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Stratigraphy of the Pre-Simpson Paleozoic Subsurface Rocks of Texas and Southeast New Mexico

VIRGIL E. BARNES, P. E. CLOUD, JR., L. P. DIXON,
R. L. FOLK, E. C. JONAS, A. R. PALMER, E. J. TYNAN

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BUREAU OF ECONOMIC GEOLOGY

THE UNIVERSITY OF TEXAS, AUSTIN

JOHN T. LONSDALE, *Director*

The benefits of education and of useful knowledge, generally diffused through a community, are essential to the preservation of a free government.

Sam Houston

Cultivated mind is the guardian genius of Democracy, and while guided and controlled by virtue, the noblest attribute of man. It is the only dictator that freemen acknowledge, and the only security which freemen desire.

Mirabeau B. Lamar

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Stratigraphy of the Pre-Simpson Paleozoic Subsurface Rocks of Texas and Southeast New Mexico

VIRGIL E. BARNES

PART 1: GENERAL DISCUSSION

ABSTRACT

The pre-Simpson Paleozoic rocks of the subsurface in Texas and southeast New Mexico comprise an essentially complete sequence of Lower Ordovician and Upper Cambrian rocks and perhaps, southward from the Llano region, some Middle Cambrian rocks as well. Not all units are found in any one place because of an erosional unconformity at the top and transgressive onlap at the bottom of the sequence.

The main purpose of this project was to determine if established or other units of the pre-Simpson sequence could be recognized in the subsurface. Secondarily, it was hoped that some short-cut method could be found by which these units could be identified. No such method was found except locally, and if one wishes to identify a part of the pre-Simpson sequence, only painstaking and careful use of time-tried geological methods will help him.

Physical and chemical methods tried and found to be of little or no value for identifying units within the pre-Simpson sequence of rocks include X-ray examination of clay-size minerals, magnetic susceptibility, thermoluminescence, and spectrochemical as well as conventional chemical analyses. The use of electric and radioactivity logging is of little or no value for distinguishing units within the Ellenburger group, but for some areas such logs can be used successfully to distinguish units within the Wilberns and Riley formations.

Of the time-honored geological methods, the paleontologic approach for regional control was indispensable during this project. However, because of the scarcity of fossils, especially where the sequence is entirely dolomite, this method cannot be used for well-to-well correlation. A search for the very small insoluble fossils, the hystrichosphaerids, was fruitless.

Binocular-microscope examination of untreated samples with plotting of observations on log strips is the easiest and most direct way of recognizing the various units within the pre-Simpson sequence of rocks. Probably the most useful property for both limestone and dolomite is grain size. The limestone of the Ellenburger group is almost invariably aphanitic or rarely microgranular, whereas the limestone of the Wilberns and the Riley formations is mostly very finely to coarsely granular. The dolomite in the sequence ranges widely in grain size, and some units have fairly characteristic sizes.

Locally sandstone units, such as those in the San Saba and at the Wilberns-Riley boundary, are readily recognized. Sparsely distributed sand grains help identify the Gorman and the lower 50 feet of the Honeycut in the Llano region, whereas the Tanyard and the rest of the Honeycut are mostly nonsandy. In the subsurface to the southwest and west as far as Pecos County, conditions are reversed, with the Gorman non-sandy and both the Tanyard and Honeycut sandy.

Glauconite is essentially confined to the Wilberns and Riley formations and absent from the Ellenburger group.

In general chert is rare in post-Honeycut beds, becomes more abundant downward,

reaches a maximum in the Tanyard, and is absent below the Tanyard except from the eastern part of the Llano region eastward, where some is present in the Wilberns. Certain types of chert are more characteristic of some units than others.

The distribution of color is an important aid in identifying some pre-Simpson units if the regional trend in color change is kept in mind. The rocks as a whole darken toward the Pecos—Val Verde County area and the Delaware basin and also are dark colored in the Panhandle and north Texas areas.

Except locally the distribution of limestone and dolomite in the subsurface is of no value for subdividing pre-Simpson rocks.

Binocular-microscope examination of insoluble residues with plotting of observations on log strips should be used only as an adjunct for recognizing the various units. Study of specially prepared insoluble residues generally is not necessary because with a little experience almost all features seen in specially prepared insoluble residues can also be seen in the untreated samples. Insoluble residues should not be used exclusively in an attempt to recognize the various units; to do so invites failure, because the most diagnostic evidence is destroyed by the acid.

Thin-section examination reveals much more than can be seen with the binocular microscope, but to obtain enough information for correlation requires a much greater outlay of time and expense. However, thin-section examination is almost indispensable for information concerning paragenesis and history of these rocks.

Many observations made during the binocular-microscope examination but not recorded on log strips may be of value for correlation and others for interpreting the history of the rock. The presence of anhydrite, for example, appears to be of some aid in correlation since it is found mostly in the Honeycut formation. Also, in the area where anhydrite is found the Ellenburger is mostly dolomite; this suggests that hypersaline water may favor the formation of dolomite as a primary precipitate at or above the sea floor. The presence of varvelike bedding also appears to support the contention that dolomite can be directly precipitated and then settle to the sea floor.

The distribution of inclined beds in more than half the wells indicates that post-Ellenburger deformation occurred throughout the area covered in this publication. The Llano region furnishes a typical example of this deformation and in fact the Llano uplift results from it. The deformation took place during the Pennsylvanian period, and it is thought that open fractures so prevalent in some areas formed at this time.

An attempt is made to distinguish between deformation that is the result of soft-sediment deformation, that which is the result of tectonic forces, and that which is the result of solution with collapse after the rocks hardened. Evidence of solution and collapse is more abundant in the area where Carboniferous rocks rest directly on the Ellenburger group.

INTRODUCTION

The study of the stratigraphy of the pre-Simpson subsurface rocks of Texas is in part a continuation of the work on the Ellenburger group in central Texas (Cloud and Barnes, 1948a) using the same and other techniques. The present study includes all sedimentary rocks in Texas and southeast New Mexico, from the top of the Precambrian to the base of the Middle Ordovician Simpson group, and thus in part anticipates work by W. C. Bell and Barnes (MS.) on the Upper Cambrian rocks of central Texas.

The present paper is the result of intensive work on these rocks from May 1952 to March 1957. It is a basic study of methods for subdividing these rocks in the subsurface. Because of the areal extent of these rocks, their complexity both from a facies and structural standpoint, and lack of samples in some areas, it was impossible actually to map in usable detail subdivisions of these rocks throughout the State. It is hoped that the results given herein can be expanded by petroleum geologists to give eventually a subcrop map of the various units of the Ellenburger group and that such a map will be of aid in finding oil.

The area involved and the localities from which data were obtained are shown in figures 1 and 2. Data for individual wells, arranged by company, are given in Appendix A. Large areas are without sample representation. Important cores from the Arbuckle facies in the northeastern part of the area are separated by hundreds of miles from the nearest cores in the Ellenburger facies. Cores from the Texas Panhandle are far from the nearest cores to the south. Likewise, the distance is great from the outcropping El Paso facies to the nearest subsurface cores. It is unfortunate for purposes of correlation that the outlying wells and surface sections are so far from the main mass of sample material, which came from an elliptical area including the southeast corner of New Mexico at one end and the Llano uplift at the other (figs. 1 and 2).

This study involved many special fields of investigation. Other authors of special sections (Part 2) were working at a disadvantage in not being aware of the whole picture. Also, they were not free to do their own sampling as the time and effort required to do so would have been prohibitive.

The thin-section samples were not equally spaced for correlation but were chosen for the purpose of studying the entire range of rock types with emphasis on special features. The sampling of some wells is complete enough to use thin sections for correlation, but the bulk of the sampling is random and rather sparse. A few thin sections received too late to be included in Folk's paper are described in Appendix B.

The following independent papers on various phases of the pre-Simpson work are integral parts of the whole:

- Paleontologic data and age evaluation for individual wells, pre-Simpson Paleozoic rocks, by Preston E. Cloud, Jr., and Allison R. Palmer
- Examination of pre-Simpson Paleozoic rocks for insoluble fossils, by Eugene J. Tynan
- Thin-section examination of pre-Simpson Paleozoic rocks, by Robert L. Folk
- Clay-size minerals in Ellenburger rocks, by Edward C. Jonas
- Chemical examination of pre-Simpson Paleozoic rocks, by Virgil E. Barnes
- Thermoluminescence of pre-Simpson Paleozoic rocks, by Virgil E. Barnes
- Use of color for correlating pre-Simpson Paleozoic rocks, by Virgil E. Barnes
- Insoluble residues of Ellenburger subsurface rocks, by Virgil E. Barnes and Lane P. Dixon

The remainder of this publication, including four of the papers above listed, was the responsibility of the writer, and it was his task to integrate and evaluate not only the data which he collected but also those of the other authors. In this integration there may be some misinterpretation of intentions of the contributing authors, but the evaluations are solely those of the writer. Other authors are responsible only for information and conclusions in their respective papers.

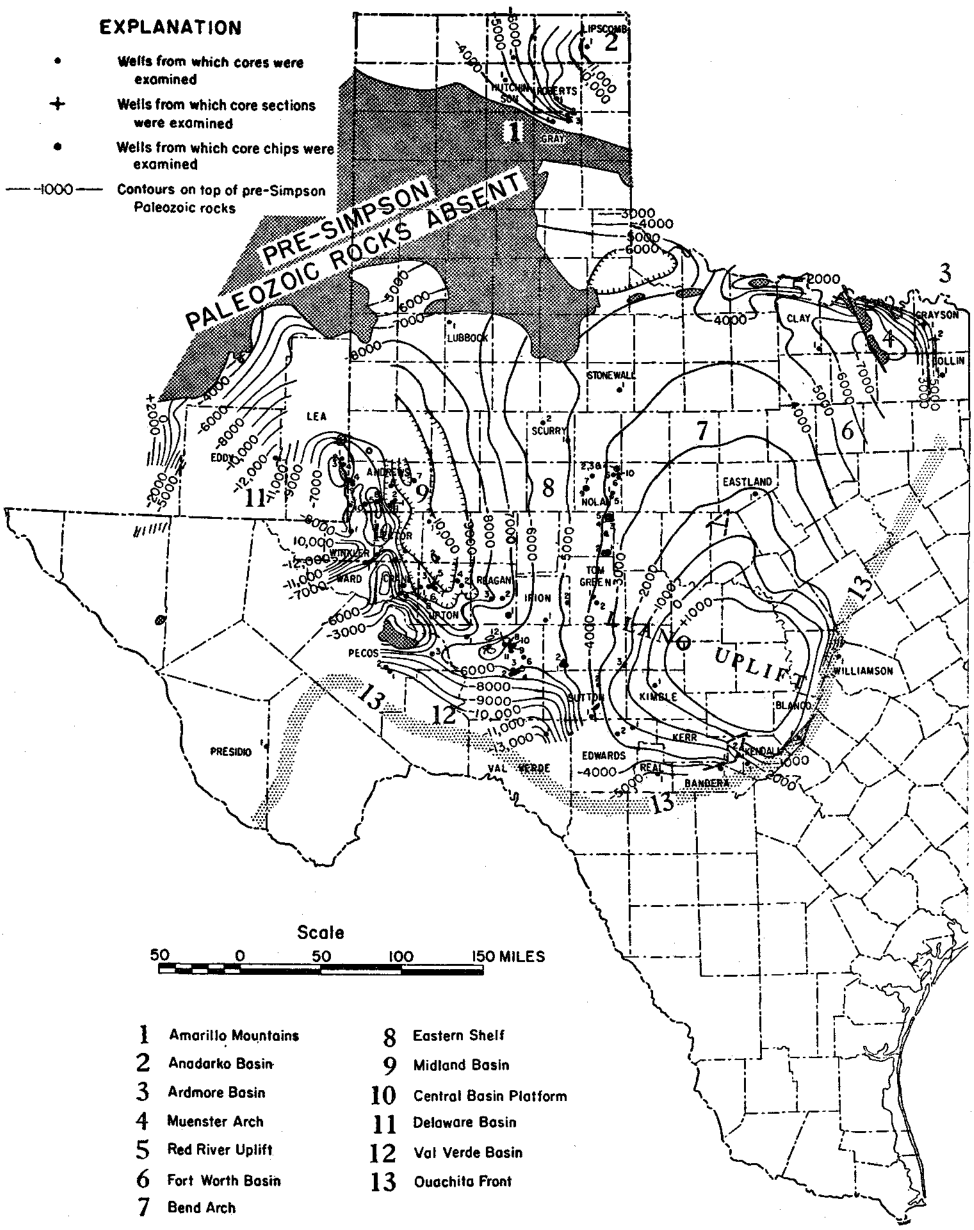

FIG. 1. Map showing present configuration of the top of the pre-Simpson sequence of Paleozoic rocks in Texas and southeast New Mexico, and wells from which cores, core sections, or core chips were examined.

NEW MEXICO

EDDY COUNTY

1. Richardson & Bass # 1 Federal-Cobb

LEA COUNTY

1. Continental Oil Co. #1 Burger B-28
2. Humble O. & R. Co. #3 "V" N. M. State
3. Humble O. & R. Co. #6 "V" N. M. State
4. Shell Oil Co. #5 State

TEXAS

ANDREWS COUNTY

1. Gulf Oil Corp. #1-E State "AM"
2. Gulf Oil Corp. #1 Texas "000"
3. Humble Oil & Rfg. Co. #18 Cowden
4. Humble O. & R. Co. #2 Evelyn Lineberry
5. Humble Oil & Rfg. Co. #37 Parker
6. Ralph Lowe #1 Southland Royalty

Fig. 1, explanation (continued)—
7. Magnolia Petr. Co. #2-36995 University
8. Shell Oil Co. #12 Lockhart
9. Shell Oil Co. #1 Pinson
10. Shell Oil Co. #7 Ratliff & Bedford
11. The Superior Oil Co. #1-36-A University

BANDERA COUNTY
1. G. L. Rowsey #2 Fee

BLANCO COUNTY
1. Roland K. Blumberg # 1 Wagner

CLAY COUNTY
1. Deep Rock Oil Co. #1 Moore Estate

COKE COUNTY
1. E. L. Doheny #1 Taylor
2. Honolulu Oil Corp. #1 Webb
3. Humble Oil & Rfg. Co. #10 Odom
4. Humble Oil & Rfg. Co. #F-90 Odom
5. Humble Oil & Rfg. Co. #F-91 Odom

COLLIN COUNTY
1. Humble Oil & Rfg. Co. #1 Miller

CRANE COUNTY
1. The Atlantic Rfg. Co. No. 1-W University
2. Humble Oil & Rfg. Co. #1-C Jax Cowden
3. Humble Oil & Rfg. Co. #3 Jax Cowden

CROCKETT COUNTY
1. Continental Oil Co. #E-1 Harris
2. Humble Oil & Rfg. Co. #1 Alma Cox
3. Humble Oil & Rfg. Co. #1-C Alma Cox
4. Humble Oil & Rfg. Co. #1-D Alma Cox
5. Humble Oil & Rfg. Co. #1-E Alma Cox
6. Humble Oil & Rfg. Co. #2 Harvick
7. Magnolia Petr. Co. #1 Shannon Hospital
8. Shell Oil Co. #5 Chambers Co. Sch. Land
9. Shell Oil Co. #9 Chambers Co. Sch. Land
10. Shell Oil Co. #10 Chambers Co. Sch. Land
11. Shell Oil Co. #12 Chambers Co. Sch. Land
12. The Superior Oil Co. #1-27 University

EASTLAND COUNTY
1. Luling Oil Co. #1 Blackwell

ECTOR COUNTY
1. Cities Service Oil Co. #1-E Foster
2. Humble O. & R. #22 Yarbrough & Allen
3. Shell Oil Co. #D-10 University

EDWARDS COUNTY
1. Humble Oil & Rfg. Co. #1 J. H. Guthrie
2. The Texas Co. #1 Phillips

GRAY COUNTY
1. Gulf Oil Corp. #1 E. A. Shackleton
2. Phillips Petroleum Co. #2 Delp
3. Phillips Petroleum Co. #1 Strickler

GRAYSON COUNTY
1. The Superior Oil Co. #1 J. E. Henderson
2. The Superior Oil Co. #1 S. L. Privette

HANSFORD COUNTY
1. Gulf Oil Corp. #1 J. R. Collard

HUTCHINSON COUNTY
1. Gulf Oil Corp. #1 Amarillo Natl. Bk.

IRION COUNTY
1. The Atlantic Rfg. Co. #1 Noelke
2. Wilshire Oil Co. #1-A Brooks

KENDALL COUNTY
1. Magnolia Petroleum Co. #1 Below

KERR COUNTY
1. G. L. Rowsey #2 Nowlin
2. Tucker Drilling Co. #1 Dr. Roy E. Perkins

KIMBLE COUNTY
1. Humble Oil & Rfg. Co. #1 Woodard

LIPSCOMB COUNTY
1. Gulf Oil Corp. #1-E Porter "A"

LUBBOCK COUNTY
1. Humble Oil & Rfg. Co. #1 Farris

MIDLAND COUNTY
1. Magnolia Petroleum Co. #1 Nobles
2. Magnolia Petroleum Co. #2-A Windham

NOLAN COUNTY
1. General Crude Oil Co. #1 George Cave
2. Honolulu Oil Corp. #2 Whitaker
3. Honolulu Oil Corp. #5 Whitaker
4. Honolulu Oil Corp. #6 Whitaker
5. Kilroy Co. of Texas #1 Roberts
6. Seaboard Oil Co. #1 TXL "C"
7. Skelly Oil Co. #1 Ater
8. Skelly Oil Co. #B-4 Boyd
9. Sun Oil Co. et al. #1-A B. K. Stone
10. U. S. Smelt., Rfg. & Min. Co. #3 TXL "A"

PECOS COUNTY
1. Phillips Petroleum Co. #1 Glenna
2. Phillips Petroleum Co. #1-C Puckett
3. Standard Oil Co. of Texas #2-1 Claude Owens

PRESIDIO COUNTY
1. Gulf Oil Corp. #1 Mitchell Bros.—State

REAGAN COUNTY
1. Amerada Petroleum Corp. #2 Hickman
2. Humble Oil & Rfg. Co. #1-G Sawyer
3. Humble Oil & Rfg. Co. #1-M University

REAL COUNTY
1. Stanolind Oil & Gas Co. #1 Knippa

ROBERTS COUNTY
1. Gulf Oil Corp. #1 John Haggard

SCHLEICHER COUNTY
1. American Trading & Prod. Corp. #1 Sauer
2. The Atlantic Rfg. Co. #1 Roberts
3. Magnolia Petroleum Co. #1 Mary Ball

SCURRY COUNTY
1. American Tr. & Pr. Corp. #1 E. Howell
2. Humble Oil & Rfg. Co. #1-B B. A. Moore

STONEWALL COUNTY
1. Seaboard Oil Co. #4 Upshaw

SUTTON COUNTY
1. Humble Oil & Rfg. Co. #1 J. D. Harrison
2. Humble O. & R. Co. #1 N. Branch Unit

TOM GREEN COUNTY
1. Humble O. & R. Co. #1 Wash. Co. Sch. L.
2. C. L. McMahon #1 J. W. Johnson

UPTON COUNTY
1. Gulf Oil Co. #1 McElroy-State
2. Humble Oil & Rfg. Co. #1 Z. Oswalt
3. Sinclair Oil & Gas Co. #9 McElroy
4. Sohio Petroleum Co. #1 Hill Estate
5. Wilshire Oil Co. #14-117 McElroy
6. Wilshire Oil Co. #14-130 McElroy
7. Wilshire Oil Co. #23-118 Windham
8. Wilshire Oil Co. #34-98 Jacobs Lvst. Co.

VAL VERDE COUNTY
1. Phillips Petroleum Co. #1 Wilson

WARD COUNTY
1. Shell Oil Co. #3 Sealy Smith

WILLIAMSON COUNTY
1. Shell Oil Co. #1 Purcell

WINKLER COUNTY
1. Gulf Oil Corp. #108-E Keystone

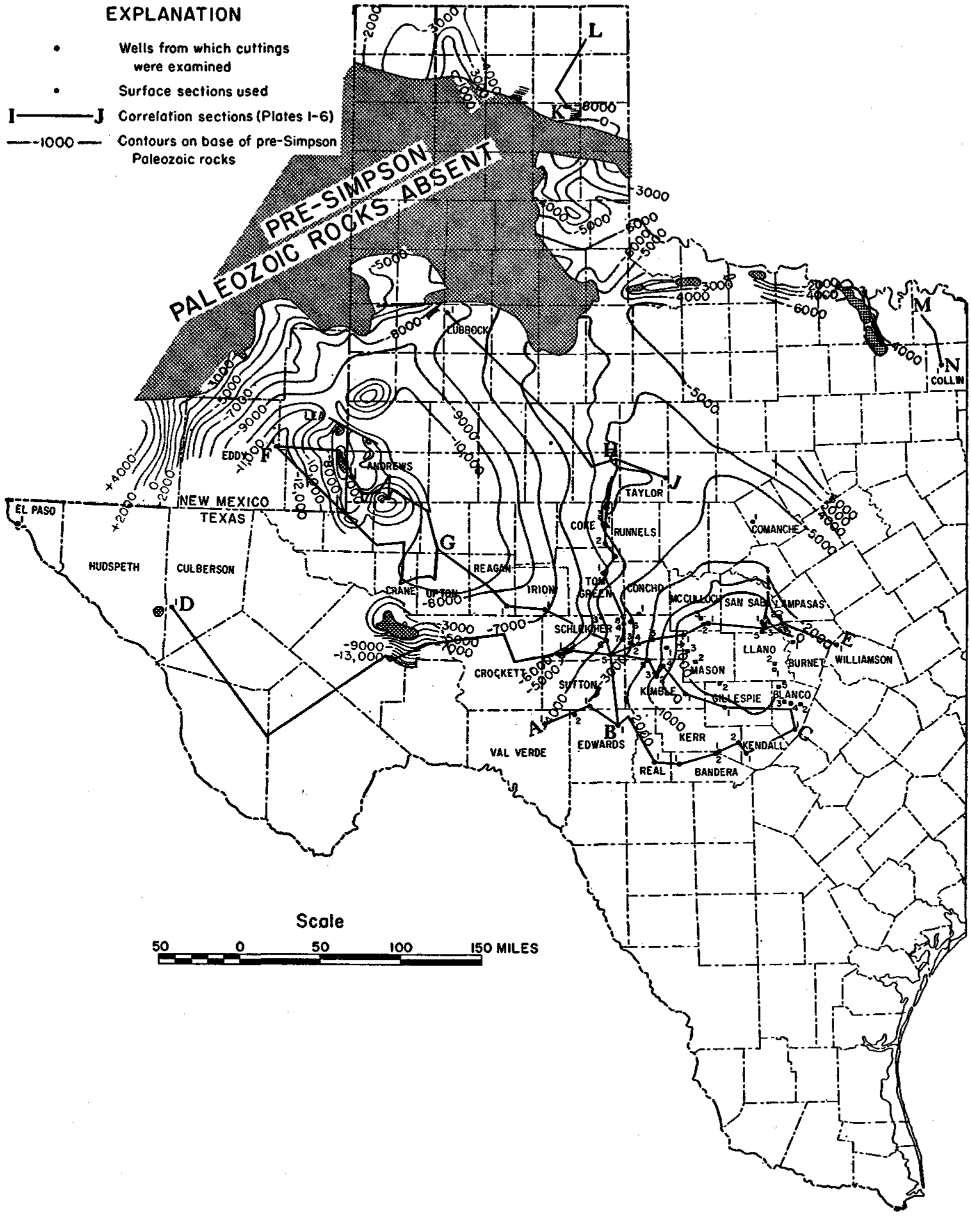

Fig. 2. Map showing present configuration of the base of the pre-Simpson sequence of Paleozoic rocks in Texas and southeast New Mexico, wells from which cuttings were examined, surface sections used either for comparison or for tests, and correlation sections.

