, calcareous, weather tan	1.0
	Pepper Formation	
1	Shale, gray, indurated, blocky, slightly calcareous, jarosite on weathered surface, weathers light gray	21.7
	Total	28.9

LOCALITY 14-B-2 (Fig. 3)

In bank of Pepper Creek approximately 400 yards southeast of U. S. Highway 81, about 4 miles northwest of intersection of State Highway 317 and U. S. Highway 190, and approximately 4 miles southwest of intersection of State Highway 36 and U. S. Highway 81, Bell County, Texas (31°05' N; 97°24' W). Limestone 31%; shale 57%; bentonite 12%.

Unit	Lithology	Thickness (feet)
	Bluebonnet Member (Lake Waco formation)	
6	Shale, tan, slightly fissile, slightly laminated, calcareous, severely weathered, weathers buff	2.0
5	Limestone, tan, thinly bedded, micro-crystalline calcite matrix, excellent porosity, limonitic, weathers light-tan, bentonite at base of unit	0.3
4	Limestone, tan to brown, medium-bedded, micro-crystalline calcite matrix, moderate porosity, wavy-bedded, extremely fossiliferous at top, weathers buff	0.7
3	Bentonite, yellow to tan, severely weathered	0.5
2	Shale and limestone. Shale, gray, laminated, calcareous, weathers tan; limestone, gray, fine-grained, well sorted and poorly rounded grains, well cemented, medium-bedded, ripple-marked, wavy-bedded, low porosity, **Inoceramus** fragments, weathers tan to buff	0.6
	Pepper Formation	
1	Shale, gray, indurated, blocky, non-calcareous, jarosite on weathered surface, weathers light-gray	1.0
	Total	5.1

LOCALITY 14-B-3

In road cut on Farm Road 2601, 0.5 mile west of intersection with State Highway 317, about 4.4 miles southwest of Moody, and 6.6 miles north-northeast of intersection of State Highways 36 and 317, Bell County, Texas (31°15' N; 97°23' W).

Unit	Lithology	Thickness (feet)
	Bluebonnet Member (Lake Waco formation)	
10	Shale, severely weathered, 3 thin lenticular limestone beds	4.0
9	Limestone, tan, very thinly bedded, very finely crystalline, weathers tan	0.3
8	Shale and limestone, severely weathered	0.6
7	Shale, severely weathered	1.0
6	Limestone, tan, thinly bedded, micro-crystalline matrix, vugular porosity with clay and limonite filling many vugs, weathers brown	0.4
5	Shale, severely weathered	0.6
4	Limestone, severely weathered, thin bentonite seam separating limestone beds, highly limonite-stained	0.6
3	Shale, covered	1.0
2	Limestone, blue-gray, thinly bedded, coarse-grained, micro-crystalline calcite matrix, **Inoceramus** fragments, weathers tan	0.3
	Pepper Formation	
1	Shale, black, fissile, blocky, jarosite on weathered surface, non-calcareous, weathers gray	4.3
	Total	13.1

LOCALITY 154-B-40 (Fig. 4)

In west facing slopes of Moody Hills approximately 900 yards east of State Highway 317, approximately 4 miles south-southeast of McGregor, and 5 miles north-northwest of Moody, McLennan County, Texas (31°23' N; 97°22' W). Limestone 31%; shale 68%; bentonite 1%.

Unit	Lithology	Thickness (feet)
	Cloice Member (Lake Waco formation)	
18	Shale, tan, fissile, very poorly laminated, calcareous, weathers light-tan	3.2
	Bluebonnet Member (Lake Waco formation)	
17	Bentonite, yellow	0.2
16	Limestone, tan, thinly bedded, porous, high carbonaceous content including cycad fragments, weathers light-tan	0.2
15	Shale, tan, fissile, poorly laminated, calcareous, severely weathered, weathers buff	1.0
14	Limestone, tan, thinly bedded, very finely crystalline, planktonic Foraminifera, etched surface, weathers buff	0.2
13	Shale, tan, fissile, thinly laminated, calcareous, severely weathered, weathers buff	1.6
12	Limestone, tan, thinly bedded, very finely crystalline, excellent porosity, planktonic Foraminifera, weathers buff	0.1
11	Shale, gray to black, fissile, thinly laminated, calcareous, weathers buff	0.7
10	Limestone, gray, thinly bedded, micro-crystalline calcite matrix, excellent porosity, lenticular, weathers tan	0.2
9c	Shale, gray to black, fissile, thinly laminated, calcareous, slight limonite content, weathers buff; thin bentonite bed at base	1.0
9b	Covered	1.0
9a	Shale, gray to black, fissile, thinly laminated, calcareous, slightly limonitic, weathers buff, 4-inch bentonite bed in middle of unit	1.0
8	Limestone, light-brown, thinly bedded, micro-crystalline calcite matrix, porous, limonitic, weathers buff	0.3
7	Shale, gray, fissile, thinly laminated, calcareous, weathers buff; thin bentonite bed in upper half	0.7
6	Limestone, light-brown, thinly bedded, micro-crystalline calcite matrix, porous, weathers buff	0.2
5	Limestone and shale. Limestone, light-brown, thinly bedded, micro-crystalline calcite matrix, low porosity, weathers buff. Shale, gray, fissile, thinly laminated, calcareous, weathers buff	0.5
4	Limestone, brown, thinly bedded, fine to medium-grained, crystalline, moderate porosity, wavy-bedded, cross-bedded, weathers buff	0.3
3	Bentonite, yellow to tan, severely weathered	0.1
2	Shale and limestone interbedded. Shale, gray fissile, laminated, calcareous, phosphate nodules and sharks teeth near base. Limestone, gray, medium-bedded, medium-grained, dominant constituents are **Inoceramus** fragments, bonded by micro-crystalline matrix	0.2
	Pepper Formation	
1	Shale, gray to black, indurated, non-calcareous, blocky, jarosite on weathered surface, weathers light-gray	23.1
	Total	35.8

LOCALITY 154-B-41 (Fig. 5)

In east bank of South Cow Bayou, 50 yards downstream from county road, about 9 miles southeast of McGregor and approximately 5 miles northeast of Moody, McLennan County, Texas (31°22' N; 97°17' W). Limestone 17%; shale 75%; bentonite 8%.