Fig. 2, explanation (continued)—

NEW MEXICO

EDDY COUNTY
1. Richardson & Bass #1 Federal-Cobb

TEXAS

ANDREWS COUNTY
1. Shell Oil Co. #1 Pinson
2. The Superior Oil Co. #1-36-A University

BANDERA COUNTY
1. General Crude Oil Co. #1 Anderson
2. G. L. Rowsey #2 Fee

BLANCO COUNTY
1. Roland K. Blumberg #1 Wagner
2. Honeycut Bend section
3. Klett-Walker section
4. Pedernales River section
5. White Creek section

BURNET COUNTY
1. Morgan Creek section
2. Tanyard section

COKE COUNTY
1. Hickok & Reynolds et al. #1 Dr. R. J. Warren
2. Honolulu Oil Corp. #1 Webb
3. Humble Oil & Rfg. Co. #F-90 Odom

COLLIN COUNTY
1. Humble Oil & Rfg. Co. #1 Miller

COMANCHE COUNTY
1. Gilcrease Oil Co. #1 Feril

CONCHO COUNTY
1. Floyd C. Dodson #1 Wilson

CULBERSON COUNTY
1. Beach Mountain section

EDWARDS COUNTY
1. Shell Oil Co. #1 Brown
2. Taylor Oil and Gas Co. et al. #1 Holman

EL PASO COUNTY
1. Franklin Mountains section

GILLESPIE COUNTY
1. L. U. Rowntree #1 Richard Kott
2. Threadgill Creek section

IRION COUNTY
1. The Atlantic Rfg. Co. #1 Noelke

KENDALL COUNTY
1. Magnolia Petroleum Co. #1 Below

KERR COUNTY
1. G. L. Rowsey #2 Nowlin
2. Tucker Drilling Co. #1 Dr. Roy E. Perkins

KIMBLE COUNTY
1. Forest Oil Corp. #1 Stapp
2. Humble Oil & Rfg. Co. #1 Bolt
3. Humble Oil & Rfg. Co. #1 Woodard
4. R. A. Irwin #1 G. R. Kothman
5. Phillips Petroleum Co. #1 Spiller

LLANO COUNTY
1. Moore Hollow section
2. Warren Springs section

LUBBOCK COUNTY
1. Humble Oil & Rfg. Co. #1 Farris

MCCULLOCH COUNTY
1. Tommy Brook Water Well
2. Camp San Saba section
3. Highway 87 section

MASON COUNTY
1. Carpenter Exploration Co. #1 Bradshaw
2. Pete Hollow section
3. Streeter section

MENARD COUNTY
1. American Republics Corp. #1 Bradford
2. Deep Rock Oil Corp. #1 Bevans
3. B. A. Duffy No. 1 Sol Mayer
4. C. H. Murdich #1 Allison
5. Phillips Petroleum Co. #1 Meta
6. Tucker Drilling Co. #1 Rogers

REAGAN COUNTY
1. Amerada Petroleum Corp. #2 Hickman

REAL COUNTY
1. Stanolind Oil & Gas Co. #1 Knippa

RUNNELS COUNTY
1. The Superior Oil Co. #1 J. E. McDowell

SAN SABA COUNTY
1. Cherokee Creek section
2. Gorman Falls section
3. Harris Ranch section
4. Kirk Ranch section
5. Little Llano River section
6. Spicewood Creek section

SCHLEICHER COUNTY
1. American Trading & Prod. Corp. #1 Sauer
2. The Atlantic Rfg. Co. #1 Roberts
3. Robert Berry #1 Thomerson
4. Phillips Petroleum Co. #1 Callan
5. Scherck & Chizum #1 D. C. O. Wilson
6. Taylor Oil and Gas Co. #1 Judkins
7. Taylor Oil and Gas Co. et al. #2 Sheen
8. Tucker Drilling Co. #1 Boyd

SUTTON COUNTY
1. Humble Oil & Rfg. Co. #1 J. D. Harrison

TAYLOR COUNTY
1. J. B. Jameson #1 Webb

TOM GREEN COUNTY
1. Richardson & Bass #1 Schwartz

VAL VERDE COUNTY
1. Phillips Petroleum Co. #1 Wilson

WILLIAMSON COUNTY
1. Shell Oil Co. #1 Purcell

ACKNOWLEDGMENTS

Study of the pre-Simpson rocks was suggested by members of Humble Oil & Refining Company. With their help and guidance an outline for such a project was devised and submitted to various other oil companies; subsequently, the following six companies contributed research grants to the Bureau of Economic Geology to subsidize the work: The Atlantic Refining Company, Gulf Oil Corporation, Humble Oil & Refining Company, Shell Oil Company, Sun Oil Company, and The Texas Company. The total contribution by the six companies was $58,552.42, and without it the project could not have been undertaken.

Equally important to the success of the project was the splendid cooperation from many companies in furnishing sample material and maps, namely: Abilene Sample Log Service, American Trading & Production Corporation. The Atlantic Refining Company, Roland K. Blumberg, Cities Service Oil Company, Continental Oil Company, Delaware Drilling Company, General Crude Oil Company, Gulf Oil Corporation, Honolulu Oil Corporation, Humble Oil & Refining Company, Ralph Lowe, Magnolia Petroleum Company, Midland Map Company, Phillips Petroleum Company, Richardson & Bass, G. L. Rowsey, Seaboard Oil Company, Shell Oil Company, Sinclair Oil & Gas Company, Skelly Oil Company, Standard Oil Company of Texas, Stanolind Oil & Gas Company, Sun Oil Company, The Superior Oil Company, Taylor Oil and Gas Company, The Texas Company, Tucker Drilling Company, Wilshire Oil Company. In addition, many other companies, too numerous to list, furnished cuttings and information indispensable to the project. In expressing appreciation to companies, it is tacitly understood that it is due to the efforts of individuals in these organizations that the cooperation was achieved. To these people the writer expresses sincerest thanks.

The work done by geologists of the U. S. Geological Survey on an informal cooperative basis has been of inestimable value to the project, particularly that by Preston E. Cloud, Jr., on the Ordovician fossils and by Allison R. Palmer on the Cambrian fossils. Dr. Cloud gave unstintingly of his time and effort to examine the great bulk of fossiliferous core. He should be commended especially for this very important work as it gives a framework of reference for the entire project, without which the results would be on an uncertain foundation.

The writer is also indebted to the authors of special papers listed on page 13 and to the following specialists who contracted to furnish thermoluminescence data for the project: J. A. S. Adams, D. F. Saunders, and E. J. Zeller, all of the University of Wisconsin.

Special acknowledgment is made to W. C. Bell, Department of Geology, The University of Texas, for his contribution of fossil identifications for a few wells and for his collaboration on the Cambrian rocks of the Llano uplift—data which are mostly unpublished. In fact, both Dr. Bell and Dr. Cloud have been so closely allied to their respective facets of this project that it is impossible to isolate their contributions.

In connection with X-ray studies, the writer wishes to express his sincere thanks to John C. Donely for his painstaking work and reports, which have been incorporated in the paper by Jonas. Dr. Joseph E. Weiss, Department of Ceramic Engineering, The University of Texas, supervised Mr. Donely's work.

Lane P. Dixon, who assisted on the project from May 1952 until June 1955, relieved the writer of much routine supervision in the preparation of cores and in maintaining a flow of cores to the project. He also made an incomplete study of the insoluble residues. Without Mr. Dixon's cheerful cooperation, the information in this publication of necessity would have been curtailed.

The writer expresses appreciation to the following for their help: To John E. Galley, Shell Oil Company, for critical reading of the final report. To L. R. Wilson, University of Massachusetts, for supervising the study on insoluble fossils. To various members of the Bureau of Economic Geology for chemical analyses, preparation of insoluble residues, preparation of samples for spectrochemical analyses, for drafting the illustrations, and for reading and criticizing the final report. To W. R. Varnell for making magnetic susceptibility and density determinations for the section on magnetic susceptibility. To F. A. Schindler for photographic work. To A. R. Embrey, Jr., and E. A. King, Jr., for routine handling, sampling, and filing of core materials. To T. E. Brown and D. W. Williams for assisting Dr. Jonas in the X-ray work. To Dixie Connor who sawed 20 thousand feet of core longitudinally. To Mrs. C. D. Sledge, Mrs. Jack Johnson, and Miss Margaret Harris for secretarial help. To Miss Mary Josephine Casey for preparing the final typescript for the printer and for many useful editorial suggestions. The writer is deeply grateful to all these people who so generously gave their time to the improvement of this publication.

The problems involved have been discussed with members of Federal and State surveys, university faculties, oil companies, and other industrial organizations. To all these the writer expresses his appreciation. Some additional acknowledgments are made at appropriate places in the publication.

GLOSSARY OF SELECTED TECHNICAL TERMS

Most of the terms defined by Cloud and Barnes (1948a, pp. 15–19) are used herein. However, the word "sublithographic," originally favored by Barnes, has been discontinued in favor of "aphanitic."

As the describing of sample materials progressed, the writer became more and more reluctant to use a nomenclature for chert containing various combining forms of semi- and sub- for porcelaneous and chalcedonic. It seems better to state the property being described, namely, the property of light transmittal as seen with unaided eye or low magnification, than to compare the chert to other substances having certain degrees of or lack of light transmittal. The terms preferred at this time are "opaque" and "translucent" and perhaps "slightly translucent." Comparing the two methods of description: A white, opaque chert is equivalent to a porcelaneous chert; a light olive-gray or medium light gray, opaque chert is equivalent to a subporcelaneous chert; a darker, nondescript, opaque chert is equivalent to a semiporcelaneous chert; a translucent chert is equivalent to a chalcedonic chert; and a slightly translucent chert is equivalent to a subchalcedonic chert. Unfortunately about half of the cores had been described before the change was made to the present terminology, and it is hoped that none of the older terms have been inadvertently retained.

Most of the pre-Simpson rocks examined are dolomite, and even though ghosts of an original granular texture may be preserved, it is not always possible to identify the origin of the grains. For example, a pellet limestone can usually be identified by the aphanitic, structureless nature of the pellets merging without a sharp boundary with the matrix in which they lie. Where such a rock is dolomitized the original grain size of the pellets is no longer detectable, and since no structure is present it may be unsafe to assume that the sediment originally contained pellets. Also, during dolomitization ooids and other grains having the shape of pellets can lose their structure and resemble pellets. For these reasons most of the dolomite preserving a granular texture is described as "originally a granular sediment" without implication of how the grains originally formed. Folk's usage (p. 100) is probably simpler, in which he calls grains of this type intraclasts and the rock either an intraclastic limestone or an intraclastic dolomite, the latter understood to have been originally a limestone. Aphanitic limestones with a granular texture are usually described (core descriptions, Appendix B) as "originally a granular sediment with aphanitic grains in an aphanitic or clear calcite matrix," whichever is present; in a few wells the grains are in part microgranular. If the writer had been aware of the word "intraclast" sooner, he would have used it in the sample descriptions in Appendix B.

So far as the word "vug" and its adjective "vuggy" are concerned, the writer prefers to follow the uniform usage found in all dictionaries consulted including the AGI (1957) Glossary. The word "vugular," supposed to convey the same meaning as the word "vuggy" (see, for example, Kelley and Silver, 1952, p. 51, 2d line), is completely unnecessary.

LABORATORY METHODS AND TECHNIQUES

For the most part, cores rather than cuttings were used for testing various techniques, since cores provide uncontaminated samples. In one well, in order to obtain a more nearly complete sequence, cores were supplemented by cuttings, hand-picked to eliminate obvious contaminants. For the final well correlations, in order to fill gaps where cores were lacking or insufficient in amount, cuttings were used and were supplemented by electric and radioactivity logs.

It was necessary to examine all cores to be sure that some critical bit of evidence might not escape detection. The procedure was as follows. As received, the core in its shipping container was laid out in order by depth. It was then sawed longitudinally using a diamond saw running in kerosene and lubricating oil; this fact should be borne in mind by anyone who may wish to examine these cores in the future. The depth and enough other information to identify each length of core was written on the core by means of a "Dri-Flo" brush marker and purplish-black writing fluid. One-half was chip sampled in 10-foot intervals, retained in the original containers, and placed in dead storage. The other half was placed in cardboard core boxes, 3 feet long and 4 inches square, and kept available for study. This half was scanned with a large reading glass for fossils, followed by binocular-microscope examination where needed, and its description recorded by dictaphone.

Usually the cores were examined wet to bring out structural and textural details. Limestone cores were briefly etched with hydrochloric acid to remove the minutely fractured surface left by the saw. The surface thus produced is essentially polished except for the less soluble material which stands in relief. On such a surface all detail can be observed. Hydrochloric acid, however, was not used on the dolomite as it dulls the surface and hides many features.

For chert description, examination of sawed surfaces is not as satisfactory as examination of broken surfaces formed by crushing. Granularity on a sawed surface is not easily seen, and in the core descriptions this property is not adequately described.

Fossiliferous cores and their matching halves were set aside. Cores for thin sectioning, as well as those containing unidentified minerals, were also set aside.

The 10-foot interval chip samples were crushed to simulate well cuttings. One set of samples was placed in small glass vials and stored in T-10 legal trays. Residues prepared from duplicate samples were placed in the next lower tray so that they could be quickly compared with the original samples. The bulk sample was retained in cloth bags and stored.

Strip logs at a scale of 20 feet to 1 inch were made by cementing the simulated cuttings to a cardboard strip. Such logs are very helpful in direct visual comparison of wells and can be rapidly examined under the binocular microscope. Mr. R. A. Bieberman, of the Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, kindly instructed the writer in preparing these logs and furnished information for the construction of apparatus for mounting the logs. The design of this apparatus and part of a log strip at reduced scale are shown in figure 3.

The cores to be thin sectioned were marked so that they could be sawed to produce a surface about the size of a thin section. This eliminates the shipping of excess rock and also makes certain the feature wanted in thin section is present. The surface to be thin sectioned, usually perpendicular to the bedding, was indicated with red pencil. The identification of the core fragment was placed on its reverse side with an ordinary steel pen nib and holder using black, light-sensitive fluid. After an appropriate length of exposure, the lettering is permanent and cannot be flaked or washed off, as so frequently happens with India ink. The fluid sets very

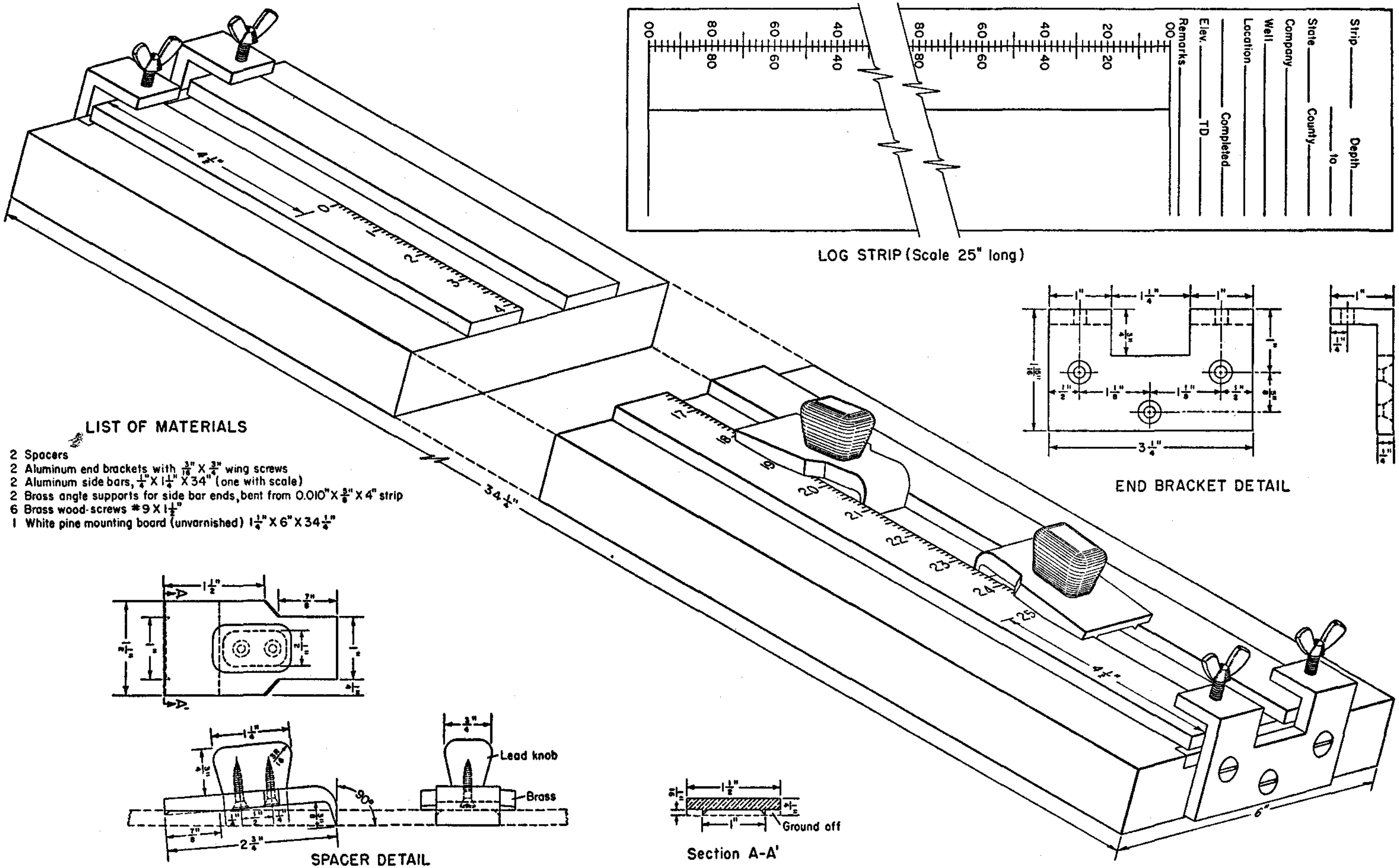

Fig. 3. Specifications for a sample-mounting device and log strip for use in mounting samples.

quickly in direct sunlight, but in more diffused light the setting time is much longer.

The fossilferous cores were slabbed in 0.25-inch slabs to reveal the maximum of fossil material. Fossils in fresh carbonate rocks of the type found in the pre-Simpson can seldom be broken free. Their identification depends on examination of cross sections, and the more surface exposed, the more cross sections and orientations will be revealed. Each slab was identified as to company, lease, well number, and depth by using light-sensitive fluid.

Chemical analyses were made both by the spectrochemical method and the gravimetric-volumetric-colorimetric method. For spectrochemical analysis a sample of at least 500 mg is desirable, with the sample ground to minus 100 mesh. The first group of samples were mostly leached in distilled water until a negative chloride test was obtained and then washed with a solvent to remove oil and other soluble organic substances, but this practice was discontinued when it was found that parallel unwashed samples did not differ appreciably from washed ones.

The relatively small amount of chemical work done by gravimetric-volumetric-colorimetric analysis was carried out by R. M. Wheeler and D. A. Schofield, of the Bureau of Economic Geology. Samples were passed through a small jaw crusher, reduced to 8 mesh in a large porcelain mortar, and a representative portion of about 60 grams ground to pass 100 mesh. For combined moisture and ignition loss an air-dried 1-gram sample was gradually raised to 1,000° C. and maintained at this temperature for an hour or until constant weight was attained. This sample was used for all other determinations except phosphorus.

The sample was dehydrated with hydrochloric acid, filtered, and the residue ignited at 1,200° C. in a platinum crucible, weighed, and then treated with hydrofluoric and sulfuric acids to volatilize the silica. The loss of weight plus the weight of silica recovered from the precipitate of trivalent elements (R_2O_3) was recorded as silica.

For determining the R_2O_3 group, the residue from the silica determination was dissolved in hydrochloric acid and combined with the filtrate from the silica determination, brought to a boil and precipitated with NH_4OH (1+1) at the change in the methyl red indicator from red to yellow. The precipitate was dissolved, reprecipitated, filtered, dried, ignited to constant weight at 1,200° C. in a platinum crucible, transferred to a fused silica crucible, and fused with potassium pyrosulfate. The fused mass was dissolved in sulfuric acid (1+9), evaporated to heavy fumes, cooled, diluted, filtered, dried, and ignited in a weighed platinum crucible. This residue is silica and its weight was added to the silica determined above.

The filtrate from the R_2O_3 determination was brought to volume in a 100-ml. volumetric flask. Suitable aliquots from this volume were used in the determination of iron as ferric oxide (Fe_2O_3) and titanium dioxide (TiO_2) photometrically (Fe_2O_3 by 0-phenanthroline and TiO_2 by hydrogen peroxide).

Alumina (Al_2O_3) was determined by subtracting the sum of the values for Fe_2O_3, TiO_2, and phosphorous pentoxide (P_2O_5) from the corrected R_2O_3.

The lime (CaO) content was determined in the filtrate from the R_2O_3 determination by double precipitation of the oxalate, filtering, calcining in a porcelain crucible, and weighing as CaO.

The magnesia (MgO) content was determined in the filtrate from the CaO determination by double precipitation with diammonium phosphate, filtering, and calcining at 1,100° C., following the method of Hillibrand et al. (1953, p. 636).

The P_2O_5 content was determined by measuring the light transmitted at 430 mu through a solution containing the yellow molybdivanadophosphoric acid complex (Kitson and Mellon, 1944) as described by Shapiro and Brannock (1956, pp. 37–38).

Insoluble residues were prepared in the usual manner, except that chemically pure hydrochloric acid was used and the entire residue collected on filter paper. The commercial acid available contained so much sulfate that gypsum was precipitated, especially on the finer residues. All the residue was collected for the purpose of learning more about the finer fraction. For logging the insoluble residues it was found advantageous to remove the minus 100-mesh fraction so that the coarser fraction could be seen more distinctly. In the usual method of insoluble-residue preparation, the finer fraction is decanted.

The technique for preparing insoluble fossils is discussed by Tynan (p. 90). No other special paleontological techniques were used.

The techniques used for magnetic susceptibility, thermoluminescence, and X-ray examination are discussed in the sections on these various subjects.

GENERAL STRATIGRAPHY

The stratigraphic sequence involved in this study is as follows:

Lower Ordovician
- Ellenburger group
  - C′ unit } In part equivalent to the C, B2b, and B2a units of Cloud and Barnes (1948a)
  - B2b′ unit
  - B2a′ unit
  - Honeycut formation
  - Gorman formation
  - Tanyard formation
    - Staendebach member
    - Threadgill member
- Wilberns formation (uppermost part)
  - San Saba member (uppermost part)

Upper Cambrian
- Wilberns formation (remainder)
  - San Saba member (remainder)
  - Point Peak member
  - Morgan Creek limestone member
  - Welge sandstone member
- Riley formation
  - Lion Mountain sandstone member
  - Cap Mountain limestone member
  - Hickory sandstone member

Formations in the Arbuckle group involved in a few wells in north Texas are the West Spring Creek formation, about equivalent to the post-Honeycut beds; Kindblade formation, about equivalent to the Honeycut formation; and Cool Creek formation, about equivalent to the Gorman formation.

Precambrian Surface

Bell and Barnes (MS.) discussing the Cambrian of central Texas stated:

> The Cambrian sea encroached from the southeast upon a mature, arid or semi-arid surface rising gently to the north and west. The less resistant rocks, such as the Packsaddle schist, most of the Valley Spring gneiss, and most of the granites, were eroded to essentially a common level, whereas the resistant rocks, such as the aplogranites and injected portions of the Valley Spring gneiss, formed isolated hills and ridges standing as much as 800 feet above their surroundings. Marble also formed ridges, but these were not so high. It is surmised that the topography of this old surface resembled somewhat that of the Precambrian portion of the Llano area today. The distribution of the various Precambrian rock types beyond the Llano area in the subsurface is shown by Flawn (1956, Pl. I).
>
> That the land was arid or semi-arid may be reasoned from several lines of evidence: (1) Wind-abraded pebbles and cobbles are common at the base of the Cambrian sequence. (2) The clay fraction is mostly absent or scarce in the Cambrian sequence, probably having been removed by wind before the coarser sediments were flushed into the sea. (3) Marble forms ridges, indicating insufficient moisture for solution to keep pace with the disintegration of the adjacent rocks. (4)[1] The sand grains show chatter marks that can be produced only by the work of wind.

That local relief existed elsewhere on the surface of the Precambrian is mentioned by Flawn (1956, p. 53), who stated:

> Recent exploration of the so-called Cambrian trend from Coke County north to Cottle County indicates that hills or peaks of hard granite or arkose gneiss protrude above a metasedimentary surface of mica schist and phyllite. In the Van Horn area the surface on which the late Precambrian? Van Horn sandstone was deposited was a hilly, deeply eroded terrain; the surface of Precambrian rocks on which Permian rocks were deposited in this same area was a rolling one with perhaps 300 feet of relief.

During the present project, little additional information about local relief on the surface of the Precambrian has been obtained, except that the Shell Oil Company No. 1 Purcell, Williamson County, is presumed to have reached a buried hill with perhaps 100 feet more relief than that of buried hills in the nearby Llano region.

Regionally, the direction of slope of the surface of the Precambrian noted by Bell and Barnes (MS., fig. 1; see fig 4 of present paper) continued westward, reaching its highest point in Lea County, New Mexico (as determined only from wells examined during this project), and there descended again westward as well as southward. In Continental Oil Company No. 1 Burger B-28, Lea County, New Mexico, only about 100 feet of Gorman rock was penetrated before the basement was reached.

The Ellenburger rocks immediately flanking the Lea County area are rich in feldspar, in part fresh and in part much altered. Folk, from his thin-section studies (pp. 104, 130), believes these materials were derived from an island chain (ancestral Central Basin Platform) of moderate

[1] Personal communication from R. L. Folk, Department of Geology, The University of Texas.

relief which shed immature arkosic sediments into the surrounding area, and that the climate of the area was warm and humid.

The degree of weathering of the Precambrian beneath pre-Simpson rocks should differ from place to place, with least weathering beneath the Riley and Wilberns formations and most beneath the Ellenburger. Flawn (1956, pp. 53–54) expressed interest in a study of the difference of weathering of the Precambrian beneath various Paleozoic units but during his basement-rock study received too few complete suites of samples from weathered to fresh rock to make the study worthwhile.

Riley Formation

The name Riley formation was proposed by Cloud, Barnes, and Bridge (1945, p. 154; further discussed by Bridge, Barnes, and Cloud, 1947) to include all the Cambrian strata in central Texas beneath the Wilberns formation. Its type section is in East Canyon, Riley Mountains, about 18 miles by road southeast of Llano and west of the road to Click. From base to top it includes three members, the Hickory sandstone, the Cap Mountain limestone, and the Lion Mountain sandstone, computed by Cloud to be 335, 421, and 24 feet thick, respectively, a total of 780 feet for the Riley formation.

The type section has now been measured, described, and zoned faunally by Bell, but the results have not been published. He measured 330 feet of Hickory sandstone, 411 feet of Cap Mountain limestone, and 33 feet of Lion Mountain sandstone, a total of 774 feet for the Riley formation.

The Riley formation is the result of a transgressive-regressive cycle of sedimentation and thins northeastward across the Llano region, ranging from slightly over 800 feet on the south to slightly over 600 feet on the north side of the region. A generalized isopach map (fig. 4), disregarding thinned sections over buried hills, shows that the Riley is probably thickest south of the Llano region and laps out about 100 miles west and a slightly greater distance northwestward from the Llano region. The Riley appears to have accumulated in a northwestward-extending arm of the sea and very likely extended beyond its present limits, since there is a disconformity at its top.

Hickory Sandstone Member

The Hickory (Pls. 30, B-E; 31, E, F) is mostly a quartz sandstone and only locally is it conglomeratic at the base, with the pebbles mostly quartz. Feldspar is important in the basal part only locally and where present is usually indicative of a nearby buried granite hill. The Hickory sandstone is mostly various shades of yellowish gray, light to medium olive gray, and greenish gray; in some areas, especially to the northwest, it is in part a very distinctive dusky red.

Grain size ranges from 2 inches and larger where conglomeratic toward the base to medium grained and finer upward; silty units with shaly bedding occur sporadically at all levels. The grains are mostly angular to subrounded in the lower part and very well rounded and polished in the upper dusky red part. In many areas of the Llano region the pebbles at the base of the Hickory are wind faceted. Cross lamination is present throughout the member, it is noncalcareous and nonglauconitic, and is gradational into the overlying slightly glauconitic, very sandy Cap Mountain limestone. The boundary between the two members in the Llano region is mapped at a topographical and vegetational break—the upper part of the Hickory sandstone forming a bench which supports a growth of deciduous trees, whereas the lower part of the Cap Mountain forms a steep slope and is covered by a dense growth of cedar. In the subsurface, the absence or near absence of carbonate and glauconite is used to separate the Hickory sandstone from the overlying Cap Mountain limestone.

The boundary between the Hickory and Cap Mountain is gradational not only vertically but horizontally as well, the upper part of the Hickory becoming younger both northward and westward. That the upper part of the Hickory in these directions is the time equivalent of the Cap Mountain of the southeastern part of the Llano region is proven by the passage of faunal and color zones laterally from one to the other. Palmer (1954, fig. 3) demonstrated the lateral transition of faunal zones from one to the other; if color were superimposed on the same diagram, it would be found that the red Hickory at the northwest encompassing the *Cedarina-Cedaria* zone and the uppermost part of the *Bolaspidella* zone passes laterally into the reddish zone of the Cap Mountain limestone to the southeast.

The red zone, about 150 to 200 feet thick, continues westward and northward in the subsurface. In some wells this zone is dark brown, but whether it is red or brown the color is from thin layers of iron oxide around well-rounded, mostly polished-appearing sand grains. About 150 feet of light-colored sandstone is beneath the red sandstone, followed by about 100 to 150 feet of pinkish sandstone, and again light-colored sandstone to the Precambrian basement. In many wells relatively pure quartz sandstone rests on the basement; in others, as much as 50 feet of sandstone contains microcline.

Complete sections of Hickory in the Llano region range from 276 feet in the southeast to 434 feet in the northwest; in the subsurface the maximum observed thickness is slightly more than 500 feet in Menard and Kimble counties. The Hickory probably thickens southeastward from this area, but in that direction no wells have been drilled through it. In all other directions it thins, both the base and top become younger, and where the overlying Cap Mountain disappears it may not be readily distinguished from the Lion Mountain sandstone. Beyond where the Cap Mountain limestone disappears, the Riley formation consists mostly of terrigenous material indistinguishable in examination of cuttings from similar material of the overlying Wilberns formation. It would probably be a simple matter to distinguish the boundary between the two formations if there were sufficient wells completely cored through this part of the stratigraphic sequence. That differences do exist is indicated by the characteristics of the electric and radioactivity logs.

CAP MOUNTAIN LIMESTONE MEMBER

The Cap Mountain limestone (Pls. 29, F; 30, A) in the Llano region consists of sandy, silty, and glauconitis limestone, roughly arranged stratigraphically from the base upward in that order. The carbonate part is mostly granular, clastic calcite; dolomite is present only as occasional rhombs or replacement of various small objects such as ooids and fossil fragments. The Cap Mountain limestone is mostly various shades of light olive gray, moderate to dark yellowish brown, yellowish gray, and greenish gray with lesser amounts of very pale to dark yellowish orange, dusky yellow, olive gray, pale olive, pale brown, moderate brown, grayish brown, reddish brown, and pale to dusky red. In the subsurface the color is more subdued, mostly very light to medium olive gray with some greenish gray where glauconitic.

In the southeastern part of the Llano region the lower part of the Cap Mountain varies from slightly to very sandy, the middle part is very silty, and the upper part is chiefly limestone, in part oolitic. Northward across the region the lower unit is largely replaced laterally by Hickory sandstone; northward in the subsurface the middle unit is next replaced; and finally the upper unit also grades laterally to Hickory sandstone (Pl. 32, E, F). Westward in western Menard County the Cap Mountain grades entirely to terrigenous materials.

In the subsurface southward from the Llano region the silty zone grades to limestone and the sandy zone grades to limestone and siltstone. The Cap Mountain as a whole thickens to 650 feet in Tucker Drilling Company No. 1 Dr. Roy E. Perkins, southeastern Kerr County, whereas its thickness in the Llano region ranges from 156 feet in San Saba County, north of Pontotoc, to 497 feet along White Creek in Blanco County. The Cap Mountain limestone probably continues to thicken in a southward direction.

The boundary with the overlying Lion Mountain sandstone is gradational and is usually chosen at the appearance upward of appreciable terrigenous material and a flat or gentle slope. From the Llano region northward in the subsurface the boundary is usually placed where terrigenous material largely disappears downward and limestone becomes dominant; southward, including the southernmost part of the Llano region, the boundary is placed at the top of the very oolitic, massive, yellowish gray to light olive-gray limestone so characteristic of the upper part of the Cap Mountain.

LION MOUNTAIN SANDSTONE MEMBER

The Lion Mountain, consisting of quartzose greensand, glauconitic quartz sandstone, sandy limestone, trilobite and brachiopod coquinite lenses, and minor shale and siltstone, comprises the upper thin member of the Riley formation. It is characteristically dusky green to grayish olive green where fresh and, especially in the lower part, is studded by contrasting white to yellowish gray, cross-bedded coquinite lenses.

In the Llano region the Lion Mountain ranges in thickness from 29 feet in the Johnson City area, Blanco County, to 68 feet in the Threadgill Creek section, Gillespie County. Its top is bounded by a disconformity. In the subsurface southward the thickness mostly remains within this range, but limestone is more abundant, terrigenous material less abundant and finer grained, and the top no longer appears to be disconformable. In fact, the Lion Mountain can not be distinguished from the overlying Welge. Northwestward from the Llano region the Lion Mountain thickens somewhat, perhaps at the expense of the Cap Mountain, and becomes less glauconitic. In some wells to the west of the Llano region a limonitic zone at the top of the Lion Mountain may represent a fossil soil. Beyond about 50 miles westward and northwestward from the Llano region the Lion Mountain sandstone cannot be certainly traced.

WILBERNS FORMATION

The Wilberns formation was named by Paige (1911), redefined by Cloud, Barnes, and Bridge (1945, pp. 155–156), and further discussed by Bridge, Barnes, and Cloud (1947, pp. 114–123), who retained the lower boundary proposed by Paige but raised the upper boundary to the top of the Cambrian. It was further redefined by Barnes, Bell, and Pavlovic (1954, pp. 30–31) and Bell and Barnes (MS.), who show that the Wilberns in the western part of the Llano region includes some Lower Ordovician rocks. The Wilberns as now visualized includes, from base to top, four members: the Welge sandstone, the Morgan Creek limestone, the Point Peak, and the San Saba.

West and north and possibly south of the Llano region, usage suggested by Cloud and Barnes (1948a, p. 30) and adopted by petroleum geologists places the Tanyard-Wilberns boundary in the vicinity of the first appearance downward of glauconite. This, however, is not true eastward where Cloud and Barnes (1948a, Pl.1) place several hundred feet of nonglauconitic dolomite in the upper part of the Wilberns formation. The first appearance downward of glauconite does not approximate a time plane. However, the boundary chosen by Cloud and Barnes between the Wilberns and Tanyard, which is also near the systemic boundary between the Cambrian and Ordovician, throughout much of the Llano region does approximate a time plane, and the only serious departure from such a plane appears to be in the western part of the Llano region where the boundary is younger.

In the western part of the Llano region the glauconitic limestone above the sandstone in the San Saba member is of Ordovician age. The sandstone, however, is probably all or at least mostly Cambrian in age. The top of the sandstone may approximate the position of the systemic boundary, and if this is true the placing of the Wilberns-Tanyard boundary at this level would follow the thought of Cloud and Barnes that the formation boundary coincides essentially with the systemic boundary.

If the glauconitic carbonate unit above the sandstone from Mason County westward were placed with the Tanyard formation, a much simplified terminology would result, at least locally. The Tanyard, as in the Llano region, would then be composed of two members, an upper thicker cherty member and a lower thinner essentially noncherty member, nonglauconitic to the east and glauconitic to the west. Eastward for a few tens of miles, from the area where sandstone is present in the San Saba member, a position equivalent to that of the top of the sandstone would have to be mapped using fossils; however, less than 50 feet of beds is involved and if the highest glauconite were used for the boundary it would not be far out of place. Even if this simplified nomenclature were to be adopted, it is probable that in some direction in the subsurface, conditions change and it will not be possible to locate the systemic boundary. For this reason, one hesitates to modify the terminology that is now fast becoming established.

As pointed out by Bell and Barnes (MS.), because of the paucity of shale and predominance of siltstone, limestone, and intraformational conglomerate, the designation "Point Peak member" is preferable to "Point Peak shale member"; they recommend that "shale" as part of the name of this member be dropped permanently. Barnes and Bell (1954b, p. 36) abandoned the name "Pedernales dolomite member of the Wilberns" and placed in the San Saba member (formerly San Saba limestone member) all dolomite so designated. This brought the nomenclature of the upper part of the Wilberns into conformity with that of the overlying Ellenburger. The San Saba member as now constituted consists of limestone, dolomite, and sandstone.

The Wilberns formation in the Llano region ranges in thickness from about 540 feet in McCulloch County to 619 feet along James River in Mason County. The 360-foot thickness in the Johnson City area reported by Barnes (Cloud and Barnes, 1948a, p. 29) is now known to be too small (Cloud and Barnes, 1957, p. 168), because part of the sequence is missing through faulting. That the thickness of the Wilberns in this part of the Llano region is not far from normal is shown by a normal thickness found in the Stratoray Oil Corporation No. 1 Stribling, Blanco County, only a few miles from the faulted section. In the subsurface southeastward from the Johnson City area, the Wilberns thickens to about 730 feet in Roland K. Blumberg No. 1 Wagner, Blanco County (Pl. 1). As the line of correlation is followed west-southwestward from this well, the Wilberns continues to thicken; it is about 1,130 feet thick in General Crude Oil Company No. 1 Anderson, Bandera County.

Westward from the Llano region the Wilberns maintains a fairly uniform thickness through Kimble and Menard counties and thins appreciably in The Atlantic Refining Company No. 1 Noelke, Irion County, just before it laps out against the Precambrian a short distance to the west. Northwestward it thins appreciably to about 230 feet in the Honolulu Oil Corporation Whitaker wells, Nolan County, and to 70 feet in Humble Oil & Refining Company No. 1 Farris, Lubbock County. The approximate line along which the Wilberns laps out against the Precambrian is shown in figure 4.

WELGE SANDSTONE MEMBER

The Welge sandstone is a coarse- to medium-grained, mostly pale to dark yellowish-brown, typically nonglauconitic, sparsely fossiliferous, well-sorted, quartz, marine sandstone. The grains characteristically are reconstituted and glitter in the sunlight. The base is characterized locally by 2 or 3 feet of earthy, reworked Lion Mountain sandstone or by poorly sorted granule beds marking the surface of disconformity on which the Welge was deposited. Its boundary with the overlying and more distinctly bedded Morgan Creek limestone is gradational within narrow limits.

Locally in the eastern part of the Llano region the Welge is in part glauconitic, and in the subsurface to the south and southeast it is a greensand indistinguishable from that in the Lion Mountain beneath (Pl. 29, D, E). The disconformity so well documented in the area of outcrop probably does not exist in these directions.

The Welge ranges in thickness from 11 feet in the White Creek section, Blanco County, to as much as 35 feet in places along the northern and western sides of the Llano region. In the subsurface in all directions from the Llano region it mostly remains within this thickness range, being perhaps thinnest to the southeast. Northwestward beyond the point where the Morgan Creek ceases to be mainly carbonate, the Welge is traced by poorly defined electric-log characteristics; eventually it can no longer be recognized in this direction.

MORGAN CREEK LIMESTONE MEMBER

The Morgan Creek limestone member (Pls. 31, A-D; 32, A-D) consists of coarsely granular, greenish-gray to light olive-gray, glauconitic limestone with interbeds of fine-grained, darker greenish-gray, silty limestone in the upper part; beds of aphanitic stromatolites are near the top in some areas. The member is typically sandy and pinkish to reddish in the basal part where it grades to the underlying Welge sandstone; elsewhere in a few areas pinkish limestone is seen only at the very top in the Morgan Creek. The top of the Morgan Creek is usually chosen at the top of the uppermost thick limestone bed rather than at the base of the lowest thin-bedded unit, except where stromatolite beds invade the lower part of the Point Peak; in such areas the top is arbitrarily placed at a point convenient for mapping. The Morgan Creek is commonly oolitic, and occasionally ooids and other small objects are replaced by yellowish-orange dolomite; in some zones thin, foot-long patches of yellowish-orange dolomite are common. In the Llano region significant dolomite and chert have been seen in the Morgan Creek in only one small area northwest of Hye, Blanco County.

The Morgan Creek ranges in thickness from 114 feet in the Camp San Saba section, McCulloch County, to 143 feet in the White Creek section, Blanco County, and maintains this thickness southward from the Llano region where it becomes increasingly difficult to distinguish from the overlying rock. In Roland K. Blumberg No. 1 Wagner, Blanco County, all except the lower 25 feet is dolomite, and dolomite is continuous upward to the middle of the Gorman. In this well the top of the Morgan Creek is arbitrarily placed at the top of coarse-grained dolomite and beneath slightly silty, fine-grained dolomite. Siltstone is common in the Morgan Creek south of the Llano region, and dolomite is prominent and some sandstone is present in the Morgan Creek in General Crude Oil Corporation No. 1 Anderson, Bandera County.

In the subsurface westward from the Llano region the Morgan Creek remains characteristic through Kimble and Menard counties, except that it grades to dolomite some place east of Deep Rock Oil Corporation No. 1 Bevans; west of the point where carbonate is present it is mostly sandstone. Northwestward from the Llano region the Morgan Creek is dominantly terrigenous; carbonate, except in a few wells, is limited to cement. Where the characteristic carbonate rocks are absent, electric logs give a hint of the interval to be assigned to the Morgan Creek, and characteristic Morgan Creek fossils were found in one well, Honolulu Oil Corporation No. 2 Whitaker, Nolan County.

POINT PEAK MEMBER

The Point Peak member is a sequence of calcareous, very light olive-gray siltstone; light olive-gray to light olive-green and yellowish-gray silty limestone; varicolored intraformational conglomerate; very light greenish-gray to very light olive-gray stromatolites; and minor amounts of dusky yellow-green to grayish-green clay-shale. In the northern and western part of the Llano region the calcareous siltstone forms a distinctive basal unit which grades upward into more calcareous siltstones interbedded with silty limestone, intraformational conglomerate, and stromatolites.