Unit	Lithology	Thickness (feet)
	Cloice Member (Lake Waco formation)	
21	Covered	4.0
20	Shale, tan, fissile, poorly laminated, calcareous, several intercalated beds of bentonite, weathers tan	3.3
	Bluebonnet Member (Lake Waco formation)	
19	Bentonite-calcilutite. Bentonite, yellow, glass shards; calcilutite, yellowish-tan, finely crystalline, well sorted grains, excellent porosity	0.2
18	Limestone, brown, thinly laminated, micro-crystalline calcite matrix, porous, lenticular, weathers yellowish-tan	0.4
17	Shale-bentonite, interbedded, severely weathered	0.5
16	Shale, gray, fissile, thinly laminated, calcareous, interbedded with 2 and 3-inch thick bentonite seams; 2 inches of limestone at top of unit, shale weathers buff	1.5
15	Shale, gray to black, fissile, thinly laminated, calcareous, interbedded with limestone and bentonite, weathers light-gray	2.3
14	Limestone, gray, thinly bedded, micro-crystalline calcite matrix, porous, high carbonaceous content, weathers buff	0.4
13	Shale, gray to black, fissile, laminated, high carbonaceous content, calcareous, concretions of bedded limestone, weathers buff. Two thin bentonite beds, 1.0 foot and 2.5 feet from base of unit respectively	2.7
12	Shale, gray to black, fissile, thinly laminated, carbonaceous, calcareous, weathers light-gray; 3-inch silty limestone bed overlies shale	0.5
11	Limestone, gray, thinly bedded, micro-crystalline calcite matrix, porous, **Inoceramus** fragments, weathers gray	0.4

[1]Refer to figure 2 for location.

10 Bentonite and shale. Bentonite, yellowish-tan, lenticular, severely weathered; shale, gray, fissile, poorly laminated, calcareous, weathers tan ---------------------------------------0.4
9 Shale, gray to black, thinly laminated, fissile, calcareous, silty, 3 thin beds of bentonite, weathers tan ----------------------2.0
8 Limestone, gray to tan, medium-bedded, micro-crystalline calcite matrix, **Inoceramus** fragments near top, porous, weathers light-brown to gray ------------------------------------0.4
7 Shale, gray to black, fissile, thinly laminated, calcareous, silty, weathers buff --0.8
6 Bentonite, yellow to tan, lenticular ----------------------0.3
5 Shale, gray to black, fissile, thinly laminated, calcareous, weathers buff ---------------------------------------0.5
4 Limestone, fine-grained, moderately sorted, poorly rounded and well cemented, **Inoceramus** fragments, moderate porosity, cross-bedded, wavy-bedded, ripple-marked, weathers tan --------0.4
3 Bentonite, yellow to tan, severely weathered ----------------0.1
2b Limestone, tan to brown, fine-grained, well sorted, moderately rounded and well cemented grains, elongate phosphate modules at lower contact, **Inoceramus** fragments, cross-bedded, weathers tan to brown --0.3
2a Shale, gray, fissile, thinly laminated, calcareous, fecal pellets, weathers light-gray -------------------------------------0.3

Pepper Formation
1 Shale, gray to black, fissile, blocky, jarosite on weathered surface, non-calcareous, weathers light-gray ---------------------1.2

Total---------------22.9

LOCALITY 154-B-42 (Fig. 6)

In northwestern bluff of South Bosque brick yard, about 7 miles southwest of intersection of U. S. Highway 84 and State Highway 6, approximately 9 miles northeast of McGregor, McLennan County, Texas (31°29' N; 97°15' W). Limestone 14%; shale 78%; bentonite 8%.

Cloice Member (Lake Waco formation)
18 Shale, gray to tan, fissile, laminated, calcareous, high iron content, weathers tan --2.0

Bluebonnet Member (Lake Waco formation)
17b Bentonite-calcilutite. Bentonite, severely weathered, grades into argillaceous calcilutite, very fine-grained, well sorted grains, high clay content, weathers light-brown ----------------------0.6
17a Shale, gray, fissile, laminated, calcareous, weathers tan --------0.4
16 Limestone, light-gray, laminated, finely crystalline, porous, contorted bedding, weathers tan ----------------------------0.2
15 Shale, gray, fissile, thinly laminated, calcareous, contains 2 bentonite beds near base, weathers light-gray ---------------3.2
14 Shale-bentonite. Shale, gray, fissile, poorly laminated, calcareous, weathers tan; bentonite, yellow -----------------------0.5
13 Shale-bentonite. Shale, gray, fissile, laminated, calcareous, weathers tan; bentonite, severely weathered -------------------0.5
12 Limestone, light-gray, laminated, finely crystalline, porous, contorted bedding, weathers tan to buff ---------------------0.2
11 Shale, gray to black, fissile, thinly laminated, calcareous, highly carbonaceous, weathers gray --------------------------1.2
10 Limestone, blue, thinly laminated, finely crystalline, porous, lenticular, weathers gray ----------------------------------0.2
9 Shale, gray, fissile, thinly laminated, calcareous, high carbonaceous content, 3-inch bentonite at base of unit is severely weathered, shale weathers gray ------------------------------3.7
8 Limestone, gray to brown, laminated, micro-crystalline calcite matrix, **Inoceramus** fragments near base, moderate porosity, weathers gray --0.4
7 Shale, gray, fissile, thinly laminated, calcareous, limonitic at base, weathers buff to tan --------------------------------0.7
6 Limestone, blue to gray, thinly laminated, distorted laminae, micro-crystalline matrix, dense, weathers gray; thin bentonite bed at base of unit --0.5
5 Shale, gray to black, fissile, thinly laminated, calcareous, oysters and sharks teeth common, weathers light-gray ----------0.6
4 Limestone, tan to white, very thinly bedded, micro-crystalline calcite matrix, porous, wavy-bedded, weathers gray to white ----0.6
3 Shale, gray to black, fissile, laminated, calcareous, limonitic, weathers tan ---0.5
2 Shale, gray to black, fissile, laminated, calcareous, phosphate nodules and sharks teeth near base, contains 2 thin beds of moderately crystalline limestone, weathers light-gray ----------1.2

Pepper Formation
1 Shale, gray, indurated, blocky, non-calcareous, jarosite on weathered surface, weathers light gray ----------------------27.7

Total----------------44.9

LOCALITY 154-B-43 (Fig. 7)

In ditch, 400 yards from county road, about 4.5 miles west of intersection of U. S. Highway 84 and State Highway 6, about 12 miles northeast of McGregor, McLennan County, Texas (31°30' N; 97°14' W). Limestone 12%; shale 78%; bentonite 10%.