The siltstone of the Point Peak is nonresistant, rarely forms ledges, and mostly produces partly covered slopes. The intraformational conglomerate commonly crops out to form discontinuous ledges. Thin, flat, silty limestone pebbles are the major constituent of the conglomerate; they are somewhat rounded, commonly laminated, and are arranged either at all angles or parallel to the bedding planes. The matrix is fine-grained limestone, generally light gray, and both matrix and pebbles contain scarce fragmental fossils.

The stromatolitic limestone is present in various forms: masses a few inches in diameter widely scattered along one horizon; continuous beds a foot or so thick that can be traced for miles; isolated larger masses 40 or more feet thick and slightly larger horizontally (Cloud and Barnes, 1948a, Pls. 18 and 19A); great bodies of rock a hundred or more feet in thickness that can be traced for miles; or in practically any-sized mass or configuration between these extremes. The large stromatolitic bioherms are mostly on the western side of the Llano region; however, they are common in the Riley Mountains. In the easternmost exposures of the Point Peak in Burnet County, large stromatolitic masses are entirely dolomite.

A laterally persistent, 1- to 3-foot, fossiliferous limestone bed near the top of the Point Peak over much of the Llano area contains silicified valves of two brachiopod genera, *Billingsella* and *Plectotrophia,* mostly confined to this interval. In the extreme eastern part of the Llano region this zone is not characteristic; *Plectotrophia* fans out through 40 feet or more of beds and passes laterally into rocks of the dolomitic facies of the San Saba member.

The boundary between the Point Peak and the overlying San Saba member ranges from gradational to fairly sharp. Where typical Point Peak siltstone is overlain by girvanella limestone, as in the Cherokee Creek and Little Llano River areas, the boundary is distinct. Elsewhere the boundary is in a gradational sequence and must be arbitrarily chosen; where stromatolitic bioherms transgress the boundary it is placed either at the bottom or at the top of the bioherm, depending upon which unit contains the bulk of the mass.

The Point Peak is of rather erratic thickness in the Llano region, ranging from 188 feet in the James River section, southern Mason County, to 25 feet in the Klett-Walker section in the Johnson City area, Blanco County. A thickness of 216 feet in the Riley Mountains may be excessive, since the section in which this amount was measured was offset along the base of a stromatolitic biostrom which may not be at a constant level. A thickness of 94 feet in the Camp San Saba section is too little, but here a thick stromatolitic bioherm has been included with the San Saba member since it extends high into that member. Disregarding the anomalous values, the Point Peak averages about 150 feet in thickness over most of the Llano region, thinning somewhat in the northeastern part of its outcrop area and rapidly from southern Burnet County southward to the Klett-Walker section. As the Point Peak thins, the San Saba member correspondingly increases in thickness, indicating a facies change in this direction. The abruptness of transition from a dominantly terrigenous to a dominantly carbonate environment may have been enhanced by a barrier of stromatolite reefs extending in a northeast-southwest direction. This speculation is supported by the finding of a thick sequence of aphanitic limestone at this position in Shell Oil Company No. 1 Purcell (Pl. 2) in Williamson County. Southwestward from this point the rocks where exposed are mostly dolomitized, and stromatolitic structure, if present, may not have been recognized. Some hint is seen that at least part of the massive, coarse-grained dolomite originally may have been reef like. In thin section, dolomite of this type mostly has composite structure; little of it contains ghosts, and most of those present are angular, breccia-like forms.

Southeastward from the Llano region the Point Peak is not recognized (Pl. 1); southward some is postulated on rather tenuous evidence, and northeast of General Crude Oil Company No. 1 Anderson, Bandera County, an appreciable amount of siltstone appears. Considering the great thickening of the Wilberns in this well, this silty interval could almost as well be assigned to the Morgan Creek on the basis of the assignment of similar material in the Rowsey wells to the east. A persistent but irregular zone of medium- to coarse-grained dolomite (Pl. 1) included in the San Saba member may occupy about the position of the Point Peak member of the Llano region.

Westward and northwestward from the Llano region, especially beyond where the carbonate rocks of the overlying and underlying units give way to terrigenous materials, the boundaries of the Point Peak are insecurely chosen on the basis of lithologic composition and have been assigned mostly from electric and radioactivity characteristics where logs of these properties were available.

SAN SABA MEMBER

The San Saba member, composed mostly of dolomite and limestone in the Llano region, varies considerably both laterally and vertically. The calcitic facies, mostly medium and fine grained, glauconitic, thinly to thickly bedded, various shades of gray, yellowish gray, light olive gray, and greenish gray to the west, becomes finer grained eastward to localities where the remaining small amount of limestone is aphanitic, white, and nonglauconitic. The basal beds in the central part of the area contain small round limestone spheres known as girvanella.

The dolomitic facies is in part fine grained, medium bedded, and various shades of gray, yellowish gray, and pinkish gray, characteristically mottled pale red and purple, and in part medium to coarse grained, massive to thickly bedded, and light yellowish gray. Typically, the western portion is mostly limestone, the eastern portion mostly dolomite with rare islands of limestone; in between, limestone overlies dolomite. However, in the extreme northwestern part of the area dolomite preserving stromatolitic structure predominates and is overlain by clean, calcareous sandstone followed by limestone. From 55 to 70 feet of sandstone has been measured; the grains are mostly of medium size and well rounded.

Originally, the dolomitic facies of the San Saba member was named the Pedernales dolomite member of the Wilberns formation, from Pedernales River in the Johnson City area, by Barnes (Cloud, Barnes, and Bridge, 1945), who subsequently abandoned the name (Barnes and Bell, 1954b, p. 35), as explained above (p. 28).

In measured sections, calcitic San Saba is overlain by calcitic Threadgill, and dolomitic San Saba is overlain by dolomitic Threadgill. The mostly granular, glauconitic, calcitic San Saba contrasts with the mostly aphanitic, nonglauconitic, calcitic Threadgill. Boundaries between these rock types are everywhere gradational through a few feet of section, and there is no evidence to indicate any interruption in sedimentation. Dolomitic San Saba typically is fine grained and varicolored, commonly mottled pale red purple; dolomitic Threadgill typically is medium to coarse grained and mostly very light gray to white. Locally, in the eastern part of the Llano region the upper part of the San Saba is coarse-grained dolomite entirely similar to that in the overlying Threadgill, and in these places no boundary can be mapped.

In the western part of the Llano region the upper 35 to 90 feet of calcitic San Saba contains a Lower Ordovician trilobite fauna. Similarity of rock characters and lack of significant evidence of sedimentary hiatus indicate continuous deposition across the Cambrian-Ordovician boundary.

The Wilberns formation and the Ellenburger group are tangible rock units that differ lithologically, whereas the systemic boundary of necessity must be defined in paleontologic terms.

Stromatolitic bioherms similar to those in the Point Peak characterize parts of the San Saba member and where present are mostly toward the base. Some chert in the eastern dolomitic facies has a structure which suggests that it replaced the granular rock that normally forms septae between stromatolitic heads and probably was formed prior to or during dolomitization. The thickest stromatolitic sequence seen is in northwest Mason County; it almost reaches the top of the San Saba member, is almost completely dolomitized, appears to have served as a barrier cutting off movement of sand eastward, and sharply bounds the western edge of the extensive sandstone body in the San Saba member.

In southwestern Mason County along James River, sandstone is equally abundant in the same stratigraphic position, but to the east along Threadgill Creek none is present. To the south in the subsurface (Pl. 3) 300 feet of sandstone is in Forest Oil Corporation No. 1 Stapp, Kimble County, but to the east, sandstone and even sand is completely absent at this level in L. U. Rowntree No. 1 Richard Kott, Gillespie County. Still farther south (Pl. 1) a 500-foot sandstone and sandy dolomite zone is in General Crude Oil Company No. 1 Anderson, Bandera County, whereas no sandstone or sand is present at this level in wells to the east. It seems likely that the extensive sandstone body of the San Saba member is sharply terminated by a north-south-oriented barrier reef exposed, so far as is known, only in northwestern Mason County. The distance between the sections shown on Plates 1 and 2 is about 80 miles, and it is believed that the barrier reef probably extends far beyond these sections both to the north and south.

The thickness of the San Saba member in the Llano region ranges from a measured 281 feet in the Threadgill Creek section, Gillespie County, to an estimated 450 feet in the Johnson City area, Blanco County; most other sections measured have a thickness of 300±20 feet. The 230 feet measured in the Everett ranch section is anomalous and this thinness is not understood, unless there is undetected faulting or the upper part is coarse-grained dolomite confused with the Threadgill.

East of the postulated barrier reef and south of the Llano region the San Saba member thickens markedly. Part of this thickening is at the expense of the Point Peak, and most of the rest is at the expense of the Threadgill member of the Tanyard formation. The 600- to 800-foot thickness of San Saba found in wells in this area is exceeded only by the 880 feet in General Crude Oil Company No. 1 Anderson, Bandera County. Much of the lower half of the San Saba in this area is medium- to coarse-grained dolomite, and in the Roland K. Blumberg No. 1 Wagner, Blanco County, medium- to coarse-grained dolomite extends to the top of the Threadgill member. The lower boundary was chosen at a change in grain size where lying on Morgan Creek limestone or at the first appearance downward of silty rocks where lying on the Point Peak. Admittedly this boundary in places is arbitrarily chosen.

To the east of the Llano region in Shell Oil Company No. 1 Purcell, Williamson County, the San Saba is similar in thickness to that measured in the nearest outcrop; the lower half is stromatolitic, in part dolomitized, and the upper half is mostly coarse-grained dolomite. Coarse-grained dolomite continues upward high into the Tanyard formation.

West of the Llano region westward from the postulated barrier reef the San Saba is sharply divided into two distinct units: a lower one, probably Cambrian in age, mostly sandstone, and an upper one, probably Ordovician in age, mostly slightly glauconitic, impure carbonate (Pl. 30, F). Directly west of the Llano region granular limestone predominates in the upper unit and fine-grained dolomite is common. To the northwest of the Llano region the unit is mostly fine-grained dolomite. After an initial thickening it again thins to disappearance in a northwestward direction, except that in one well, Seaboard Oil Company No. 4 Upshaw, Stonewall County, the unit is exceptionally thick (Pl. 5). The lower sandstone unit also thins northwestward and eventually laps out against the Precambrian.

The upper boundary of the San Saba member west of the postulated barrier reef fluctuates from place to place, and two workers seldom choose the boundary at the same place; furthermore, a characteristic low spontaneous potential value on electric-log curves seldom coincides with the lithologic boundary, most being above and a few below. The lower boundary of the San Saba, like the upper one, is not distinctive, and in this area electric logs were useful in trying to decide where to place it.

The boundary between the sandstone and carbonate facies of the San Saba member, however, is easily recognized by independent workers and is very pronounced on electric logs. This boundary, in the area where sandstone and carbonate are present, furnishes the most easily recognized and satisfactory reference plane found in the entire pre-Simpson group of rocks, with the possible exception of the boundary between the Welge sandstone and the Morgan Creek limestone.

Ellenburger Group

The general stratigraphy of the Ellenburger group is discussed by Cloud and Barnes (1948a, pp. 30–35), and the reader is referred to that publication as background for the following discussion. Cloud and Barnes recognized that the Ellenburger in the Llano region is truncated by erosion; that the uppermost formation, the Honeycut, is very likely not completely exposed even in the thickest section; and that other units of formational rank might be present in the Lower Ordovician above the Honeycut formation in the subsurface. It was demonstrated during the present project that both these surmises are true. Younger Honeycut rocks are definitely present in Shell Oil Company No. 1 Purcell, Williamson County, east of the Llano region, and still youner ones appear to be present in several west Texas wells. In some of these same west Texas wells other units are recognized which may correlate with those designated by Cloud and Barnes (1948a, pp. 72–74) in the El Paso formation of Beach and Franklin Mountains.

For many years all rocks of Lower Ordovician age in the subsurface of west Texas and southeast New Mexico have been called Ellenburger, and this usage should continue even though the rocks are in part much younger than those of the Llano region and actually correlate with rocks in the El Paso formation. Until more is learned about the rocks above the Honeycut formation, it may be just as well to refer to them as post-Honeycut beds or in the subsurface use the units of the Beach Mountain section with a prime mark, since the units do not entirely correspond.

Tanyard Formation

The Tanyard, divided into subequal parts in the Llano region, consists of a thinner lower member, the Threadgill—average 234 feet, mostly noncherty; and a thicker upper member, the Staendebach—average 359 feet, mostly cherty. Each member is composed of calcitic and dolomitic facies with dolomite predominant especially in the subsurface. In the Llano region the Threadgill member is typically coarse-grained, light-colored dolomite, and in the subsurface to the east and southeast the member is composed of similar dolomite. The Threadgill is limestone in one well south of the Llano region, and it is fine- and very fine-grained dolomite in one well at the edge of the outcrop area in northwestern Mason County. Westward from the Llano region, as explained elsewhere (pp. 32–33), Wilberns-type lithology transgresses the Threadgill member, and the unit is no longer retained in the Tanyard formation of the Ellenburger group.

The Staendebach, where dolomitic, is typically fine and very fine grained in the lower part and fine to coarse grained in the upper part, contrasting sharply with the overlying mostly microgranular and very fine-grained dolomite of the Gorman. Where the sequence is limestone the boundary is not always securely placed. Lack of sand grains, characteristic of the Tanyard in the Llano region, is not characteristic a short distance to the south, southwest, west, and northwest; in the same directions the Gorman becomes nonsandy, whereas in the Llano region it is sandy.

This unit is cherty, with more abundant quartzose chert and quartz druse than in any other unit. Oolitic chert is common, especially in the upper part, and in some wells is found to the base of the member.

In the Llano region and some of the immediately adjacent subsurface, the Tanyard is nonsandy. Westward and southwestward sand shortly makes its appearance, becoming more abundant westward, and in the Beach Mountain section the unit is sandstone. The Tanyard formation is mostly light colored but becomes somewhat darker westward where it is about the same color as the Gorman.

The Tanyard thickens slightly southwestward from the Llano region to about 710 feet in General Crude Oil Company No. 1 Anderson, Bandera County, and the interval between the top of the Tanyard and the top of the sandstone in the San Saba has thickened considerably to 890 feet, which is about 300 feet more than in the Llano region. In other directions the Tanyard either maintains its surface thickness or thins slightly.

GORMAN FORMATION

The Gorman formation of the Llano region averages 463 feet in thickness and consists of a lower dolomitic facies, mostly microgranular, and an upper calcitic facies. The relative proportion of limestone and dolomite ranges widely from section to section, and the chief lithologic distinction from adjacent formations, other than the mostly finer grain size of the dolomite, is the presence of widely scattered sand grains in a few beds throughout the formation. The break from sandy to nonsandy beds at the base of the formation is sharp, but at the top sandy beds lap over the boundary for about 50 feet into the Honeycut formation. The boundary between the two formations is placed at the base of an alternating sequence of beds, either limestone and dolomite or, if limestone is absent, different grain sizes of dolomite. The upper part of the Gorman is mostly massive limestone in outcrop, and even in the subsurface, where it is mostly dolomite, the grain size is more nearly uniform than in the immediately superjacent Honeycut.

In the subsurface to the east and southeast the Gorman has the same characteristics as found in outcrop. However, only a short distance to the south, southwest, west, and northwest one of its chief distinctions disappears, namely, the presence of sand grains. In the same direction the Tanyard beneath and the Honeycut above become sandy, whereas in the Llano region only about the basal 50 feet of the Honeycut is sandy. The Gorman again becomes sandy in Pecos County and remains sandy westward as far as traced.

The chief criterion for the recognition of the Gorman where it is dolomite in the subsurface is its finer grain size. This is well shown in the correlation section (Pl. 1) where the overlying Honeycut formation also is dolomite and distinctly coarser grained. The grain-size difference at the base of the Gorman is much more pronounced than that at the top of the Gorman. Westward in the subsurface the grain-size difference between the Gorman and adjacent formations becomes less distinct, but in most wells the distinction remains valid even though the Gorman has coarsened. Farther west in the Beach and Franklin Mountains sections the grain-size difference is no longer valid.

The Gorman formation to the east is about the same color as the Honeycut formation and to the west is darker than the lower half of the Honeycut. Chert is more abundant in the Gorman formation than in the Honeycut formation and more of it is dolomitic. Sandy chert is common in the vicinity of the Llano region and west of Pecos County. The *Archaeoscyphia* spiculiferous chert zone near the middle of the Gorman formation was recognized in only a few wells west of the Llano region.

The Gorman thickens slightly to the east and southeast of the Llano region, and in other directions it mostly thins except directly west of the Llano region where its thickness remains about the same. In this direction also it finally thins, reaching a thickness of about 320 feet in Gulf Oil Corporation No. 108-E Keystone, Winkler County, and about 250 feet in the Beach Mountain section, Culberson County.

Photographs of subsurface Gorman rocks are shown on Plates 18, F; 22, B-D, F; 23, B-D; 27, C-F; and 33, C.

HONEYCUT FORMATION

The Honeycut formation in its lower part in the Llano region is an alternation of either limestone and dolomite or dolomite of different grain sizes distinct from the massive carbonate rocks beneath in the Gorman. Except for the basal 50 feet, the Honeycut may also be distinguished from the Gorman by the absence of sand grains. In the subsurface in certain directions, as explained above, this relationship no longer holds true—the Gorman loses its sand and the Honeycut becomes slightly sandy throughout.

In its type section the Honeycut, 679 feet thick, is roughly divisible into three divisions—a lower alternating sequence of limestone and dolomite, a middle one of microgranular dolomite, and an upper one of limestone topped by an unconformity. A hundred feet of truncation can be demonstrated within a mile of the type section, and in crossing the Llano region northwestward the whole of the Honeycut and part of the Gorman are truncated along this unconformity. In the subsurface to the east additional beds are present at the top of the Honeycut (Pl. 2) without evidence that the top of the formation has been reached.

The Ellenburger in no place east of the longitude of Upton and Pecos counties was thick enough for the top of the Honeycut to be present, but west of this line additional beds are present. As can be seen in Plates 1 to 3, the grain size of the Honeycut decreases upward. The top boundary is placed at a grain-size change, the Honeycut formation being finer grained and darker colored than the overlying B2a′ unit. The grain-size change may correspond to one which takes place about 50 feet above the alternate base of the B2a unit of Cloud and Barnes (1948a, Pl. 16) in the Beach Mountain section.

In at least the western part of its occurrence the Honeycut formation can be divided into an upper finer grained, darker-colored unit and a lower coarser grained, light-colored unit. The entire formation becomes lighter in color east and east-northeastward. The Honeycut formation is chertier than any of the overlying units; spicules and ooids are very common, whereas they are very scarce in the units above.

Photographs of subsurface Honeycut rocks are shown on Plates 18, A-E; 19, A-F; 20, D-F; 21, A-G; 22, A, E. G; 23, A, E, F; 24, E-G; 25, F; 27, A, B; 28, A-F; and 29, A-C.

POST-HONEYCUT BEDS

The tentative correlation of the post-Honeycut beds, all dolomite in the subsurface, with the Beach Mountain section is shown in Plate 2. Since the units recognized in the subsurface are partly but not entirely equivalent to those in the Beach Mountain section, they are identified by a prime mark. For example, unit B2a′ is the subsurface unit partly equivalent to unit B2a of the surface, and each of the boundaries of unit B2a′ is somewhat higher stratigraphically than the corresponding boundary of B2a. Unit B2b′ of the subsurface appears to be equivalent to about the upper two-thirds of unit B2b of the surface. Unit C′ of the subsurface appears to include all of unit C of the surface and probably higher beds as well.

Unit B2a′ (Pls. 20, A-C; 24, C, D; C-E), about 120 to 140 feet thick, is somewhat coarser grained and lighter colored than the units above and below. It is thinner in the subsurface than the zone thought to represent it in Beach Mountain. It is somewhat sandy and in Gulf Oil Corporation No. 1 McElroy-State, Upton County, very sandy. Much oolitic chert is in the unit in this well, whereas chert of any type is scarce at this level in other wells.

Unit B2b′ (Pls. 24, B; 25, A, B; 26, B), about 250 to 350 feet thick, is a finer grained and slightly darker-colored unit resting on the coarser-grained dolomite of unit B2a′. The upper boundary of unit B2b′ coincides with a color change, and there is no appreciable change in grain size. Sand is very scarce, chert is scarce, one sample is oolitic, and spiculiferous chert was seen in only one well. The hundred feet of conglomeratic beds in Gulf Oil Corporation No. 1 McElroy-State falls within this unit; an attempt to explain this occurrence and similar ones will be found on page 63. This unit thickens in the subsurface as compared with Beach Mountain; however, if both the B2b′ and B2a′ units are combined they about equal the combined thickness of the B2b and B2a units of Beach Mountain.

Unit C′ (Pls. 24, A; 26, A, C-F), 50 to 200 feet thick, is distinguished from unit B2b′ solely on the basis of its distinctly lighter color, a property not recorded on the graphic logs. Chert, in part spiculiferous, and sand are scarce and oolitic chert is very scarce. It is thickest in the wells of Presidio and Pecos counties and is absent northward in Upton County. This change of thickness of unit C′ and also the fact that Simpson rocks lie directly on all post-Honeycut units as well as on the Honeycut formation indicate that an erosional unconformity intervenes between the Ellenburger and the superjacent Simpson. It is possible that areas may be found where unit C′ is thicker, and that other younger units could be present somewhere in the subsurface beneath the Simpson.

Arbuckle Group

The rocks of the Arbuckle group are described briefly by Cloud and Barnes (1948a, pp. 63–65), and their partial correlation with the Cambrian and Ordovician rocks of central Texas is indicated. Subsequently, Ham, McKinley, and others (1954) have mapped the entire exposure of these rocks in the Arbuckle Mountain region, and Ham (1955), in a field trip guide, gave a résumé of years of work, started in 1943, on the Arbuckle group of the Arbuckle Mountain region. Nothing is given on the correlation of these rocks with those of central Texas.

The Arbuckle group is divided into several units (see terminology of Ham, 1955) named, from the bottom up, the Fort Sill limestone, Royer dolomite, Signal Mountain limestone, and Butterly dolomite approximately equivalent to the Wilberns formation; the McKenzie Hill limestone approximately equivalent to the Tanyard formation; the Cool Creek limestone (Pl. 33, F, G) approximately equivalent to the Gorman formation; the Kindblade limestone approximately equivalent to the Honeycut formation; and the West Spring Creek limestone (Pl. 33, D, E) approximately equivalent to the post-Honeycut beds of this publication.

Since wells in Grayson and Collin counties, Texas, are near the Arbuckle Mountain region, and since the Lower Ordovician rocks in these wells compare closely with those of the Arbuckle group and not with those of the Ellenburger group, Arbuckle terminology is used. Rocks in the Texas Panhandle intermediate in character between Arbuckle and Ellenburger rocks are included with the Ellenburger because they are dolomite and thus more closely resemble the bulk of Ellenburger rocks.

Beds that Overlap the Ellenburger

A hiatus made up of one to several unconformities is believed to exist at the top of the Ellenburger. In west Texas a period of erosion must have followed the deposition of the Ellenburger during which truncation of all post-Honeycut units and some Honeycut beds took place. To accomplish such truncation before the start of deposition of Simpson rocks required an appreciable time.

Rocks mostly of Simpson age rest on the Ellenburger west of a line connecting Sutton and Scurry counties. East of this line the rocks resting on the Ellenburger are mostly Carboniferous in age (Pl. 33, A, B). The writer has paid no particular attention to the exact unit resting on the Ellenburger in the subsurface, but at the surface in the Llano region he has seen various units of the Devonian, Mississippian, and Pennsylvanian resting directly on the Ellenburger, and the various units are mostly unconformable among themselves.

The unconformity at the base of the Cretaceous truncates all of the Paleozoic units in the Llano region, and in two wells, Roland K. Blumberg No. 1 Wagner, Blanco County, and Tucker Drilling Company No. 1 Dr. Roy E. Perkins, Kerr County, Glen Rose rocks rest directly on the Honeycut.

Isopach Data

In order better to visualize the history of the pre-Simpson sequence of rocks, they are divided into three units and their distribution and thickness are shown as follows: Riley and Wilberns formations, figure 4; Tanyard and Gorman formations, figure 5; Honeycut formation and all post-Honeycut Lower Ordovician beds, figure 6. All contouring is generalized because of few data. In the area along Red River and the Muenster arch, even though the contours are spaced as closely as possible some are somewhat displaced from their true positions. The areas in which pre-Simpson Paleozoic rocks are absent and the position of the Ouachita front (Flawn, 1956, Pl. 1) are shown on each figure. Data were also used from other sources: Sellards and Hendricks (1946) in conjunction with Flawn (1956) for total thickness; Hendricks (1952, Pls. 3 and 4) for thickness of some units in a few wells; Ham (1955, figs. 1 and 2) for thickness of the various units in the Arbuckle Mountains; Collins (1952) for limited data in the Texas Panhandle; and Cloud and Barnes (1948a) for thicknesses in the Wichita Mountains.

The distribution and thickness of the Riley formation (fig. 4) are almost entirely controlled by the configuration of the Precambrian surface on which it was deposited, and only very locally in the subsurface has some been removed by post-Ellenburger erosion. Some interstratal thinning and pre-Wilberns erosion may have taken place shoreward. The Riley laps out against Precambrian rocks an average distance of about 100 miles northward and westward from the Llano region. The location of the feather edge of the Riley formation to the northeast is uncertain. At the south edge of the Llano region the Riley is 750 feet thick and appears to be thickening southward.

The distribution and thickness of the Wilberns formation and equivalent rocks likewise are in part controlled by the configuration of the Precambrian surface beyond the point where the Wilberns rests on the Riley formation, and only locally in the subsurface has some been removed by post-Ellenburger erosion. Some interstratal thinning has taken place shoreward in the central area but such thinning is most important in the northeastern region. Westward the Wilberns continues beyond the feather edge of the Riley formation for only about 40 miles and northwestward about three times as far (fig. 4). The boundary of equivalent beds to the north and northeast is beyond the area of the map. In the Llano region the Wilberns averages about 600 feet in thickness and continues to thicken southward, reaching in excess of 1,000 feet in General Crude Oil Company No. 1 Anderson, Bandera County. In the Arbuckle Mountains area of Oklahoma, equivalent rocks of the Timbered Hills and Arbuckle groups by interstratal thickening reach a thickness of 2,000 feet, and again by interstratal thinning reach a thickness of 1,200 feet before they pass beneath cover to the east.

The Wilberns and Riley formations within the area south of the Llano region

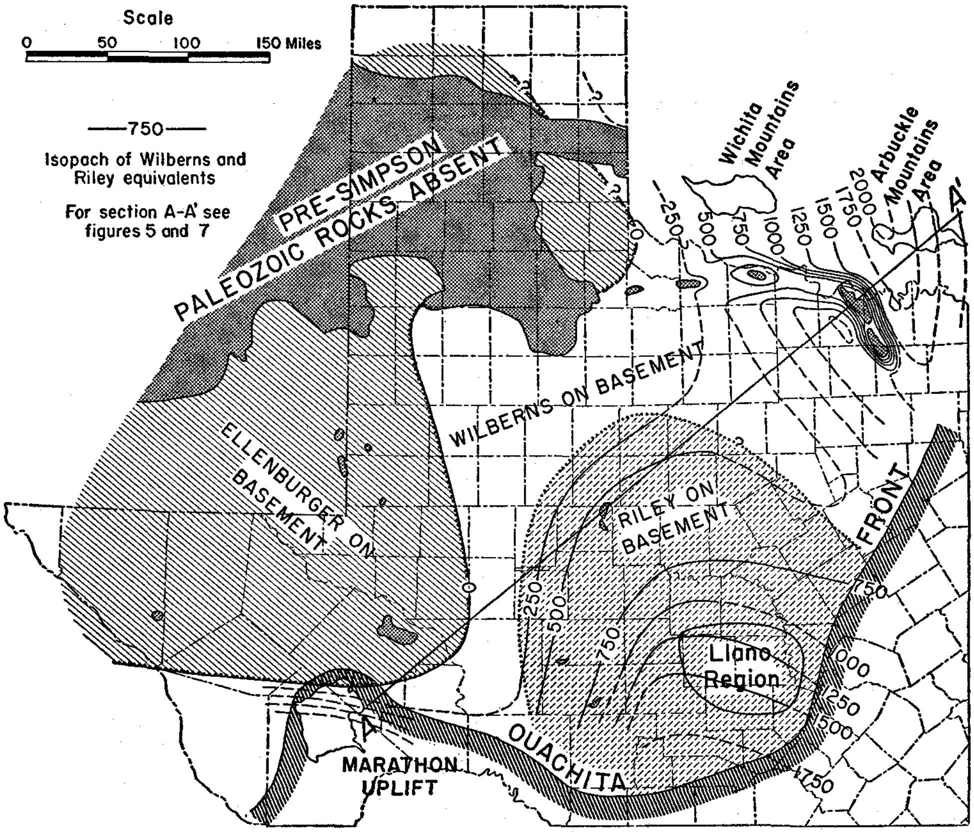

FIG. 4. Isopach map of Riley and Wilberns equivalents in Texas and southern Oklahoma.

where they still can be reached by drilling probably exceed 2,000 feet in thickness. Their combined thickness in Tucker Drilling Company No. 1 Dr. Roy E. Perkins, Kerr County, with only 125 feet of the Hickory sandstone penetrated is 1,795 feet. In General Crude Oil Company No. 1 Anderson, Bandera County, a combined thickness of 1,506 feet was drilled and only 325 feet of Cap Mountain limestone was penetrated.

The distribution and thickness of the Tanyard formation in the western region are mostly controlled by the configuration of the Precambrian surface, and in the central region it has in part been thinned by erosion and in places entirely removed. The Gorman formation rests on the Precambrian only on the northern part of the Central Basin Platform and locally in Pecos County. In the central region post-Honeycut erosion has removed it in a rather large area and thinned it elsewhere in places where it is not directly overlain by the Honeycut formation. The combined thickness of the Tanyard and Gorman formations is shown in figure 5, as well as the areas in which each rests directly on the Precambrian. Their combined thickness increases both eastward and southward from the Llano region reaching 1,105 feet in Roland K. Blumberg No. 1 Wagner, Blanco County. The equivalent rocks of the El Paso formation and Bliss sandstone thicken westward. Equivalent rocks of the Arbuckle group thicken interstratally to 2,200 feet in the Arbuckle Mountains of Oklahoma but thin again to 1,500 feet before they pass beneath cover to the east.

The distribution and thickness of the Honeycut formation and post-Honeycut Lower Ordovician beds are shown in figure

6. These rocks have been eroded from a large part of the central and northwestern areas and are thinned by erosion elsewhere. They thicken rather rapidly, in part interstratally, from these areas southward and eastward. They are thickest in the Arbuckle Mountains where they reach 2,800 feet but, as with other rocks in the pre-Simpson sequence, again thin eastward interstratally to 1,850 feet before passing beneath cover. Elsewhere the thickest measurement recorded for these rocks is 1,435 feet in Phillips Petroleum Company No. 1-C Puckett, Pecos County.

The distribution and thickness of all pre-Simpson Paleozoic rocks are shown in figure 7. They are absent in the northwestern area in part because the older rocks have lapped out against the Precambrian, in part because of erosion before Simpson rocks were deposited, in part because of later periods of erosion, and in part be-

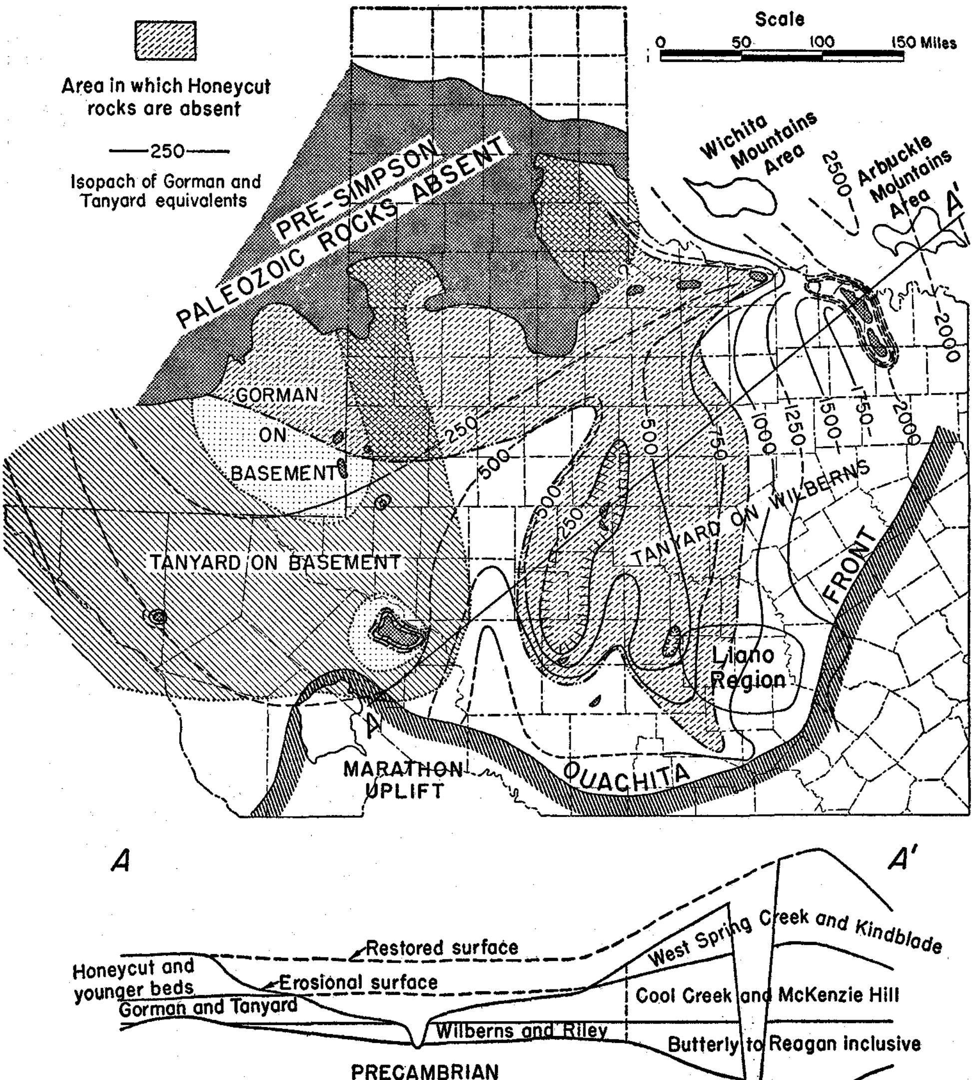

FIG. 5. Isopach map of Tanyard and Gorman equivalents in Texas, southeast New Mexico, and southern Oklahoma.

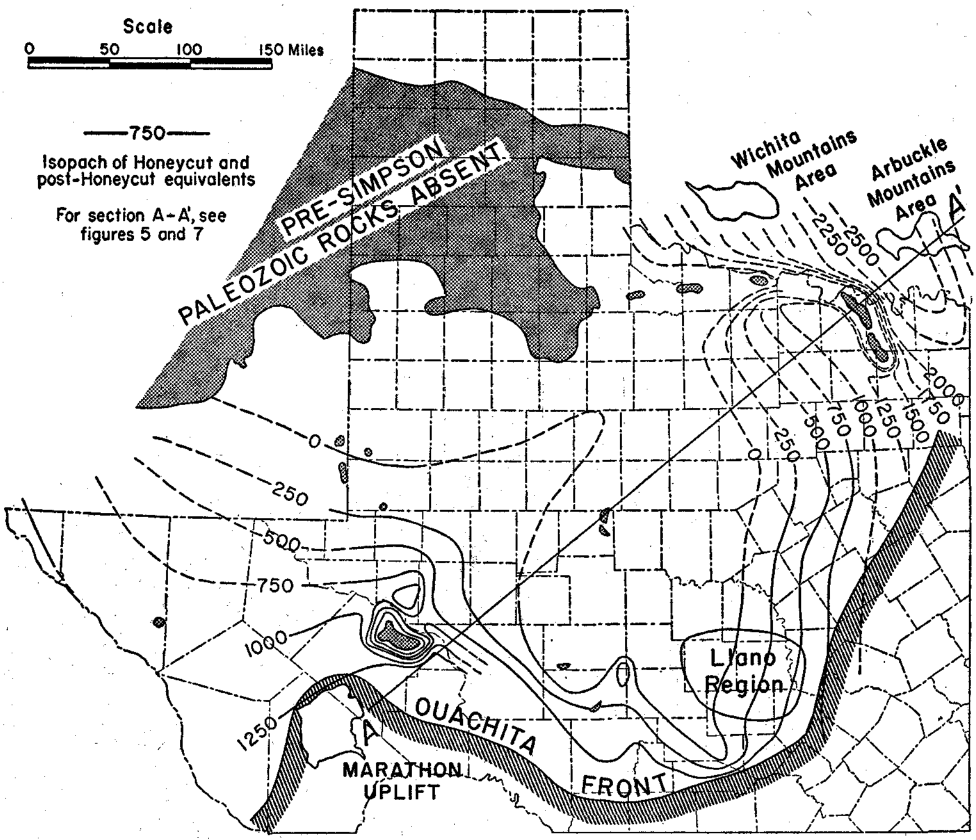

FIG. 6. Isopach map of Honeycut and post-Honeycut equivalents in Texas, southeast New Mexico, and southern Oklahoma.

cause of interstratal thinning. They thicken from a feather edge in the central part of the area to a known thickness of 7,000 feet in the western part of the Arbuckle Mountains of Oklahoma and then decrease to 4,550 feet in thickness before passing beneath cover to the east. Ham (1955, figs. 1 and 2) showed that most of this thinning is interstratal, and interstratal thinning may be almost as pronounced westward.

The Arbuckle and Timbered Hills groups of rocks appear to have been deposited in a northwest-southeast-trending trough which probably extended from central southern Oklahoma into the Texas Panhandle. The extent and trend of the trough in the other direction are unknown, but the amount of rock equivalent to the Honeycut and post-Honeycut Lower Ordovician beds in Humble Oil & Refining Company No. 1 Miller, Collin County, suggests that the trough may change to a southward trend.

Pre-Simpson Paleozoic rocks thicken both eastward and southeastward from the Llano region and to the southeast exceed 3,200 feet in thickness. In this area it is thought that they must be thickest somewhere beneath the Ouachita foldbelt, possibly in a trough connecting with the one passing through the Arbuckle Mountains area.

The thickest sequence of pre-Simpson Paleozoic rocks found in the subsurface in west Texas is 1,725 feet in Phillips Petroleum Company No. 1-C Puckett, Pecos County, and the rocks appear to be thickening southward. Pre-Simpson rocks in the Marathon region measure 1,940 feet (Wilson, 1954a, 1954b) and the bottom of the Paleozoic sequence is not exposed. Equivalent rocks in the El Paso formation and Bliss sandstone of the Franklin Mountains area, El Paso County, measure 1,840 feet and appear to be thickening westward.

Cross sections showing the variation in thickness of these units from Pecos County to the Arbuckle Mountains area are included in figures 5 and 7. In figure 5 the contact between the Tanyard and Wilberns is shown as a horizontal line in order to depict better the configuration of the Precambrian surface. Interstratal thickening, however, exaggerates the depth of the basin in the Arbuckle area. The interstratal thickening for the younger units is also well shown. In figure 7 the probable top of the Ellenburger at its thickest is used as a horizontal line. This section shows clearly the cross section of the trough in which the pre-Simpson sediments accumulated, that the trough was fairly broad, and that it must have subsided rather uniformly.

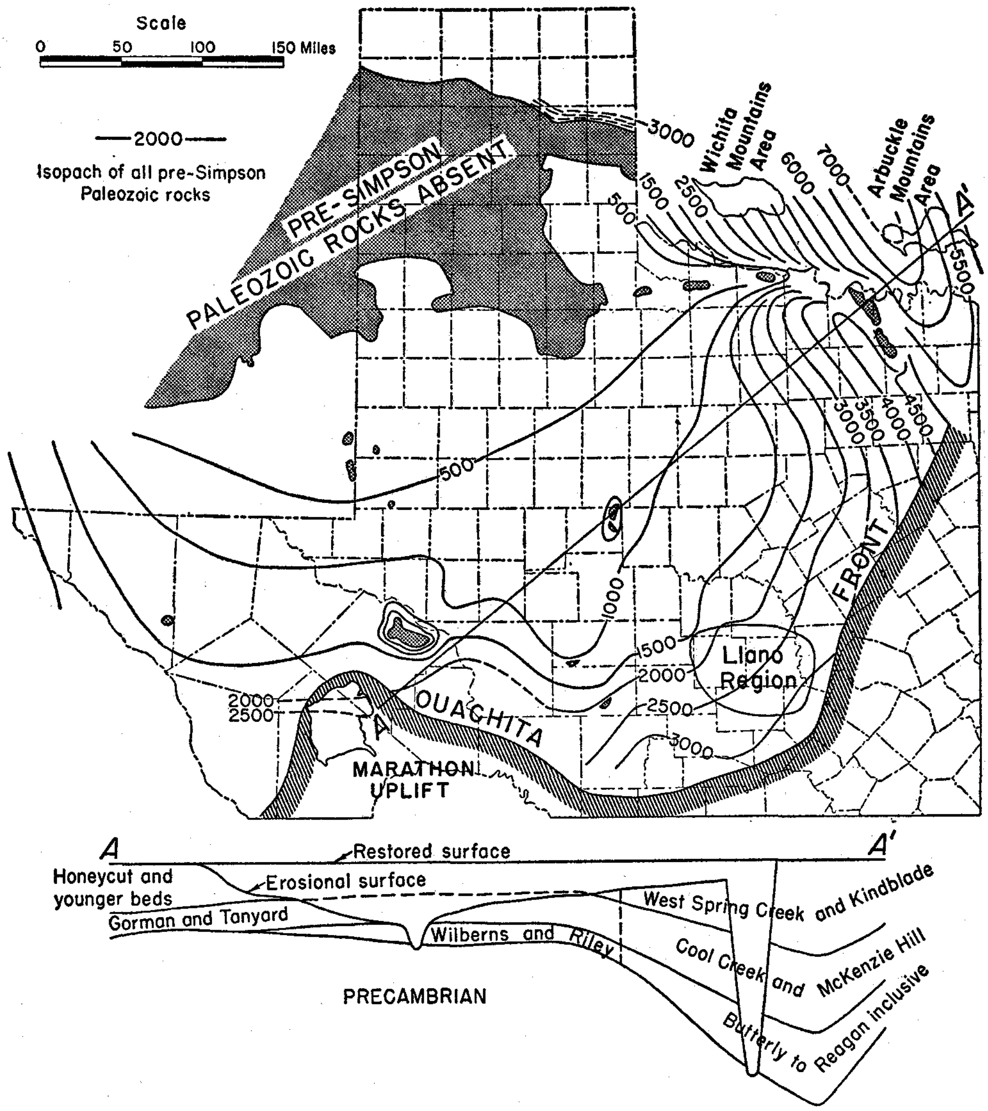

FIG. 7. Isopach map of pre-Simpson Paleozoic rocks in Texas, southeast New Mexico, and southern Oklahoma.

CORRELATION TECHNIQUES AND CRITERIA

The purpose of this project was to determine if established or other units of the pre-Simpson sequence could be recognized in the subsurface and correlated from place to place. All readily applicable techniques were to be exhaustively tested in the hope that at least one would be found that would be reliable and practicable. Some of the techniques have limited value, at least locally, but the most reliable methods of correlation that can be used are the time-honored geological ones.

Therefore, correlation of the various rock units from well to well within the subsurface pre-Simpson is based primarily on the character of the rock as a whole and secondarily on the character of the accessory lithic constituents as viewed with a low-magnification binocular microscope. For correlation from area to area and with the surface sections, both fossils and lithic character were used, whereas regional correlation is based wholly on fossils.