Cloice Member (Lake Waco formation)
15 Covered --2.0
14 Shale, gray to tan, slightly fissile, laminated, calcareous, weathers tan --3.0

Bluebonnet Member (Lake Waco formation)
13 Bentonite-calcilutite. Bentonite, yellow, grades into calcilutite; calcilutite, yellow to tan, well sorted grains, weathers tan --0.9
12 Shale, gray to black, fissile, thinly laminated, calcareous, weathers tan, contains 4 bentonite beds ---------------------3.0
11 Bentonite, yellow to tan; extensive fractured shale seam in center of bentonite bed ------------------------------------0.5
10 Shale, gray to black, fissile, thinly laminated, calcareous, contains limestone concretions, lenticular coal seam, weathers light-gray ---2.1

9 Limestone, blue, thinly laminated, cross-laminated, finely crystalline, porous, weathers gray --------------------------0.7
8 Shale, gray to black, fissile, thinly laminated, calcareous, weathers light-gray; two thin bentonite beds in upper half of unit --2.6
7 Limestone, dark-gray, thinly bedded, very finely crystalline, **Inoceramus** fragments near top, moderate porosity, weathers gray; thin bentonite bed at base --------------------------0.4
6 Shale, gray, fissile, thinly laminated, calcareous, weathers gray --1.0
5 Limestone, blue, thinly laminated, very finely crystalline, porous, contorted bedding, weathers gray -------------------0.2
4 Shale, gray, fissile, thinly laminated, calcareous, weathers light-gray --0.6
3 Limestone, dark-gray, thinly laminated, micro-crystalline calcite matrix, porous, some distorted laminae, weathers light-gray -----0.5
2 Shale, dark gray, fissile, thinly laminated, calcareous, phosphate nodules, sharks teeth, 2 thin limestone beds, weathers light-gray ---0.7

Pepper Formation
1 Shale, dark gray, fissile, blocky, fractured, non-calcareous, weathers light-gray --5.2

Total---------------23.4

LOCALITY 154-B-44 (Fig. 8)

In tributary of Aquilla Creek, about 1,000 yards north of county road, about 21 miles south of Hillsboro, and about 11 miles north of Waco, McLennan County, Texas (31°44' N; 97°09' W). Limestone 17%; shale 80%; bentonite 3%.

Cloice Member (Lake Waco formation)
19 Covered --2.3
18 Limestone, gray, very thinly laminated, very finely crystalline, argillaceous, weathers tan ------------------------------0.2
17 Shale, gray to tan, fissile, laminated, calcareous, weathers buff to light-gray ---3.0
16 Limestone, gray, very thinly laminated, very finely crystalline, argillaceous, some **Inoceramus** fragments, weathers tan --------0.2
15 Shale, gray to tan, fissile, laminated, calcareous, weathers buff to light-gray ---3.7

Bluebonnet Member (Lake Waco formation)
14 Calcilutite, yellow, argillaceous, weathers light-tan to reddish-brown --0.7
13 Bentonite, yellow to white, fractured -----------------------0.2
12 Shale, gray to tan, fissile, laminated, calcareous, jointed near top, weathers tan to gray --------------------------------3.6
11 Limestone, tan, thinly laminated, finely crystalline, porous, **Inoceramus** at base, weathers light-tan -----------------------0.2
10 Shale, light-gray, thinly laminated, calcareous, thin bed of pseudo-aragonite near middle, weathers light-gray -------------1.0
9 Limestone, light-gray, thinly laminated, distorted laminae, porous, weathers brownish-gray ---------------------------0.2
8 Shale, tan to gray, fissile, thinly laminated, calcareous, thin bentonite bed about 5 inches above base of unit, weathers light-tan --1.2
7 Limestone, gray to tan, thinly laminated, finely crystalline, porous, weathers light-gray --------------------------------0.4
6 Shale, gray to black, fissile, laminated, calcareous, thin bentonite bed 18 inches from base of unit, weathers light-gray ------2.0
5 Limestone, blue to tan, **Inoceramus** fragments (some whole specimens) in micro-crystalline calcite matrix, weathers brown --0.6
4 Bentonite, yellow to white, lenticular -----------------------0.2
3 Shale, gray to black, fissile, thinly laminated, calcareous. Limestone, tan, fine to very fine-grained, lenticular, near top of unit, weathers light-gray -----------------------------0.8
2b Limestone, blue, fine-grained, moderately sorted to well sorted and well cemented grains, cross-bedded, thinly bedded, low porosity, fossiliferous, weathers gray -----------------------0.5
2a Shale, gray to black, fissile, laminated, calcareous, phosphate nodules, sharks teeth, intercalated thin limestone beds, weathers light-gray ---0.5

Pepper Formation
1 Shale, gray to black, indurated, blocky, non-calcareous, jarosite on weathered surface, weathers dark-gray -------------4.1

Total---------------25.6

LOCALITY 154-B-45 (Fig. 9)

In tributary of Aquilla Creek, about 200 yards west of county road, about 15 miles south of Hillsboro, and about 4 miles west of West, McLennan County, Texas (31°47' N; 97°11' W). Limestone 14%; shale 80%; bentonite 6%.