Methods and techniques investigated for subdividing and correlating pre-Simpson rocks are discussed in succeeding pages and their importance evaluated.

Paleontological Methods

Study of macrofossils and larger microfossils.—Fossils were indispensable for the pre-Simpson project in furnishing a framework of reference and instilling confidence in correlation made by other criteria. Throughout much of the subsurface pre-Simpson, fossils are scarce, and therefore the use of fossils is not feasible for correlation from well to well. Furthermore, with rare exceptions fossils can be found only in cores, and most coring programs are carried on in rock least likely to be fossiliferous. Even in continuously cored sections fossils are scarce, much too tedious to find and prepare, and many are too poorly preserved to be identified.

As new areas are drilled, paleontologic materials should be carefully preserved and evaluated as a check on other methods of correlation. For the present project P. E. Cloud, Jr., and A. R. Palmer, of the U. S. Geological Survey, identified and evaluated most of the fossil material (pp. 73–85). They refer to previous basic work, make fossil identifications and age evaluations, and illustrate the fossils commonly of use (Pls. 34 and 35).

Study of insoluble fossils.—The chitinozoans and hystrichosphaerids, insoluble in hydrochloric and hydrofluoric acid, are the fossils most likely to be present in lower Paleozoic rocks, and some forms have been recognized in Precambrian rocks in other areas. In view of their presence in equivalent rocks elsewhere on earth, the search for these forms appeared to hold as much promise as any line of research for subdividing pre-Simpson rocks. Unfortunately, these forms appear to be absent in pre-Simpson rocks of Texas and southeast New Mexico.

The insoluble-fossil work was done by E. J. Tynan at the University of Massachusetts (pp. 87–93). His conclusions are:

> Insoluble fossils are essentially absent in the pre-Simpson rocks and therefore are of no value for correlating these rocks. It is concluded that either the Upper Cambrian and Lower Ordovician were not periods of abundant insoluble fossil population, or the environment of deposition of these rocks in Texas and New Mexico was not compatible with insoluble fossil growth.

These conclusions may not be final because Dr. L. R. Wilson, who supervised Mr. Tynan's work, in letter of January 3, 1956, stated:

> Why all this material is barren of hystrichosphaerids is disturbing. I have not seen anything like it and would like to continue the search myself. If nothing is forthcoming from the new samples, I would appreciate the opportunity of examining more from other geographic locations. It is strange that we have not found these forms for the richest assemblage I know is from an Ordovician chert similar in lithology to that you have sent.

Petrographic Methods

BINOCULAR-MICROSCOPE EXAMINATION OF UNTREATED SAMPLES

Of the three types of samples commonly collected, cuttings are the least time consuming to use but not necessarily the best for correlating pre-Simpson rocks. The advantage of using cuttings is that a quick view can be obtained of all the rock types and most of the accessory constituents in the interval sampled, providing the cuttings were properly and carefully taken. To observe the same things in an equivalent length of core takes much longer; however, much additional information can be recorded that is not observable in cuttings. Core chips (one chip per foot or larger interval) are the least satisfactory samples. Rarely is a core chip representative—if it yields a sample of the dominant rock type it will mostly miss accessory constituents, or if sampled for an accessory constituent, the dominant rock type may not be represented.

Distribution of grain size.—Grain size is perhaps the most useful property to record. The aphanitic limestone of the Ellenburger is distinct from the granular limestone of the Wilberns, and about the only chance for confusion is with aphanitic bioherms in the Wilberns. Most of the limestone younger than the Ellenburger is also granular; however, even if aphanitic, other properties are sufficient to separate the two.

Dolomite grain size is of special value because several units can be recognized. However, to be confident of the position of a unit, considerable stratigraphic section should be penetrated, as units of the same grain-size characteristics recur, and also within any unit other grain sizes usually are present. Laterally grain size may change, but all units so far recognized can be traced, since they maintain their relative grain sizes.

Cloud and Barnes (1948a, p. 24) found that

> grain size of the dolomite is an important clue to correlation of the Ellenberger and associated carbonate rocks of the Upper Cambrian . . . microgranular dolomite is excessively rare in the Tanyard formation, and, except in the lower part of the Staendebach member, very fine-grained dolomite is uncommon in the Tanyard. Conspicuous zones of microgranular to very fine-grained dolomite feature the lower part of the Gorman formation, the middle of the Honeycut formation, and locally the upper or lower parts of the Pedernales dolomite [San Saba member] of the Wilberns formation. The dolomites of the Threadgill member of the Tanyard formation are characteristically medium to coarse grained, and those of the Staendebach member are mostly fine to medium grained. Except in the northwestern corner of the Llano region there is a conspicuous break in grain size of the dolomites at or near the Tanyard-Gorman boundary, from coarser below to finer above. Except in the southeastern corner of the region the Cambrian-Ordovician boundary displays a similar though reversed break where it is in dolomite. A less conspicuous break from coarser grained dolomites below to finer grained dolomites above is a common feature of the contact between the Threadgill and Staendebach members of the Tanyard formation where it is in dolomite.

Most of the dolomite grain-size differences found in central Texas can be traced in the subsurface. However, the Threadgill member of the Tanyard formation is characteristically medium to coarse grained where dolomite in the Llano region, but to the west it is mostly fine grained and passes laterally into glauconitic rocks of the upper part of the San Saba member. The microgranular and very fine-grained Gorman in the Llano region is between units which on the average are coarser grained; from Pecos County westward, however, the Gorman is mostly fine grained, but here again the units above and below average somewhat coarser.

In the Llano region where perhaps half of the Honeycut is limestone, no trend in the dolomite grain size was noticed. In the subsurface to the west where it is entirely dolomite the lower half is definitely coarser than the upper half. The overlying B2a′ unit is a coarser-grained unit and the B2b′ and C′ units above this are finer grained.

East and southeast of the Llano region the grain-size difference between the Wilberns and Tanyard formations largely disappears, and other criteria must be looked for to separate these two.

Distribution of quartz sand.—For the Llano region Cloud and Barnes (1948a, pp. 23–24) found that

> The local abundance of quartz-sand, the frequency in vertical distribution of arenaceous

zones, and the character of the sand are of critical importance in the stratigraphy of the Ellenburger and associated Upper Cambrian rocks . . . The simple presence of sand grains in Ellenburger rocks suggests, although it does not prove, a post-Tanyard age; and sand in relative abundance indicates the Gorman formation or the lower 50 feet of the Honeycut.

In the subsurface a short distance to the west and south of the Llano region this distribution of sand is not true. The Gorman in these directions is devoid of sand and both the Tanyard and the Honeycut are sandy. Sand reappears in the Gorman in Pecos County and becomes more abundant westward. A cursory examination of the sand reveals no marked differences in the degree of roundness, frosting, or sorting above at least the middle of the Wilberns except in the vicinity of high areas of Precambrian rocks, where angular quartz and feldspar are common. In the red zone which passes laterally from the Cap Mountain to the Hickory the sand is well rounded and appears polished, that in the Welge and Lion Mountain is commonly reconstituted.

Distribution of glauconite.—With reference to Cambrian and Ordovician rocks of central Texas, Cloud and Barnes (1948a, p. 23) stated "the presence of glauconite as a common accessory mineral is presumptive evidence of a Cambrian age for the rock in which it occurs. Such glauconite is likely to be globular if from limestone and interstitial if from dolomite." It is now known (Barnes and Bell, 1954a, p. 30; Bell and Barnes, MS.) that the boundary of the Cambrian and the Ordovician in the western part of the Llano region falls within the upper part of the glauconitic Wilberns formation, and that in the subsurface to the west as much as 200 feet of glauconitic rock is probably of Ordovician age.

Within the Llano region (see Cloud and Barnes, 1948a, Pl. 14) as much as 300 feet—and in the Johnson City area, where it is now recognized that faulting has cut out section (Cloud and Barnes, 1957, p. 168), possibly more than 400 feet—of the upper part of the Wilberns *appears* to be nonglauconitic. The reason for equivocation about the presence of glauconite in surface rocks is that this part of the Wilberns in the adjacent subsurface is in part slightly glauconitic. Glauconite might therefore exist in the surface rocks and either not have been seen or be altered beyond recognition.

The paucity of glauconite in the Wilberns east and southeast from the Llano region argues against its use alone in the placement of the boundary between the Wilberns and the Tanyard formations. In fact the deep burial of these rocks in the Ouachita trough in this direction probably saves us from the dilemma of having to try to subdivide a monotonous series of coarse-grained nonglauconitic dolomite strata into recognizable units.

Distribution of chert.—Chert is rare in units B2a′, B2b′, and C′ in all wells except Gulf Oil Corporation No. 1 McElroy-State, Upton County, and without paleontological control and on the basis of chert and grain size alone, unit B2a′ of this well would have been placed at the top of the Tanyard formation. Chert is more abundant in the Honeycut formation than in overlying units; both translucent and opaque varieties are present, and spicules and ooids are common.

Cannonball chert, so common in the Honeycut formation of central Texas, was recognized only in cores from a few wells.

Chert, both translucent and opaque varieties, in part dolomitic, is more abundant in the Gorman formation than in the Honeycut. Sandy chert is common in the Gorman in the vicinity of the Llano region and west of Pecos County. The *Archaeoscyphia* spicular chert zone near the middle of the Gorman was recognized in only a few wells west of the Llano region.

The Tanyard formation, except for its lower third which in the vicinity of the Llano region is essentially noncherty, is perhaps the chertiest unit of the Ellenburger. Opaque and dolomitic varieties predominate, and quartz druse and quartzose types are more abundant than in any other unit. Oolitic chert is common especially in the upper part and in some wells is found to the base of the unit. The basal noncherty zone westward from the Llano region is glauconitic, and for this reason it is placed in the Wilberns formation.

The Wilberns is mostly noncherty except from the eastern part of the Llano region eastward. Chert where present is similar to that in the Tanyard but mostly is not as abundant. Reddish to blackish, granular, quartzose chert is common along the Wilberns-Tanyard contact in Burnet County, and when similar chert was found to the east in Shell Oil Company No. 1 Purcell, Williamson County, it was used to define the contact even though the dolomite above this point is slightly glauconitic.

Distribution of color.—The pre-Simpson rocks vary considerably in color both regionally and from unit to unit. When comparing colors of the various units, it is well to remember that the rocks as a whole darken toward the Pecos-Val Verde County area and that they are also darker in north Texas and the Panhandle.

Unit C′ is somewhat lighter colored than unit B2b′, which in turn is slightly darker than unit B2a′. The upper part of the Honeycut formation is also darker than unit B2a.′ To the west the Honeycut is distinctly divisible into a dark-colored upper unit and a light-colored lower unit. Eastward the upper unit becomes somewhat lighter and the distinction in color is not nearly so pronounced. To the east the Gorman is about the same color as the Honeycut, but to the west it is darker.

To the west the Tanyard is of about the same color as the Gorman, but to the east it is somewhat lighter. The Wilberns dolomite in the eastern area is about the same color as the Tanyard dolomite; elsewhere it is various shades of greenish gray. Other rocks of the Wilberns commonly are various shades of olive gray and greenish gray, with locally in the vicinity of the Llano region a reddish zone at the base of the Morgan Creek limestone, and still more locally in the eastern part of the region a thin reddish zone at its top.

The Lion Mountain sandstone where typically developed is dark green and contrasts sharply with the underlying light-colored Cap Mountain limestone. Locally to the west of the Llano region the top of the Lion Mountain is a dark brown limonitic zone which may represent an ancient soil. The upper part of the Cap Mountain limestone is lighter colored than the Morgan Creek limestone, but downward it darkens to greenish gray. In the Llano region a reddish zone in the lower part of the Cap Mountain passes laterally into the red Hickory sandstone of Mason County and adjacent areas of the subsurface. The lower part of the Hickory sandstone is mostly light colored.

Distribution of major lithic features.—The distribution of limestone and dolomite, while of some importance in the Llano region and immediately adjacent subsurface as useful contributory evidence, is of little importance for identifying geologic units in the rest of the subsurface. Aphanitic limestone is more widely distributed in the Honeycut formation than in either the Gorman or Tanyard formations. It disappears from the Honeycut also in the Crockett-Pecos County area and reappears again on the Central Basin Platform. The Honeycut of Beach Mountain (Cloud and Barnes, 1948a, pp. 71–75) does not contain limestone; however, a short distance to the west in the Diablo Plateau granular limestone is present similar to that farther west in the Hueco and Franklin Mountains but entirely different from the aphanitic limestone of the Central Basin Platform area and the Llano region.

The Wilberns, which is predominantly limestone in much of the Llano region, is mostly dolomite in the subsurface to the southeast and terrigenous material in the subsurface to the west. The sandstone body in the San Saba member of the Wilberns in the western part of the Llano region continues westward about 100 miles from a north-south line through the western part of Mason County. The top of this sandstone body westward fairly closely parallels other boundaries above it, and it is judged that in the area of its occurrence it is as reliable a horizon marker as can be found in the pre-Simpson sequence, except possibly for the boundary between the Welge sandstone and Morgan Creek limestone in the Llano region and adjacent subsurface.

The Welge and Lion Mountain combination of sandstones likewise furnishes a reliable zone of reference in its area of occurrence, but westward, as the limestone of the overlying and underlying formations is replaced by terrigenous materials, the recognition of these units becomes problematic. To the southeast the Welge becomes a greensand indistinguishable from the Lion Mountain except with the aid of fossils.

The Hickory sandstone, a basal transgressive unit, rises in the section northward and westward toward the land area of that time, displacing the Cap Mountain laterally. It has not been ascertained if lithologic differences exist by which the terrigenous materials of the Riley and those of the Wilberns can be distinguished to the point of lap out of the Riley against the Precambrian rocks.

BINOCULAR-MICROSCOPE EXAMINATION OF INSOLUBLE RESIDUES

With certain important exceptions, about the same results in correlation can be obtained by using insoluble residues as with untreated samples. In addition to the time and expense in preparing residues, the bulk of the sample is destroyed. If residue alone is examined, one does not know whether the rock was originally limestone or dolomite. The grain size cannot be determined in residues except where it is preserved as molds. The color of the rock also is indeterminable except possibly where reflected by the color of the residue—and in many samples the color of the residue is not that of the rock from which it was obtained.

The advantage of using insoluble residues is that the minor constituents of the rock are brought into sharp focus, the diluting effect of the soluble material having been removed. A few constituents are revealed that might be missed in untreated samples, for example, silt and occasionally chert when it is of the same color and texture as that of the enclosing rock. However, most of the constituents found in residues can be seen in the original rock; perhaps not as conveniently, but this is often compensated for by the knowledge that constituents such as sand actually seen in chips of rock of the right formation are not caving from some younger formation. An ideal procedure, of course, would be to include all information obtainable by examining both residues and untreated samples, but if time and expense are important factors only untreated samples should be used. In the present project insoluble substances (pp. 44–46) found in untreated samples were carefully described and used in combination with all other available information in making the final correlations (Pls. 1–6). The results of insoluble-residue examination alone are described on pages 191–198 and Plate 17.

THIN-SECTION EXAMINATION

More can be learned about a rock by thin-section examination than by any other petrographic method. Not only can most features recorded from binocular-microscope examination of both residues and untreated samples be seen in thin section, but also many other features as well. It has been shown above that pre-Simpson rocks are divisible into correlatable units by using less exacting petrographic methods; consequently, it seems likely that they could also be divided into correlatable units by using thin sections, providing the density of sampling is sufficient. However, during the present project no concerted attempt was made to use thin sections for this purpose since many wells are represented by very few thin sections (see fig. 11). The chief aim has been to determine the properties and origin of pre-Simpson rock types; emphasis at this time is on those from the Ellenburger group, the Wilberns and Riley rocks being reserved for later treatment. Several hundred thin sections of these older rocks have been assembled by the Bureau of Economic Geology, and it is hoped that eventually this material will be examined and included in a report on the Cambrian rocks of the Llano region.

In his paper on thin-section examination of chiefly Ellenburger rocks, Folk discusses "Stratigraphic correlation and regional changes" (pp. 127–130). He found no stratigraphic zone traceable over the entire area, but in the region of Winkler and Upton counties he did find a zone near the Honeycut-Gorman boundary characterized by oolitic beds and composite dolomite. In other localities similar oolitic and composite dolomite zones appear elsewhere in the sequence. In the western area chert appears to occur consistently in the lower part of the sequence, whereas in the east it tends to occur throughout. A belt from Pecos County through Lea County, New Mexico, is characterized by arkosic sand related to a "linear highland or chain of islands" (ancestral Central Basin Platform). Sand in general is more abundant in the lower part of the sequence, but Folk mentions that there are some conspicuous exceptions.

For sampling Ellenburger cores, Folk estimates a sample density of perhaps one thin section per 10 feet in each well as sufficient for finding a stratigraphic zonation. Since such sampling would be random, it appears to the writer that it might be quite unrepresentative; the same conclusion applies to core-chip sampling (p. 44). The present sampling was done by Barnes for the purpose of determining the paragenetic sequence—the time and mode of formation of the lithic constitutents—and to shed some light on the depositional conditions. For this purpose the first cores examined were thin sectioned at small but irregular intervals; as the work progressed, fewer and fewer thin sections were made, and these were mostly of unusual or complex rock types.

It would cost considerably more and take longer to obtain with thin sections as much usable information for purposes of correlation as can be obtained with a binocular-microscope examination. However, other information obtained on depositional history, paragenesis, and structural history might outweigh the intitial cost. Thin-section examination of sedimentary rocks is a special field, and a specialist is required for such examination if most value is to be derived from its use. A word of caution should be injected here because a specialization once started tends to dominate the field excluding other methods of approach.

Physical Methods

Electric and radioactivity logging.—Study of electric and radioactivity logs revealed nothing that could be used for correlation within the Ellenburger group except possibly locally. The top of the Ellenburger in most areas is indicated by a sharp decrease in spontaneous-potential and in gamma-ray radiation intensity and a sharp increase in resistivity and neutron radiation intensity unless the overlying rock is a limestone having similar lithologic characteristics.

In the area where sandstone is present in the San Saba member of the Wilberns a rather characteristic spontaneous-potential curve is produced by the sandstone and the overlying mostly glauconitic carbonate rock. The spontaneous-potential of the Ellenburger declines as this zone is approached, followed by a sharp increase and a plateau. The sharp increase in spontaneous-potential usually occurs before the first glauconite is reached, suggesting that the change may be caused by an increase in clay or silt. The resistivity for this carbonate zone follows about the same pattern as the spontaneous-potential in some wells but is not as definitive. The gamma-ray radiation intensity curve may or may not reflect the spontaneous-potential curve.

There is a sharp drop in spontaneous-potential at the top of the sandstone in the San Saba, and the San Saba sandstone mostly has a low spontaneous-potential and gamma-ray activity and an intermediate resistivity. The Point Peak member shows an increase in spontaneous-potential and gamma-ray activity and a low resistivity. In the Morgan Creek the spontaneous-potential and gamma-ray activity remain about the same but there is a sharp increase in resistivity. In the Welge the gamma-ray activity drops sharply and the spontaneous-potential and resistivity also drop. In some wells the exact opposite appears to be true, but this may be caused by mis-matched logs and samples.

In the Lion Mountain sandstone the *gamma-ray radiation intensity increases*, the resistivity is low, and a high spontaneous-potential peak is usually somewhere within the unit. In the Cap Mountain limestone the spontaneous-potential is low, the resistivity intermediate, and the gamma-ray activity mostly high but erratic. At the top of the Hickory sandstone the gamma-ray radiation activity and resistivity drop and the spontaneous-potential increases. Throughout the rest of the Hickory sandstone these curves are in part erratic. In the Precambrian the spontaneous-potential, resistance, and gamma-ray radiation activity increase.

X-ray examination of clay-size minerals.—The study by Jonas (pp. 131–143) of the clay-size minerals is useful for interpreting conditions existing during Ellenburger deposition but shows little promise of being useful for dividing and correlating the Ellenburger. The study was restricted geographically, and only rocks of the Ellenburger group were examined. It is unknown what a study of the clay-size minerals of the Wilberns and Riley formations might reveal, or if a study of the clay-size minerals over a wider area of Ellenburger occurrence might yield more useful information.

Magnetic susceptibility.—Shortly after his death in 1952, the Geophysical Society of Tulsa proposed publication of a group of magnetic susceptibility papers as a memorial volume in honor of Dr. Joseph A. Sharpe. At the time papers for such volume were being solicited, measurements on pre-Simpson rocks and Llano region rocks were complete and two papers were therefore prepared for the volume (Barnes, 1953a, 1953b). Since the position of geologic boundaries in the wells studied was not known at that time, the early figure 1 (Barnes, 1953b) is reproduced as figure 8 to show the data in proper geologic relationship.

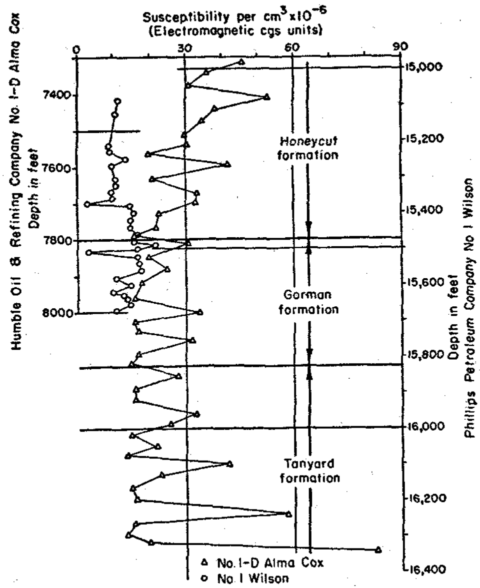

FIG. 8. Relationship of depth to magnetic susceptibility for Phillips Petroleum Company No. 1 Wilson, Val Verde County, and Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County.

It is concluded that magnetic susceptibility measurements using spot samples are of no value for subdividing the Ellenburger part of the pre-Simpson sequence of rocks; also that it is unlikely, so far as the Ellenburger is concerned, that continuous logging of magnetic susceptibility will yield usable results.