Bluebonnet Member (Lake Waco formation)
11 Limestone, buff, thinly bedded, abundant carbonized plant material, weathers light-tan ---------------------------------0.4
10 Shale, gray to black, fissile, slightly laminated, calcareous, weathers gray to tan ------------------------------------0.8
9 Bentonite --0.3
8 Covered --?
7 Shale, severely weathered ---------------------------------1.0
6 Shale, tan, slightly fissile, slightly laminated, calcareous, weathers buff --0.4
5 Limestone, tan, thinly laminated, very finely crystalline, abundant carbonized plant material on upper surface, unevenly bedded, weathers buff --0.2
4 Calcilutite, yellow, weathers buff to light-tan ----------------0.2
3c Shale, light-gray, fissile, laminated, calcareous, some carbonized plant material, weathers buff ------------------------------0.4
3b Limestone, tan, very finely crystalline, thinly bedded, weathers buff ---0.2
3a Shale, tan, fissile, slightly laminated, calcareous, weathers buff ---0.2
2b Limestone, blue to gray, very thinly laminated, micro-crystalline calcite matrix, porous, weathers yellow to tan ----0.2-1.0
2a Shale, gray to black, fissile, laminated, calcareous, weathers light-gray to tan --0.1

Pepper Formation
1 Shale, gray to black, indurated, blocky, jointed, non-calcareous, jarosite on weathered surface, weathers light-gray ------8.2

Total---------------12.6+

LOCALITY 154-B-46

In tributary of South Fork of Cow Bayou, about 400 yards west of Farm Road 2113, approximately 8 miles south-southeast of McGregor and about 3 miles north-northeast of Moody, McLennan County, Texas (31°21' N; 97°18' W).

Cloice Member (Lake Waco formation)
4 Shale, covered --22.0

Bluebonnet Member (Lake Waco formation)
3 Shale and limestone, severely weathered. About 6 limestone beds alternating with shale beds approximately 2 feet thick. Several thin beds of bentonite; petrified wood fragments common near base --15.3
2 Limestone, blue-gray, medium-grained, well sorted, very poorly rounded and well cemented grains, cross-bedded, ripple-marked, **Inoceramus** fragments, low porosity, weathers brown -----------1.2

Pepper Formation
1 Shale, black, fissile, blocky, non-calcareous, jarosite on weathered surface, weathers gray ------------------------------5.7

Total---------------44.2

LOCALITY 109-B-15 (Fig. 9)

In tributary of Aquilla Creek, about 600 yards west of county road, approximately 4 miles northwest of West, and about 11 miles south of Hillsboro, Hill County, Texas (31°53' N; 97°11' W). Limestone 15%; shale 85%.

Bluebonnet Member (Lake Waco formation)
11 Shale, tan, fissile, very poorly laminated, calcareous, carbonized plant material common, weathers light-tan ----------------2.4
10c Limestone, tan, thin-bedded, finely crystalline, limonitic, carbonized organic material common, weathers buff ------------0.2
10b Shale, tan, fissile, poorly laminated, calcareous, weathers buff---0.4
10a Limestone, tan, thin-bedded, finely crystalline, carbonized organic material common, weathers buff -----------------------0.2
9 Shale, gray, fissile, laminated, calcareous, weathers tan --------2.0
8 Limestone, tan, very finely crystalline, weathers light-tan ------0.2
7 Shale, gray, fissile, thinly laminated, calcareous, weathers tan ----2.2
6 Limestone, blue, laminated, finely crystalline, laminae not continuous, weathers light-tan ---------------------------------0.5
5 Shale, gray, fissile, thinly laminated, calcareous, limonitic, weathers tan ---0.4
4 Limestone, blue to gray, very thinly laminated, micro-crystalline calcite matrix, porous, weathers yellow to tan -------------0.6
3 Shale, tan, fissile, slightly laminated, calcareous, weathers tan ---0.4

Woodbine Formation
2b Shale, tan, indurated, blocky, sandy, calcareous, weathers tan ----0.5
2a Sandstone, tan, medium to fine-grained, sub-angular to sub-rounded, well sorted grains, friable, weathers tan ------------0.5
1 Sandstone, tan, medium to fine-grained, sub-angular to sub-rounded, well sorted grains, friable, weathers tan ------------17.7

Total---------------28.2

LOCALITY 109-B-16 (Fig. 10)

In north bank of Cobb Creek, about 200 yards west of county road, about 7.8 miles northwest of West, and about 7.4 miles southwest of Hillsboro, Hill County, Texas (31°56' N; 97°11' W). Limestone 30%; shale 66%; bentonite 4%.

Cloice Member (Lake Waco formation)
13 Shale, tan, fissile, very poorly laminated, carbonaceous, severely weathered at top of unit, weathers dark-tan ----------2.3

Bluebonnet Member (Lake Waco formation)
12 Bentonite, yellow ---0.2
11 Shale, gray, fissile, poorly laminated, calcareous, carbonaceous, weathers buff; thin limestone bed at top of unit --------------2.0
10 Limestone, tan, very finely crystalline, porous, high limonite content, weathers buff; 1-inch shale near middle --------------0.4
9 Shale, gray, fissile, laminated, calcareous, bentonitic, weathers buff --1.6
8 Limestone, buff, thin-bedded, finely crystalline, porous, alternating light and dark bedding, fossiliferous near top, weathers dark-brown ---0.3
7 Shale, gray, fissile, thinly laminated, calcareous, bentonitic, weathers buff ---0.4
6 Limestone, blue to gray, thinly laminated, finely crystalline, porous, **Inoceramus** and ammonites, weathers buff ------------0.3
5 Calcilutite, yellow, fine-grained, friable, bentonite near top of unit ---0.5
4 Limestone, gray, thinly laminated, micro-crystalline calcite matrix, slightly cross-laminated, porous, weathers buff; thin interbedded shale ---0.6
3 Limestone, tan, medium to fine-grained, well-sorted, poorly rounded and well cemented grains, cross-bedded, **Inoceramus** fragments, low porosity, weathers brown --------------------0.3

Woodbine Formation
2 Sandstone, tan, medium to fine-grained, sub-angular to sub-rounded grains, calcite cemented, friable, limonite-stained, weathers brown --0.6
1 Sandstone, buff, medium to fine-grained, sub-angular to sub-rounded grains, friable, limonite-stained, weathers tan ----------2.0

Total---------------11.5

LOCALITY 109-B-17 (Fig. 11)

In small creek, 300 yards north of county road, about 4.5 miles south-southwest of Hillsboro and about 4 miles south-southeast of Peoria, Hill County, Texas (31°57' N; 97°11' W). Limestone 35%; shale 63%; bentonite 2%.

Cloice Member (Lake Waco formation)
13 Shale, gray to tan, poorly laminated, calcareous, weathers buff ---2.0

Bluebonnet Member (Lake Waco formation)
12 Bentonite, yellow, severely weathered ------------------------0.2
11 Shale, gray, fissile, thinly laminated, calcareous, weathers buff --1.7
10 Limestone and shale. Limestone, tan, very finely crystalline, very porous, high limonite content, weathers buff; shale, gray, poorly laminated, calcareous, carbonaceous, weathers buff ------0.3
9 Shale, gray, fissile, thinly laminated, calcareous, carbonaceous, lenticular beds of coal, weathers buff. Thin limestone bed in lower third of unit --0.7
8 Limestone, yellow to gray, laminated, very finely crystalline, silty and porous, weathers buff -----------------------------0.2
7 Shale, gray, fissile, laminated, calcareous, jointed, with clay in joints, weathers buff --------------------------------------2.7
6 Limestone, yellow to gray, laminated, very finely crystalline, very porous, **Inoceramus** at top, weathers buff -----------------0.4
5 Shale, gray to black, fissile, thinly laminated, calcareous, weathers buff; 1-inch bentonite bed in middle of unit ----------0.7
4 Limestone and shale. Limestone, gray, finely crystalline, high limonite content, porous, weathers light-brown ----------------0.7
3 Shale, gray to tan, fissile, slightly laminated, calcareous, sandy, weathers buff --0.8
2 Limestone, blue to gray, fine-grained, well-sorted, moderately rounded grains, cross-bedded, **Inoceramus** fragments, porous, weathers brown ---0.2

Pepper Formation
1 Shale, gray to dark gray, indurated, blocky, calcareous, jarosite on weathered surface, weathers light-gray -------------------1.6

Total---------------12.2

LOCALITY 109-B-18

In ditch along county road, about 5.5 miles west of Hillsboro and about 1.3 miles north of Peoria, Hill County (32°00' N; 97°14' W).

✓Bluebonnet Member (Lake Waco formation)
2 Limestone, blue-gray, medium-grained, poorly sorted, poorly rounded grains, micro-crystalline calcite matrix, **Inoceramus** and ammonite fragments, reptile vertebrae common, weathers tan -1.2

Woodbine Formation
1 Orthoquartzite, tan, fine-grained, moderately sorted and medium-rounded grains, massive-bedded, calcite cement, low porosity, weathers buff --2.2

Total---------------3.4

LOCALITY 109-B-19

In small creek, 15 yards south of county road, about 7 miles northwest of Hillsboro and about 7 miles northeast of Peoria, Hill County, Texas (32°05' N; 97°13' W).

Eagle Ford Group
3 Shale, severely weathered, several thin limestone beds (1-inch or less thick) near top of unit ----------------------------2.0+
2 Clay, tan, bentonitic, weathers buff -------------------------3.2

Woodbine Formation
1 Orthoquartzite, medium-grained, moderately sorted and moderately rounded grains, massive-bedded, calcite cement, low porosity, weathers buff --3.1