Thermoluminescence.—The recording of glow curves showing the amount and distribution of thermoluminescence in pre-Simpson Paleozoic rocks proved to be of little value in subdividing this group of rocks. The glow curves for limestone within the Ellenburger have no characteristics by which the Ellenburger can be subdivided, but the low-temperature peak of most Ellenburger limestone is more intense than the low-temperature peak of most Wilberns and Riley limestone.

Dolomite mostly yields erratic results, probably reflecting the complex history of dolomite genesis. In general, the low-temperature peak is more intense than the high-temperature peak for the younger and finer-grained dolomite. The reverse is true of the older and coarser-grained dolomite; however, there are many exceptions.

Chemical Methods

Spectrochemical analyses. — Spectrochemical analysis of dolomite was found to be useless for subdividing the pre-Simpson rocks. Limestone shows some irregularity in composition that might be useful for subdividing and correlating the rocks locally in the vicinity of the Llano region.

A sequence of limestone thick enough for definitive spectrochemical work was penetrated in only one well, Magnolia Petroleum Company No. 1 Below, Kendall County. In this well the chemical constituents are erratically distributed above a point 200 feet above the base of the Honeycut formation; below this point to the middle of the Tanyard formation the rock is of rather uniform composition. Below the middle of the Tanyard most constituents except magnesia (MgO), cupric oxide (CuO), and strontium oxide (SrO) are more abundant and somewhat erratically distributed. The lower part of the San Saba member, the Morgan Creek limestone, and the limestone in the Lion Mountain sandstone are especially rich in iron and soda (Na_2O). The Cap Mountain limestone, except for a high manganous monoxide (MnO) and SrO content, resembles more nearly the Ellenburger than it does Wilberns rocks.

Most of the analyses for other wells in the southern region are of Honeycut rocks, which are similar to those of the Honeycut in the Below well except that in the Below well titanium dioxide (TiO_2) is more erratically distributed and nickel monoxide (NiO) is present; in Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County, Na_2O is more abundant.

A few analyses of Cambrian rocks from the same group of wells show that the Cambrian carbonate rocks are notably more impure than the Honeycut rocks. This is shown by the lower lime (CaO) and higher silica (SiO_2), alumina (Al_2O_3), iron, TiO_2, barium oxide (BaO), chromic sesquioxide (Cr_2O_3), and NiO content of the Cambrian rocks. SrO is slightly lower and CuO is about the same as in the Honeycut formation.

Spectrochemical analyses of limestone from Humble Oil & Refining Company No. 1 Miller, Collin County, show little of value for subdividing the part of the Arbuckle group encountered in that well, except possibly for the presence of Cr_2O_3 in the upper part of the West Spring Creek formation. The results from this well also indicate that spectrochemical analysis will be of little value for regional correlation of pre-Simpson rocks.

Gravimetric, volumetric, and colorimetric analyses.—During the present project, gravimetric, volumetric, and colorimetric analytical methods have been used mainly to check the accuracy of spectrochemical methods for SiO_2, Al_2O_3, iron, and TiO_2 and to complete the 44 analyses from Phillips Petroleum Company No. 1 Wilson, Val Verde County, for CaO and MgO. The only work specifically done in the hope that it might be used for dividing pre-Simpson rocks was the colorimetric analysis for phosphorous pentoxide (P_2O_5) in the Wilson well and in two Llano region surface sections.

It was found that a distinct division exists about 200 feet below the top of the Wilberns formation with rocks below containing mostly 0.029 to 0.355 percent P_2O_5 and those above 0.003 to 0.033 percent, the higher values being mostly in the Honeycut formation. It is predicted that P_2O_5 will be found to be relatively richer to the top of the Wilberns in the area west of the Llano region than in the overlying Ellenburger.

Isotope analysis.—During the present project no attempt was made to use isotope analysis as a tool for subdividing pre-Simpson rocks, mainly because at the start of the project in 1952 too little experimental work had been accomplished to define the limitation of various methods. Such investigations are costly, and facilities were limited. Since 1952 rapid strides in isotopic research have been made, and methods and materials are now actually being investigated, using active isotopes, that might eventually lead to absolute age determinations for some sedimentary rocks.

The relative abundance of certain stable isotopes may also be of use in subdividing a group of rocks since the relative abundance of some isotopes is influenced by the conditions under which sediments are formed. As conditions change, a difference in the relative isotopic composition should take place, and in such cases these differences might be used for identifying rock units.

GENESIS OF THE LITHIC CONSTITUENTS

Limestone

For a discussion of the genesis of aphanitic limestone such as that of the Ellenburger, the reader is referred to Cloud and Barnes (1948a, p. 89; 1948b, pp. 44–45; 1957, pp. 181–182) who compare its origin with that of the lime-muds accumulating on portions of the Bahama Banks today. However, one fact not sufficiently stressed is the abundance of limestone in the Ellenburger made up of previously existing rock particles (intraclasts) composed of aphanitic grains, granules, and pebbles in either an aphanitic calcite matrix or a clear calcite matrix (Pl. 23, E, F).

Intraclasts of this type probably could have formed only in very shallow seas where portions of the sea bottom at low tides were exposed to the repeated drying action of the sun, causing sufficient precipitation of calcium carbonate to produce some cementation in a surface layer mostly a fractional part of an inch thick. During storms these cemented layers would be churned to fragments, the fragments in part mixed with the underlying uncemented mud (part of Pl. 23, F) and in part winnowed free of the finer interstitial material—the interstices being filled by clear calcite at later date (Pl. 23, E and part of F).

The smaller intraclasts may be confused with the apparently less abundant pellets of the pelleted limestone mentioned by Cloud and Barnes (*op. cit.*). The relative abundance of the two materials determined during the present project was based on binocular-microscope examination of sawed surfaces, whereas if thin sections were examined the abundance of pelleted rock might be found to be greater. Pellets are less easily seen as they are mostly smaller and merge imperceptibly with the matrix in which they rest, whereas intraclasts are sharply bounded. Pellets probably were barely cohesive enough to hold together while being buried by a snow of lime-mud, whereas intraclasts were so well cemented that they could stand strong buffeting without disintegrating.

The biohermal limestone of the Wilberns formation and the granular bioclastic and oolitic limestones of both the Wilberns and Riley formations (Pls. 29, D-F; 30, A; 31, A-D) are mostly easily distinguished from the Ellenburger aphanitic limestone. The origin of the granular and biohermal limestones is fairly well understood and will not be discussed here.

Dolomite

For a discussion of the genesis of dolomite the reader is referred to Cloud and Barnes (1948a, pp. 89–95; 1948b, pp. 45–50; 1957, pp. 182–186). During the present project little was seen to change their conclusions so far as the Ellenburger is concerned, except the finding of anhydrite rather widely distributed in the western area, where the Ellenburger is almost entirely dolomite. Direct precipitation of dolomite as outlined in their "point 10" (1948a, p. 94) or their "point 3" (1957, p. 183) may be more important than previously realized.

The varve-like graded bedding (Pls. 24, A; 25, A, B; 26, B–F; 29, B) so common in dolomite in the upper part of the Ellenburger in the subsurface may be evidence of primary dolomite deposition. The formation of such dolomite may take place during evaporation of hypersaline water, the variation of rhomb size being controlled by the rate of evaporation—the slower the evaporation, the smaller the rhomb. In general, the smaller the rhombs, the darker the color, indicating a period of slower accumulation during which finely divided clay and organic matter settled, furnishing loci for pyrite precipitation.

Cross-bedding and other minute bedding irregularities in these thinly bedded materials (Pl. 29, B) require the presence of a granular material. Such features could not be formed with the impalpable lime-mud of the Ellenburger, and there is no evidence of pre-existing rock particles (intraclasts) or pellets. Therefore, the granular material must have been dolomite and primary dolomite at that.

Anhydrite is a common constituent of the Ellenburger in the same area where evidence for formation of primary dolomite is best, thus supporting the suggestion that dolomite might have been precipitated in hypersaline waters. That these waters were enclosed is not indicated. Circulation may have been slow because of the presence of banks even more extensive than those postulated by Cloud and Barnes (1948b, fig. 3; 1957, p. 197), but there is no evidence to indicate absence of circulation.

That part of the dolomite of the Ellenburger was originally limestone is shown by the presence of ghosts of fossils, ooids (Pls. 18, B; 25, C), pellets, and intraclasts (Pls. 18, F; 19, A; 21, A, F; 23, B; 25, C; 26, A) whose boundaries as seen in thin section transect dolomite rhombs. These objects were calcite at the time they became part of the sedimentary sequence, and while little evidence was seen to date the time of dolomization it must have taken place while sea water was free to circulate through the sediments, as sea water is the only source of magnesium for large-scale dolomitization such as that found in the Ellenburger. Bedding irregularities are very commonly preserved by intraclastic dolomite (Pl. 18, B).

Where "intraclast" is used in the following discussion, it is to be understood that this word does not actually appear in the core description (Appendix B) or plate titles (pp. 200–230), but that it applies to previously existing particles of rock described in various ways, such as "intraformational conglomerate," "intraformational granule conglomerate," or as "aphanitic or micro-granular grains, granules, and pebbles in an aphanitic, microgranular or clear calcite matrix."

Intraclasts (see core descriptions, Appendix B) are mentioned oftener per unit length of limestone core than for equivalent lengths of dolomite core, indicating that intraclasts may be commoner in limestone than in dolomite. However, since intraclasts are often very faint in dolomite (Pl. 21, F), they could easily be missed, and the apparent difference in intraclast content may not be real. If an appreciable fraction of dolomite is primary, then the dolomite without intraclasts should be increased by the amount of primary dolomite and the observed relative abundance may be correct.

Observations on dolomite genesis confined to one or at most only a few observations follow: The dolomite along the vertical stylolite in Plate 33, E, must be much younger than the rock enclosing it, if the stylolite is similar in age to most other stylolites examined. The dolomite may have been transferred in solution from older dolomite which is thought to have been formed shortly after deposition, such as that occupying the nearby burrow.

Aphanitic limestone breccia in Plate 28, A, is invaded by medium-grained argillaceous dolomite; when the core was examined as a whole, the limestone appeared to be a 6- or 8-inch fractured mass with shaly dolomite swirled around it, suggesting that the whole was involved in submarine slumping. The shaly dolomite probably was limestone at the time, replacement took place later; the dolomite invaded fractures in the aphanitic limestone and also formed isolated rhombs in the limestone.

Intimate association and alternation of limestone and dolomite are illustrated in Plate 28, D, where eyes of limestone are enclosed by dolomite, and stringers of dolomite follow the limestone bedding, and in Plate 28, F, where alternating beds of dolomite and limestone are separated by stylolites. In Plate 33, D, cross-bedding is minutely outlined by dolomite as if the dolomite existed at the time the cross-beds were formed. Other features preserved in dolomite are mud cracks in microgranular dolomite (Pl. 21, D), the cracks having been filed by sandy, fine-grained dolomite. Features interpreted as mud cracks are present also in Magnolia Petroleum Company No. 1 Mary Ball, Schleicher County, depth 4,540 to 4,542 feet.

Dolomite in Plate 33, E, definitely secondary but still probably formed near the sea floor, replaces a burrow; dolomite in Plate 28, C, E, appears not only to have replaced burrows but spread out from them as well; and a much-burrowed rock completely dolomitized is illustrated in Plate 25, D. Filled vertical tubelike forms of uncertain origin, possibly in part borings, are in Gulf Oil Corporation No. 108-E Keystone, Winkler County, depth 9,615 to 9,625 feet; Gulf Oil Corporation No. 1 McElroy-State, Upton County, depth 12,723 feet; and Phillips Petroleum Company No. 1-C Puckett, Pecos County, depth 13,417 to 13,437 feet.

The origin of vertical cylindrical disturbances in Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, depths 15,540 to 15,541, 15,546, 15,549, and 15,579 feet, is not apparent unless possibly caused by rising gas bubbles. Similar features are in Humble Oil & Refining Company No. 6 "V" N. M. State, Lea County, New Mexico, depth 7,685 feet; and Magnolia Petroleum Company No. 1 Below, Kendall County, depths 4,349 (Pl. 29, B), 4,312 to 4,317, and 4,345 to 4,347 feet.

Composite dolomite described by Folk (p. 108) occurs in rather persistent stratigraphic zones, and because the crystals are mostly large he suggests that they grew slowly, possibly replacing an unconsolidated lime gravel (large intraclasts) after considerable depth of burial. If Folk's interpretation is correct, then the composite dolomite zones might furnish the most favorable place to prospect for oil in the Ellenburger in hopes that areas would be found where the space between intraclasts (lime gravel) is not filled by dolomite.

Chert

Much of the chert examined was formed at an unknown time after the sediments were deposited but before most of the breccia, veins, and stylolites were formed. Some chert must have been formed very soon after the sediments were deposited since it is involved in slump structures formed while the sediment was still soft. Chert of this type (Pl. 21, C) replacing a granular, oolitic sediment has frayed boundaries as if the chert at the time of deformation were a soft gelatinous mass. Other chert (Pls. 21, G; 22, D) appears to be later, having replaced limestone already involved in soft-sediment deformation.

Evidence for chert replacement of already existing lime sediment or limestone is furnished by the presence in the chert of objects, or at least ghosts of objects, such as previously existing particles of rock (intraclasts) (Pls. 21, C; 23 C), fossils, ooids (Pls. 18, F; 33, G), and pellets. Both of the examples of chert replacing oolitic limestone may be unusual, since in one (Pl. 33, G), oolitic chert serves as a matrix for an intraformational conglomerate in which the pebbles are not replaced; and in the other an oolitic intraclast of pebble size (Pl. 18, F) was apparently replaced after it was incorporated in the sediment, as explained in the caption for the photograph (p. 200). Numerous examples of chert preserving pre-existing objects or their ghosts are mentioned in the core descriptions and others are illustrated by Folk (pp. 260, 262).

Some nodular chert (Pl. 22, C) may have been formed on the sea bottom, as indicated by conformation of the bedding to the shape of elongate nodules and lack of relict structure. Bedded chert (Pl. 27, D) may also have formed on the sea bottom. Chert of similar lithology, such as the spool-like mass (Pl. 28, B) and isolated breccia fragments (Pls. 22, E; 23, D), gives no clue to its origin.

The chert above the Ellenburger in Skelly Oil Company No. 1 Ater, Nolan County (Pl. 33, A, B), in part appears to be replacing silty shale, and this is confirmed by thin-section examination. Chert of this type must form near the sea bottom, otherwise compaction during burial should limit the movement of water and largely inhibit chertification. Features which appear to be stylolites are present in the chert, suggesting that the stylolites formed after chertification. That stylolites do form in chert is shown in a chert breccia about 50 feet below the top of the Ellenburger in this same well, by numerous stylolites along which chert fragments interfinger (Pl. 33, C).

Other stylolites within chert are figured (Pl. 22, D) and many other examples are noted in the core descriptions (Appendix B). That stylolites formed after dolomitization and chertification is demonstrated by the interfingering of chert and dolomite along stylolites (Pls. 21, F, G; 22, B, E; 27, B, D); many other examples are cited in the core descriptions. Limestone and chert also occasionally interfinger along stylolites (Pl. 33, G), and there are many examples within chert of ooids and other objects, or their ghosts, partly missing along stylolites.

That most of the chert was formed before the veins were formed is shown in the core descriptions by the numerous mention of chert cut by veins. Calcite veins are perhaps most abundant, numerous other types are common, and practically every type vein described was seen cutting chert at some place, including chert veins of several types. Some olive-gray chert in Gulf Oil Corporation No. 108-E Keystone, Winkler County, depth 9,602 feet, is in partly open vertical fractures.

Some veinlike forms confined to chert are sharply terminated at the chert boundary. For example, reddish-brown, argillaceous dolomite veins are confined to a chert bed in Humble Oil & Refining Company No. 1-C Alma Cox, Crockett County, depth 8,579 feet. It is difficult to see how veins of this type could fill shrinkage or other type cracks unless the chert formed on the sea floor. The chert may have been deposited as a gelatinous bed which developed shrinkage cracks as it hardened, and the cracks became filled by argillaceous sediment before normal deposition of lime-mud (or possibly microgranular dolomite) was resumed. These veinlike masses are cut by veins of light gray, pyritiferous clay which traverse both the chert and the enclosing microgranular dolomite.

Veins of light gray fine-grained dolomite in Magnolia Petroleum Company No. 1 Below, Kendall County, depths 4,214 and 4,216 feet, are confined to chert, and veinlike forms of calcite (Pls. 28, B; 29, A) also confined to chert appear to be replacing it.

That much of the chert was formed before brecciation is indicated by the numerous mention in the core descriptions of chert breccia fragments and brecciated chert. In some wells, such as Phillips Petroleum Company No. 1 Wilson, Val Verde County, most of the chert is brecciated. Breccia fragments of one type chert in a matrix of another type are occasionally seen, as, for example, in Humble Oil & Refining Company No. 22 Yarbrough & Allen, Ector County, depth 10,636 feet; and at several levels in Phillips Petroleum Company No. 1 Wilson, Val Verde County, in which dark-colored opaque chert fragments are in a light gray transclucent chert matrix.

Grains and pebbles of chert were occasionally seen. Pebbles in basal conglomerate in Gulf Oil Corporation No. 108-E Keystone, Winkler County, are likely from the Ellenburger and perhaps from nearby. If the interval involved in soft-sediment deformation in Gulf Oil Corporation No. 1 McElroy-State, Upton County, depth 12,578 to 12,583 feet, containing chert granules and pebbles, is actually intraformational conglomerate, then the chert to form the pebbles must have formed on the sea bottom or, at most, only a few inches beneath.

Grains of detrital chert in the sandstone of the upper part of the Wilberns formation in General Crude Oil Company No. 1 George Cave, Nolan County, are not easily explained, unless they are actually from the Precambrian or carried a long distance if they are from the Cambrian. The nearest known nondetrital chert at the same stratigraphic level is in San Saba County, at least 100 miles seaward from Nolan County.

Vugs lined by very quartzose chert mostly grading inward to a crust of quartz crystals are fairly common in several wells. One vug in Gulf Oil Corporation No. 1

Mitchell Bros.—State, Presidio County, depth 15,856 feet, has a center of anhydrite, and 11 feet higher in the well anhydrite appears to be intergrown with pale red, opaque chert. Vugs in Gulf Oil Corporation No. 108-E Keystone, Winkler County, depth 9,245 feet, are in part filled by olive-gray clay and in part by olive-gray chert identical in appearance, suggesting that part of the clay was replaced by chert.

Cannonball chert, similar to that described by Cloud and Barnes (1948a, pp. 16 and 95–96; 1957, pp. 187–188), in Magnolia Petroleum Company No. 1 Mary Ball, Schleicher County, depth 4,457 feet, is no more fossiliferous than the enclosing limestone, thus possibly detracting some from the argument favoring the formation of this type of chert as rollers on the sea bottom.

Glauconite

During the present project the distribution of glauconite was noted but no attempt was made to collect data on its genesis. Cloud (1955) has recently reviewed the physical limits of glauconite formation, listing selected references, and the reader interested in glauconite genesis is referred to his paper. Those readers who are more particularly interested in glauconite in pre-Simpson rocks are referred to Cloud and Barnes (1948a, pp. 97–98; 1948b, pp. 53–55) and the section on "Well correlation" in this paper (pp. 67–71).

Feldspar

Feldspar derived from pre-existing rocks is common in an area more or less coincident with the Central Basin Platform, but elsewhere in the Ellenburger it is rare. Authigenic feldspar is mostly rare in the Ellenburger except in the lower part of the Tanyard formation, and it is common in much of the Cambrian, being abundant at some levels such as in the Point Peak member of the Wilberns formation. Tiny grains of pre-existing feldspar mostly served as nuclei around which the crystals grew. The overgrowth must have been added either in situ or shortly before the grains reached their resting place, as no signs of abrasion are seen.

Berg (1952) reported rock in the Franconia formation with as much as 48 percent authigenic feldspar, cited evidence that it formed in situ, and concluded that clay minerals probably furnished a large part of the alumina and silica, and sea water supplied the potassium for its formation.

Clay

Minute amounts of clay are present throughout the Ellenburger, and in some units it is fairly common. It occurs interstitially in some dolomite in aggregates of megascopic size; in some rocks where it is fairly common it is so finely disseminated that individual aggregates cannot be seen, but its presence is indicated by the "dirty" appearance of the rock. Clay along stylolites is mostly of two types—thin beds which served as loci for solution of the adjacent rock, and clay released from the rock by solution. Clay of one or the other of these types or of both is almost universally present along stylolites. A third type of clay rarely seen along stylolites has been injected from clay veins or from clay serving as breccia matrix.

Clay is common in breccia matrix in veins and occasionally is found in vugs. Much of that found in breccia and veins is foreign to the Ellenburger, having worked its way downward along openings formed by solution and collapse during periods of emergence, the clay being from overlying formations or from residual material along unconformities.

The character and origin of clay indigenous to the Ellenburger are treated in the paper by Jonas (pp. 131–143). Clay is more plentiful in the Wilberns and Riley formations than in the Ellenburger, being most abundant in the Point Peak member of the Wilberns. During this project no special work was done on the clays beneath the Ellenburger.

Quartz Sand

Cloud and Barnes (1948a, pp. 23–24, 96–97; 1948b, pp. 52–53; 1957, pp. 188–

189) have discussed the distribution and origin of sand within the Ellenburger for the rocks of the Llano region and arrived at certain conclusions, which will not be repeated here. In the expanded area of the present study, it is found that the sand in the Gorman and lower 50 feet or so of the Honeycut formation may have been derived from a different quarter than thought by Cloud and Barnes, possibly from the east or northeast instead of the east or southeast, as indicated by the disappearance of the sand in this interval southwestward from the Llano region. Sand again reappears, however, westward in the Pecos County area.

The nonsandy units in the Llano region, the Tanyard and most of the Honeycut formations, become sandy to the southwest of the Llano uplift, thus reversing the relationship found by Cloud and Barnes in the Ellenburger of the Llano region.

Anhydrite

The presence of anhydrite in Ellenburger rocks was first called to the writer's attention by Lincoln E. Warren, Gulf Oil Corporation, who (letter of February 24, 1947) asked for verification of the identity of a mineral thought to be anhydrite found in insoluble residues from Stanolind Oil & Gas Company No. 1 Todd "A," Crockett County, from about 250 to 450 feet beneath the top of the Ellenburger.