Total---------------8.3+

APPENDIX III

MINERALOGIC PERCENTAGES DETERMINED BY X-RAY DIFFRACTION

Unit No.	Calcium Montmorillonite	Sodium Montmorillonite	Illite	Kaolinite	Gypsum	Quartz	Calcite	Carbon
LOCALITY 14-B-1								
1	--	--	--	5	2	60	30	2
2a	--	--	5	20	3	18	50	2
2b	--	--	--	5	--	4	90	--
2c	--	--	5	20	4	16	50	2
2d	--	--	--	8	--	2	90	--
3a	30	--	15	15	--	15	20	3
3b	10	--	5	--	--	4	82	--
3c	30	--	15	15	--	15	20	3
3d	10	--	5	--	--	4	82	--
4	4	--	--	--	--	5	90	2
5	5	--	--	--	--	--	95	1
6	2	--	--	--	--	8	90	1
8a	8	--	--	--	--	--	90	1
8b	Covered							
8c	8	--	--	--	--	--	90	1
LOCALITY 14-B-2								
1	25	--	--	--	5	45	12	11
2a	18	--	--	2	2	20	54	--
2b	--	--	--	6	--	4	90	--
4	3	--	--	--	--	--	96	1
5	10	--	--	2	--	--	88	--
LOCALITY 14-B-3								
4	--	--	--	--	--	--	90	8
LOCALITY 154-B-40								
1	20	--	--	15	--	60	--	3
2	5	--	--	--	--	12	72	4
3	44	--	--	12	--	8	36	--
4	5	--	--	--	--	1	93	1
5	5	--	--	--	--	1	90	3
6	--	--	--	--	--	1	95	--
7	10	--	--	5	--	8	75	2
8	5	--	--	--	--	1	94	1
9a	--	40	--	5	--	--	50	5
9b	Covered							
9c	40	--	--	--	--	10	50	3
10	--	12	--	--	--	1	85	1
11	5	--	--	--	1	12	70	7
12	--	5	--	--	--	1	85	2
13	20	--	--	5	--	10	55	5
14	5	--	--	--	2	1	85	4
15*	25	--	--	5	--	8	55	5
16	5	--	--	5	--	1	85	1
17a	70	--	--	24	--	6	--	--
17b	18	--	--	14	--	4	60	7
LOCALITY 154-B-41								
1	20	--	--	15	--	60	--	--
2a	15	--	--	15	1	5	65	1
2b	--	--	--	--	--	1	94	1
3	Severely weathered							
4	--	--	--	--	1	1	94	1
5	15	--	--	10	4	10	44	10
6	15	--	--	--	8	4	78	--
7	5	5	--	--	2	5	70	7
8	--	--	--	--	--	3	92	1
9a	15	--	--	10	12	--	52	9
9b	5	--	--	5	5	8	60	11
10	15	--	--	5	5	8	65	2
11	10	--	--	--	1	2	85	1
12	15	--	--	10	1	10	60	6
13a	25	--	--	5	1	15	45	9
13b	10	--	--	8	--	15	55	8
14	5	--	--	--	2	2	89	2
15a	10	--	--	--	2	10	70	7
15b	15	--	--	5	2	10	60	9
16a	85	--	--	15	--	--	--	--
16b	50	--	--	20	1	2	15	10
17	20	--	--	--	--	10	60	5
18	10	--	--	--	--	1	86	2
19	90	--	--	--	--	10	--	--
20	10	--	5	--	--	--	75	3
LOCALITY 154-B-42								
1	20	15	--	15	2	40	--	8
2a	10	--	--	5	5	10	65	5
2b	10	--	--	3	8	8	60	7
3	5	--	10	--	10	10	55	10
4	--	--	--	--	--	2	90	3
5	10	--	--	10	2	6	65	8
6a	20	--	--	15	3	1	60	--
6b	--	--	--	--	1	1	90	1
7	10	--	--	5	2	8	60	13
8	--	10	--	--	--	--	88	2
9	10	10	--	--	8	10	50	11
10	10	--	--	--	1	2	85	2
11	18	--	16	8	2	6	50	2
12	5	--	--	--	--	2	85	6
13a	15	--	--	5	5	5	60	9
13b	85	--	--	--	8	--	5	--
14a	15	--	--	5	5	5	60	9
14b	70	--	--	15	4	--	10	--
15	15	--	--	5	5	5	60	9
16	5	--	--	--	1	2	85	4
17a	10	10	--	5	2	8	55	10
17b	80	--	--	5	5	1	10	--
18	10	--	--	5	1	8	70	5
19	--	5	--	--	--	1	90	2
20a	12	--	5	--	1	9	70	4
20b	60	--	--	5	--	2	25	--
LOCALITY 154-B-43								
1a	10	--	--	12	--	65	--	8
1b**	--	--	--	5	1	8	78	2
2	--	--	--	4	1	7	81	7
3	--	--	--	--	--	3	92	4
4	5	--	--	--	3	12	76	4
5	12	--	--	7	--	4	75	3
6	--	--	--	10	1	15	70	4
7a	25	--	--	10	--	10	50	--
7b	13	--	--	--	--	3	80	4
8***	--	--	--	6	1	8	75	2
9	--	--	--	--	1	2	90	7
10	--	--	--	--	7	10	70	12
11a	30	--	12	2	--	15	48	--
11b	20	--	--	2	--	8	50	2
11c	40	--	20	15	--	25	--	--
12	--	10	--	--	3	12	70	4
13a	65	--	--	18	--	--	15	--
13b	50	--	--	--	4	--	40	--
14	11	--	--	4	1	8	70	4
LOCALITY 154-B-44								
1	10	--	--	20	--	65	--	[illegible]
2a	--	5	--	2	4	15	65	8
2b	--	--	--	5	2	10	80	1
3	8	--	--	12	4	8	63	2
4	45	--	--	--	5	10	40	--
5	--	--	--	--	--	--	95	2
6	5	--	--	5	1	10	70	9
7	--	--	--	--	--	8	90	3
8	10	--	--	5	5	10	60	8
9	5	--	--	--	1	3	85	3
10	15	--	--	10	5	6	60	6
11	--	--	--	--	1	4	90	1
12a	5	--	--	3	2	12	68	10
12b	15	--	--	--	5	15	55	10
13	90	--	--	--	2	4	5	--
14	20	--	--	--	4	--	75	4
15a	20	--	--	5	2	10	50	8
15b	20	--	--	--	2	10	55	10
16	10	--	--	--	--	1	85	2
LOCALITY 154-B-45								
1	30	--	--	10	4	45	10	1
2a	8	--	--	10	1	19	60	1
2b	7	--	--	2	1	5	80	2
3a	15	--	--	8	--	12	62	2
3b	5	--	--	--	--	2	88	3
3c	10	--	--	10	1	8	60	3
3d	6	--	--	5	--	1	85	5
4	25	--	--	15	--	2	50	5
5	5	--	--	5	--	1	88	1
6	10	--	--	10	2	15	55	5
7	Severely weathered							
8	Covered							
9	19	--	--	15	2	20	34	--
10	10	--	--	9	2	4	70	4
11	--	--	--	12	2	22	60	2
LOCALITY 154-B-46								
2	--	--	--	--	--	--	90	1
LOCALITY 109-B-15								
1	5	--	5	--	--	82	10	--
2a	--	45	--	30	--	20	--	3
2b	--	20	5	15	--	--	60	3
3	--	--	5	15	1	25	50	4
4	--	--	--	10	--	--	85	2
5	--	--	--	15	--	15	65	5
6a	--	5	--	15	2	15	50	10
6b	--	--	--	10	1	5	80	1

* Sample contains 2% rhodochrosite

** Sample contains 4% phosphate

***Sample contains 3% rhodochrosite

7	--	--	--	10	1	10	70	8
8	--	--	--	5	--	4	85	6
9	35	--	--	15	--	10	35	2
10a	5	--	--	5	2	5	80	--
10b	10	--	--	16	--	12	52	5
10c	5	--	--	5	3	7	75	--
11	15	--	--	20	4	15	45	4
LOCALITY 109-B-16								
1	10	--	5	--	--	80	5	--
2	--	25	15	--	--	60	1	1
3	10	--	--	5	--	10	75	2
4	--	--	--	--	--	8	87	2
5	--	--	--	25	--	25	45	5
6	--	--	--	5	--	4	85	1
7	25	--	--	15	--	10	45	--
8	--	--	--	--	--	5	90	3
9	10	--	--	10	--	15	55	5
10	8	--	--	--	--	2	90	1
11	10	--	--	10	3	20	55	2
12	25	--	10	20	--	30	10	--
13	15	--	--	25	4	15	35	2
LOCALITY 109-B-17								
1	5	--	5	20	3	60	10	--
2	--	15	--	5	2	8	70	--
3	15	15	--	8	2	4	50	8
4	10	5	--	--	3	4	75	2
5a	60	--	--	35	--	5	--	--
5b	60	--	--	35	--	4	2	--
5c	--	--	5	20	2	25	40	7
6	--	5	--	--	--	--	90	1
7a	10	--	--	10	4	15	50	11
7b	20	--	--	7	3	18	50	2
8	--	--	--	--	--	10	87	2
9a	15	--	--	5	5	10	60	5
9b	--	--	--	8	2	5	80	3
9c	15	--	--	5	5	10	60	5
10	25	--	--	--	--	2	75	--
11	10	--	--	10	4	15	60	3
12	30	--	5	20	3	30	10	--
13	20	--	--	17	3	10	45	6
LOCALITY 109-B-18								
2	--	--	--	--	--	3	90	3
LOCALITY 109-B-19								
2	--	--	--	--	--	20	80	--
3	20	--	--	--	--	40	40	--

APPENDIX IV

MICROFAUNAL ABUNDANCE[1]

Unit	*Hedbergella amabilis*	*Hedbergella brittonensis*	Others[2]	Total[3]	*Gumbelina*
LOCALITY 154-B-40					
2	26,444	1,928	1,560	29,932	493
5	33,664	2,688	1,792	38,144	512
7	41,344	2,048	256	43,648	384
9a	55,680	2,944	4,224	62,848	1,280
9c	58,880	11,280	3,328	73,488	13,568
11	24,960	1,280	1,664	27,904	4,224
13	8,804	1,664	384	10,852	0
15	76,800	8,832	3,304	87,936	33,792
17b	31,701	4,211	1,623	37,535	2,421
LOCALITY 154-B-41					
2a	16,000	3,200	1,728	20,928	0
5	3,840	1,984	0	5,824	0
7	5,312	7,808	1,280	14,400	128
9a	5,248	1,600	256	7,104	128
9b	24,832	1,804	1,664	28,300	64
13a	28,248	2,304	832	31,384	2,496
13b	25,342	2,013	624	27,979	2,042
15a	8,596	15,084	6,226	29,906	6,848
15b	21,224	1,856	896	23,976	960
16	28,632	6,848	1,088	36,568	8,640
17	10,496	12,416	3,712	26,624	3,840
20	21,248	30,720	7,872	59,840	2,496
LOCALITY 154-B-42					
2a	20,416	2,880	0	23,296	320
2b	12,160	25,176	704	38,040	64
3	20,608	31,680	960	53,248	10,240
5	12,800	12,032	1,024	25,856	3,712
7	13,013	8,940	41	21,994	3,201
9	8,192	8,064	512	16,768	14,208
11	8,462	4,261	641	13,364	11,420
13	7,680	39,936	2,816	50,432	3,328
15	9,282	42,496	4,096	55,874	6,656
16	17,152	41,472	4,352	62,976	5,376
18	46,592	109,066	4,096	159,754	99,940
LOCALITY 154-B-43					
2	48,256	4,736	256	53,248	1,280
4	33,920	13,056	512	47,488	492
6	46,720	19,328	2,788	68,836	4,484
8	83,200	21,504	1,024	105,728	11,904
10	33,024	8,320	3,072	44,416	11,392
12	12,160	3,584	0	15,644	128
14	60,800	28,800	2,944	92,544	10,240
LOCALITY 154-B-44					
2a	8,260	3,420	2,264	13,944	0
3	22,328	14,848	4,608	41,784	2,944
6	41,784	29,440	2,504	73,728	9,344
8	17,536	14,208	3,584	35,328	6,144
10	10,240	21,400	1,920	33,560	7,120
12a	16,304	15,152	1,152	32,608	1,664
12b	14,651	11,980	1,156	27,787	986
15a	35,584	33,280	1,408	70,272	3,100
15b	20,480	18,204	512	39,196	3,100
17	27,776	15,000	1,536	44,112	4,096
LOCALITY 154-B-45					
3a	5,462	107	52	5,621	511
3c	7,706	192	64	7,962	666
6	4,951	271	92	5,314	821
10	48,384	2,944	1,152	52,480	3,582
12b	11,648	2,816	128	14,592	512
19b	38,400	3,456	1,024	42,880	7,552
LOCALITY 109-B-15					
3	83,200	3,840	1,024	88,064	1,408
5	18,048	2,176	1,152	21,376	6,400
7	57,600	4,992	896	63,488	1,920
9	80,640	3,456	640	84,736	128
11	39,740	5,748	1,119	46,607	4,001
LOCALITY 109-B-16					
5	37,488	2,432	640	40,560	640
7	41,600	3,328	768	45,696	512
9	49,896	6,912	896	57,704	17,664
11	50,026	8,042	962	59,030	8,561
13	5,641	2,712	1,620	9,973	2,113
LOCALITY 109-B-17					
3	63,104	19,072	768	82,944	768
4	18,688	7,808	384	26,880	1,920
5	30,592	6,400	384	37,376	128
7a	97,280	22,400	512	120,192	30,976
7b	40,576	14,592	1,024	56,192	20,352
9a	35,584	18,944	1,664	56,192	40,960
9c	41,961	14,511	3,620	60,092	32,426
11	63,488	15,232	4,352	83,072	2,688
13	2,624	576	64	3,264	256

[1]Abundance values represent the number of specimens in a cubic centimeter of the 80-180 mesh separate or residue. Refer to Appendix V.
[2]Predominantly *Clavihedbergella simplex* Morrow.
[3]Total planktonic Foraminifera, excluding *Gumbelina*.

APPENDIX V

METHODS AND PROCEDURES

MAPPING PROCEDURE

The Waco sheet (U. S. Army Map Service, Corps of Engineers, Waco NH14-3; scale 1/250,000, contour interval 50 feet) was enlarged to 1/125,000 for use as a base map. In the northern half of the area, mapping was undertaken on 7½-minute quadrangle maps with a scale of 1/24,000 (contour interval 10 feet) and transferred to the base map. Aerial photographs (1/20,000) were used in southern McLennan County.

Data for subsurface mapping were obtained from electric logs of approximately 150 wells; 68 key wells are listed in Appendix I. The isopach map (fig. 2) is based on surface and subsurface data.

CALCITE PERCENTAGE

A sample weighing 5 to 9 grams was pulverized (-80 mesh), weighed and placed in a 250 ml flask. Dilute hydrochloric acid (10:1) was slowly poured over the sample until vigorous reaction ceased. Acid was added until the flask was filled; the reaction was allowed to continue for 24 hours, until all calcium carbonate was dissolved.

Ashless filter paper was weighed, the sample was filtered and washed with 250 ml of distilled water, and dried at room temperature for 48 hours before being placed in an oven for 4 hours. The sample and filter paper were weighed and the percentage of residue was determined.

CARBON PERCENTAGE

The residue from the calcium carbonate analyses on ashless filter paper was placed in a weighed crucible and heated by a Fisher burner for 1 hour. The crucible and sample were cooled to room temperature and weighed. The weight of carbon, driven off as volatiles, was determined and converted to a percentage value.

X-RAY PROCEDURES

Sampling.—Every observable lithologic type was sampled. Where the unit is greater than 1 foot, it was channeled and divided into 2 or more overlapping units. Samples were selected to avoid intensely weathered material.

Preparation.—Samples representing a large vertical section were thoroughly mixed. Samples were pulverized and sifted through a Tyler screen (200 mesh/in^2; .074 mm), and placed in a desiccator which maintained a relative humidity of 50 percent for 48 hours.

X-ray procedure.—The samples (200 mesh and 50 percent humidity) were x-rayed under the conditions following:

1. span- 2-36° 2 theta
2. speed- 2° 2 theta per min.
3. scale- 80
4. time constant- 3 sec.
5. scale factor- 30 K

Interpretation.—Two methods are available to estimate the approximate mineralogic composition of bulk samples from X-ray diffraction patterns: (1) prepare and run a suite of known compounds, comparing their patterns with unknown patterns, or (2) determine the percent of calcium carbonate of each sample by insoluble residue method, compare the known percent to the intensity of the calcite diffraction line, and estimate the percentage of other constituents by relative comparison of intensities with the calcite diffraction line. The latter method was adopted.

MICROFAUNAL ANALYSIS

One hundred grams of sample were boiled and washed through 34, 80 and 180 mesh Tyler screens. Foraminifera were absent in the 0-34 and 34-80 mesh separates.

Foraminifera in a cubic centimeter of the 80-180 mesh separate were counted; population counts were made of each species in the sample. Cubic centimeter samples containing abundant Foraminifera were split by microsplit technique into fractions, such as 1/2, 1/4, 1/16, and the microfossils in the fractional sample were counted and converted to a one cubic centimeter equivalent by multiplying x2, x4 or x16. All microfaunal abundance data on figures 4-11 are individuals x10^3/cm^3 of the 80-180 mesh residue. Precise population figures for each species are included in Appendix IV.

INDEX

BAYLOR GEOLOGICAL PUBLICATIONS*

Baylor Geological Society

1. Type electric log of McLennan County. 1"-100'; 1"-50'-$2.00.
2. Reptile charts—Comparison of flying and swimming reptiles. $0.10 each. Comparison of the dinosaurs. $0.10 each.
3. Guide to the mid-Cretaceous geology of central Texas, May, 1958. $4.50 per copy.
4. Location map of logged wells in McLennan County, 1959. 1"-1 mile, $7.50 per copy.
5. Layman's guide to the geology of central Texas, 1959. Out of print.
6. Collector's guide to the geology of central Texas, 1959. Out of print.
7. One hundred million years in McLennan County, 1960. Out of print.
8. Cretaceous stratigraphy of the Grand and Black Prairies, 1960. $5.00 per copy.
9. Popular geology of central Texas, west central McLennan County, 1960. Out of print.
10. Popular geology of central Texas, Bosque County, 1961. $1.00 per copy.
11. Popular geology of central Texas, northwestern McLennan County, 1961. $1.00 per copy.
12. Popular geology of central Texas, southwestern McLennan County and eastern Coryell County, 1962. $1.00 per copy.
13. Upper Cretaceous and Lower Tertiary rocks in east central Texas, Fred E. Smith, Leader, 1962. $1.00 per copy.
14. Precambrian igneous rocks of the Wichita Mountains, Oklahoma, Walter T. Huang, Leader, 1962. $1.00 per copy.
15. Why teach geology? A discussion of the importance and cost of teaching geology in high schools, junior colleges and small 4-year institutions. Free upon request. 27 pp. (1961)

Baylor Geological Studies

16. Holloway, Harold D. (1961) The Lower Cretaceous Trinity aquifers, McLennan County, Texas: Baylor Geological Studies Bull. No. 1 (Fall). $1.00 per copy.
17. Atlee, William A. (1962) The Lower Cretaceous Paluxy sand in central Texas: Baylor Geological Studies Bull. No. 2 (Spring). $1.00 per copy.
18. Henningsen, E. Robert (1962) Water diagenesis in Lower Cretaceous Trinity aquifers of central Texas: Baylor Geological Studies Bull. No. 3 (Fall). $1.00 per copy.

---

*Publications available from Baylor Geological Society or Baylor Geological Studies, Baylor University, Waco, Texas

BAYLOR UNIVERSITY

GEOLOGY