Anhydrite is present in sixteen wells examined during the present project, and a résumé of its distribution is given in Appendix C. These wells are all situated west of a line projected southward from the eastern side of the Texas Panhandle. Peripheral wells in which anhydrite was found include Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County; Richardson & Bass No. 1 Federal-Cobb, Eddy County, New Mexico; Phillips Petroleum Company No. 2 Delp, Gray County; Seaboard Oil Company No. 1 TXL "C," Nolan County; and Humble Oil & Refining Company No. 1 North Branch Unit, Sutton County.

The absence, or possibly nonrecognition, of anhydrite in five extensively cored wells within this area is not easily explained. These are Gulf Oil Corporation No. 108-E Keystone, Winkler County; No. 1 Texas "000," Andrews County; Phillips Petroleum Company No. 1 Glenna and No. 1-C Puckett, Pecos County, and No. 1 Wilson, Val Verde County.

Four or five of the recorded occurrences of anhydrite show fairly definitely that anhydrite comprised part of the Ellenburger sediments. The interstratification of anhydrite and dolomite about 70 feet above the base of the Honeycut formation in Shell Oil Company No. 12 Lockhart, Andrews County, is probably the most convincing, and the anhydrite along the bedding in Gulf Oil Corporation No. 1 McElroy-State, Upton County, the same distance above the base of the Honeycut is probably in part primary even though some anhydrite along the bedding in this well is definitely in veins. The grains, granules, and small pebbles of anhydrite in intraformational conglomerate in the B2b′ unit in Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, seem incontrovertible evidence that anhydrite was forming in the Ellenburger sea. The anydrite crystals in shale at the top of the Honeycut in Humble Oil & Refining Company No. 22 Yarbrough & Allen, Ector County, must be syngenetic, and it seems likely that masses of anhydrite, one of which was mostly replaced by quartzose chert, in Gulf Oil Corporation No. 1 Mitchell Bros.—State was formed at or near the sea floor.

All other occurrences are in veins (Pl. 24, B), vugs, breccia matrix (Pls. 21, B; 24, C), or as linings of open fractures, and in each occurrence the host rock is dolomite, not limestone. If the anhydrite, as is thought by the writer, was indigenous in pre-Simpson rocks, this fact may be significant.

Since anhydrite is present above the Ellenburger the question of downward migration along fractures formed during orogenesis might arise. Structural changes since the termination of Permian anhydrite deposition, however, are not believed to be sufficient to produce such widespread fracturing. If, however, anhydrite is present in the Silurian, as observed by John E. Galley (personal communication), then a strong case could be made for its origin from above. The writer saw anhydrite in veins a few feet above the Ellenburger in Gulf Oil Corporation No. 1-E State "AM," Andrews County, and the Ellenburger in this well is free of anhydrite.

However, it seems likely to the writer that the anhydrite in pre-Simpson rocks was mostly indigenous and since has been largely redistributed to its present locations. Anhydrite is nearly ten times as soluble as dolomite in pure cold water, and the two may retain a similar solubility ratio even with impure water of the type causing solution within the Ellenburger. A significant amount of dolomite has been dissolved within the Ellenburger, as can be demonstrated by the examination of stylolites (Pl. 27, A—F; and several photographs on Pls. 18–31). While the dolomite was being dissolved, it is likely that an even larger amount of anhydrite would be dissolved, if present. It is possible, therefore, that the Ellenburger originally contained significant interbedded anhydrite and that most of these beds now have been removed, with some of the anhydrite transferred to vugs, veins, breccia matrix, and rarely lining open fractures. It is also possible that some of the breccia may be of a collapse type from the solution of anhydrite.

Where anhydrite is present elsewhere in the world, the carbonate rock associated with it is commonly dolomite, and such a relationship may not be accidental. Perhaps conditions favorable to the deposition, or near deposition, of anhydrite are favorable to the direct precipitation of dolomite, thus explaining why the Ellenburger in such a large area of its subsurface occurrence in west Texas and southeast New Mexico is mostly dolomite. The Ellenburger in this area, then, might be a somewhat restricted basin deposit and thus not directly comparable with the Ellenburger of the Llano region, which was deposited in an open-sea, banks environment.

Likewise westward in the Diablo Plateau and Hueco and Franklin Mountains, the rocks equivalent to the Ellenburger, the El Paso limestone, are distinctly different and may have been formed in a shelf environment adjacent to land, as indicated by the granularity of the limestone and relatively greater abundance of sand. If the presence of limestone is indicative, the water must have been less saline (or cooler) than in the restricted basin, but the barrier to limit circulation between the shelf facies and the restricted basin facies is not explained, unless possibly Kelley and Silver (1952, pp. 46–49) have revealed the answer in the stromatolitic buildups described in the Bat Cave formation, which they correlate with Lower Ordovician rocks equivalent to the Honeycut formation and younger Lower Ordovician rocks of Cloud and Barnes (1948a).

Most of the anhydrite is in the Honeycut formation with the lowest primary anhydrite logged about 70 feet above its base. All the anhydrite beneath the Honeycut formation is in minor secondary occurrences, and of that above, the major occurrence was in samples from Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County. This suggests either that the Mitchell Bros.—State is miscorrelated or that conditions for anhydrite deposition persisted longer in a southern direction. The second explanation is probably correct, as the thickness of section with anhydrite in it exceeds that found in any other well.

SEDIMENTARY, SOLUTION, AND TECTONIC STRUCTURES

Analysis of Data

Numerous observations were recorded, most of them being of little value for subdividing and correlating units within the pre-Simpson sequence of rocks but of greater value for interpreting the history of these rocks. Observations were made on original bedding features such as bed thickness, cross-beds, ripple-marks, mud cracks, and disturbance by organisms, as well as features induced later such as tilting, contortion, and brecciation. Other features described include veins, fractures, vugs, and stylolites. The order of filling of veins and vugs was recorded and the sequence of events determined when possible.

In Appendix D (pp. 695–720) the various features except original bedding features are briefly reviewed for each well followed by an interpretation of the processes operating to cause the various structural features. Some structures which appear to be similar may be produced in one of several ways. Breccia, for example, may be formed by gravity-induced movement early in the history of a sediment while it is still soft and incoherent; it may be formed after lithification during periods of tectonism; it may be formed in soluble rocks by solution and collapse; or it may be formed by some combination of these processes.

The attitude of a bed likewise may be the result of any of these processes. Inclined beds in a group of rocks like those of the Ellenburger, if the inclination is fairly uniform and the drill hole is vertical, indicate tectonic deformation. Some of the inclination of beds reported may not be real because the writer has no knowledge that the drill holes are vertical. Beds inclined at various angles and associated with contorted zones suggest soft-sediment deformation. Beds inclined at various angles may be present in breccia produced by solution and collapse, or even by tectonism.

The assignment of the origin for any feature described is based on observation of a very small part of the whole, and evidence may or may not be clear. For example, evidence for soft-sediment deformation is clear-cut where beds are contorted (Pls. 22, D; 25, F; and 29, C) or smeared out (Pl. 20, B). Also evidence is clear when some beds are partly lithified and fragments of these beds are frayed (Pls. 20, A; 21, C; and 22, G) or where the fragments merge imperceptibly with the matrix, producing a mottled appearance (Pls. 18, A; and 20, E). Evidence may not be so clear where fragments are distinct (Pls. 21, C; 27, E); however, the matrices are characteristic of ones formed during soft-sediment deformation.

Matrix composed of material similar to the fragments or to nearby strata usually indicates a breccia formed early while the sediments were in part soft; one composed of secondary minerals deposited between fragments, with or without voids, may indicate a tectonic breccia—however, similar material is also common in collapse breccia—and a matrix composed of material foreign to the formation indicates breccia formed by solution and collapse probably related to an erosional unconformity.

Even though the fragments shown in Plate 19, C, appear to have been well indurated at the time they formed, the matrix is similar to some of them, suggesting that the whole is a product of early deformation while some of the sediment was soft. The breccia in Plate 23, A, showing interfingering of fragments and matrix along stylolites, may be early as the matrix is similar to some of the coarser grained fragments. The evidence in Plate 23, D, is conflicting: The matrix in the lower part is probably locally derived, but that in the upper part is sandstone characteristic of younger strata. This may be an example of solution and collapse with infilling from above, even though this level is 200 feet beneath the top of the Ellenburger.

The evidence is also conflicting in Plate 20, F. The distinctness of the breccia fragments and the presence of voids filled by white, secondary dolomite in the matrix suggest that the breccia is a tectonic breccia, yet the gray matrix is a rock type that could be locally derived. If seismic forces were active during sedimentation, the features preserved might be caused by both soft-sediment and tectonic deformation.

Stylolites have not been recognized in breccia fragments formed during soft-sediment deformation, and either they are rare in tectonically formed ones or possibly tectonic breccias are rare. A fragment with an early set of weak stylolites, possibly in a tectonic breccia, is shown in Plate 22, E. Stylolites may also be present in fragments formed during solution and collapse.

Some veins fill fractures resulting from tectonism; others, possibly related to clastic dikes, form during soft-sediment deformation; and others form as a result of solution and collapse. Whether or not a vein originates from the filling of tectonic fractures may be difficult to decide. Ones of relatively pure minerals—dolomite, calcite, anhydrite, quartz—or in part void may fill tectonic fractures, but their formation in connection with solution and collapse is not ruled out. These veins may be multiple but commonly are monomineralic. Veins wholly of quartz, such as those in Phillips Petroleum Company No. 1 Wilson, Val Verde County, are believed to fill only the most recent fractures which include joints as well as planes along which there was translation, and these are thought to be entirely tectonic. Most faults are caused by tectonism, yet displacements observed in some cores may be caused by soft-sediment deformation and others by solution and collapse.

In those veins formed by infilling from above of fractures resulting from solution and collapse during periods of erosion, the filling may be either residuum formed during erosion of the Ellenburger, or material in part completely foreign to the Ellenburger and introduced during some subsequent period of erosion. In Phillips Petroleum Company No. 1 Wilson, Val Verde County, material of a type that might be derived from residuum is found below the Tanyard-Gorman boundary. This suggests that an emergence took place at least locally following the Tanyard.

The origin of vugs was not ascertained during the present investigation. That vugs were open when the veins and breccias formed is indicated in a few wells by similar materials deposited in the same order in each. The contact between different substances in vugs in a few wells is plane, and in all observed cases these plane contacts are parallel to the bedding, indicating that the vugs were filled while the beds were horizontal.

Deformation produced by solution and collapse should be mostly in the upper part of a stratigraphic sequence; however, Barnes and Bell (1954a, p. 17; 1954c) demonstrated the presence of Marble Falls limestone between Cap Mountain limestone blocks, both at the level of the Hickory sandstone. The Marble Falls in this case fell at least 2,000 feet into an open sink formed by collapse of the entire Upper Cambrian and Lower Ordovician sequence into a solution cavern in marble in the Precambrian Packsaddle schist. This, of course, is an exceptional example, and similar occurrence could take place only where marble is present in the underlying Precambrian. However, this example does illustrate the principle that soluble rock will dissolve if conditions are right, and it is therefore possible for collapse features to be present anywhere in a carbonate sequence both stratigraphically and geographically. In general, collapse features formed in the upper part of the sequence will be easier to recognize because of near-surface infilling of residuum or foreign material, whereas with depth these materials may be lacking.

Rock deformed while soft can be present anywhere in a stratigraphic sequence but should be more prevalent where the sediment was deposited on the steeper slopes of the sea bottom. Large shelf or flat-bottomed basinal areas may be essentially free of such rock. Soft-sediment deformation varies widely in scale—in some cases a quarter-inch bed may be deformed and in others great thicknesses and volumes of rock are involved. If, however, deposition took place in a seismic area the bottom slope may be gentle and movement still occur. Disturbed zones were noted in some cores which may possibly have been caused by earthquakes, as if cracks had momentarily opened at the crest of earthquake waves, the walls started to slump, and the cracks again immediately closed.

The information on sedimentary, solution, and tectonic structures assembled in Appendix D is tabulated (table 1, in pocket) starting with the area, hereinafter referred to as the central area, east of a line from Scurry County to Sutton County. In this area Carboniferous rocks, with few exceptions, rest directly on the Ellenburger. The tabulation starts in the northwestern part of this area, moves toward the Llano region, proceeds around the region clockwise, and then continues westward.

The second area includes wells in west Texas and New Mexico in which rocks mostly older than the Carboniferous rest directly on the Ellenburger, the transition between the two areas taking place at about Edwards County. The remaining wells are in widely separated areas including Presidio County, Lubbock County, the Panhandle, and north and northeast Texas.

In this tabulation no allowance is made for vertical variation within a core; consequently, it does not bring out differences that might exist between stratigraphic units. The amount of core examined ranges from just a few feet in some wells to over a thousand feet in others; in those with only a few feet, features might be absent which would be present if more core had been available. Also, this method of portrayal does not indicate the density of data within a well.

When examined broadly it is found that certain criteria are more numerous in some areas than in others, as shown in table 2. The criteria are sorted into three groups: those thought to support tectonic deformation; those thought to support solution and collapse with infilling; and those thought to support deformation before the sediments were completely lithified. These criteria are arranged from left to right in each group according to degree of reliability.

The strongest evidence for tectonic deformation is evenly distributed throughout the whole region, whereas the rest of the evidence is mostly confined to the western area. All evidence used for solution and collapse with infilling is present in the central and western area, with such evidence being much less abundant in the Panhandle and northeastern area. All evidence points to the prevalence of soft-sediment deformation in the western area, with lesser amounts in the other areas.

The region involved in this project is so large that the geologic history is unlikely to be the same for all portions, and since the record in the western area appears to be the most complex, the events in this area will be listed indicating similarities and differences in adjacent areas. All of the Cambrian and much of the Tanyard are missing in this area. These rocks where present in other areas display few, if any, features of structural significance dated before the start of the Gorman. In one well, Phillips Petroleum Company No. 1 Wilson, Val Verde County, infilled material in veins and breccia in the upper part of the Tanyard suggests a period of emergence of unknown extent at the end of the Tanyard during which solution, collapse, and infilling took place.

The absence of the lower part of the stratigraphic sequence in the western area is due to nondeposition caused by the presence of a peninsula or island chain (ancestral Central Basin Platform) aligned roughly in a north-south direction with the highest point, so far as revealed by the wells examined, in Lea County, New

TABLE 2. *Analysis of criteria for determination of type of deformation in various areas.*

	Criteria for type of deformation																			
	Tectonic											*Collapse*						*Soft sediment*		
Area	Inclined beds	Open fractures	Quartz veins	Sphalerite and galena in veins	White coarse-grained dolomite veins	White coarse-grained dolomite breccia matrix	Other fairly pure dolomite veins	Other fairly pure dolomite breccia matrix	Anhydrite veins	Anhydrite breccia matrix	Two periods of brecciation	Foreign fragments in veins	Foreign fragments in breccia matrix	Clay veins	Clay in breccia matrix	Impure dolomite veins	Impure dolomite in breccia matrix	Contorted beds	Breccia matrix similar to fragments	Motled as if deformed
Central	X	X	....	....	....	....	....	....	....	....	....	X	X	X	X	X	X	S	S	X
Western	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Panhandle	X	X	....	S	X	S	....	....	....	....	....	....	S	S	S	S	S	X	S	....
Northeastern	X	S	....	....	....	....	X	S	....	....	....	....	....	X	S	S	X	X	....	....

X—Predominant; S—Some

Mexico. Carbonate sediments deposited flanking this high area, before it was buried during the Gorman, contain sporadically distributed feldspar and angular quartz.

The sea bottom probably sloped away from the high area, giving an unstable footing for the accumulation of the sediments, thus accounting for the abundance of slump structures. Slump structures are also present in that part of the Ellenburger overlapping the highest part of the buried landscape, which should have been fairly flat. This suggests either that the bottom actually sloped instead, or that seismic activity became important so that less slope, or for certain types of disturbance no slope, was needed for this type of deformation to take place. If such a period of seismic activity occurred it may be responsible in the western area for much of the early breccia having features of both tectonic and soft-sediment deformation.

Eventually the Ellenburger emerged, not only in the western area but probably in the entire region, and variable amounts of it were eroded, amounting in places to hundreds of feet. During this time lithification continued until deformation of a soft-sediment type could no longer occur, solution and collapse with infilling took place, and perhaps those vugs unrelated to fracturing and brecciation formed. Eventually the sea again encroached, sedimentation resumed, and seismic activity possibly reached a peak.

Seismic activity may be responsible for the anomalous condition found in Gulf Oil Corporation No. 1 McElroy-State, Upton County. In this locality a great sheet of Ellenburger may have slid over a jumbled mass of Simpson sediment, including conglomerate, most of which had cascaded to a low point on the sea bottom either at the foot of a fault scarp or in a valley eroded in the Ellenburger during the period of emergence before Simpson deposition started. That this condition is not unique is indicated by similar relationships mentioned to the writer by various geologists as occurring in other localities in an area reaching into three counties.

Simpson-like materials in veins and breccia in the Ellenburger may attest periods of emergence during or following the Simpson when solution and collapse took place allowing the infilling of unconsolidated and semiconsolidated Simpson. Similar material in the Ellenburger beyond the present known limits of the Simpson may indicate a wider former distribution of the Simpson.

Coarse-grained dolomite veins in both Ellenburger and Simpson rocks may indicate continuation of seismic activity well into or beyond Simpson deposition; possibly most of the white coarse-grained dolomite veins and breccia matrix, filled or partly filled fractures, and breccia formed about this time. The greater abundance of voids in breccia, veins, and vugs in the western area may be explained by the effective sealing of the Ellenburger in this area by the overlying sedimentary column, limiting the passage of solutions.

Evidence of solution and collapse is more abundant in the area where Carboniferous rocks rest directly on Ellenburger rocks than it is in the western area where the Ellenburger is overlain by Simpson rocks. In the central area, because younger rocks rest on the Ellenburger, it is likely that periods of emergence during which solution, collapse, and infilling could take place were more numerous, thus accounting for the large number of vein types and breccia matrices seen in some cores. In such cores age relations may be complex, certain type veins recurring from time to time.

The filling of space in veins and breccia was mostly completed before stylolites formed. Younger calcite veins are in only a few cores, and in only a few are seen stylolites which formed previous to brecciation, as evidenced by feebly developed stylolites in breccia fragments (Pl. 22, E). Some of the weak stylolites not associated with veining and brecciation may also belong to older periods of stylolite formation. Stylolite formation and elimination of porosity were probably completed or nearly so by the time of the mid-Pennsylvanian orogeny, at which time the rocks throughout the area examined appear to have been block-faulted similar in manner to the way they are faulted in the Llano region.

It is thought that open fractures formed at this time and that these fractures remained open because of very restricted movement of mineralizing solutions. Some solution movement did take place as shown by the occurrence of dolomite, quartz, calcite, and a few other crystals along the fractures, and in one locality, Phillips Petroleum Company No. 1 Wilson, Val Verde County, the fractures are completely filled by quartz. The Ellenburger in this locality may have been more deeply buried than in any other examined, and perhaps the temperatures and pressures were such that the mobility of quartz was much increased.

Sphalerite and galena probably were introduced relatively late, as indicated in a few cores where sphalerite along stylolites appears to be younger than the stylolites. This still leaves a large interval of time during which these minerals could have been introduced, and the most logical time is related either to the period of mid-Pennsylvanian faulting or to the much later period of mineralization so common westward in New Mexico.

Following or perhaps in part concurrent with the mid-Pennsylvanian period of faulting much of the Ellenburger and some Wilberns rocks, especially in the central area, were eroded. The faulting probably effectively blocked the migration of fluids within the pre-Simpson group of rocks as a whole, and any circulation established was probably between younger rocks and pre-Simpson rocks within individual fault blocks. The "Cambrian trend" production is probably Carboniferous oil that migrated into Cambrian rocks after the faulting took place. Dead oil or bitumen in some of the Cambrian sandstone could be cited as evidence of indigenous oil, but it seems more likely that this material is a residue of oil that entered the sandstone early during the faulting and later mostly escaped where the sandstone was bared by erosion.

It is not beyond the realm of possibility that the Ellenburger gas and oil production is not indigenous Ellenburger oil. This may be borne out by the presence of bitumen mostly in places where it must be relatively young, such as coatings on the insides of voids and vugs or as coatings on crystals in open fractures or lining other openings, and its rarity in places where it could have formed early.

Regional Structure

The configuration of the top of the pre-Simpson sequence of Paleozoic rocks is shown in figure 1, and the configuration of the bottom (top of Precambrian) in figure 2. The contours (fig. 1) depict an erosional surface which truncates all of the Lower Ordovician beds and locally some Cambrian beds as well. The contours also reveal much information about the structure of the pre-Simpson group of rocks, since the relief of this surface greatly exceeds the thickness of the sequence, and the erosional surface cuts the beds at a very low angle. The configuration of the Precambrian surface is discussed by Flawn (1956, pp. 53–57) and shown in detail in his Plate I.

The dominant features shown in figure 1 are the Llano uplift and the rather knobby Central Basin Platform, with the Midland basin between and the Delaware basin to the west not fully contoured. If the eastern edge of the Eastern shelf is considered as the western edge of the Llano uplift, then the Bend arch is little more than part of the Llano uplift with a narrow saddle between it and the Red River uplift. The Red River uplift appears to continue eastward joining the southeastward-trending Muenster arch. The Fort Worth basin is bordered in part by these raised areas and in part by the Llano uplift as more broadly defined here.

In the southern part of the area the rocks plunge abruptly to more than 13,000 feet below sea level in the Val

Verde basin; they perhaps plunge even more abruptly off the Llano uplift to the south and east beneath the Ouachita fold-belt. In the Texas Panhandle region the pre-Simpson rocks dip abruptly from the Amarillo Mountains northeastward into the Anadarko basin to a depth of more than 11,000 feet below sea level. They also appear to dip abruptly from the Red River uplift and Muenster arch into the Ardmore basin.

The structure west of the Delaware basin is imperfectly known except that it is a basin-and-range type with a few blocks, such as that forming the Franklin Mountains, steeply tilted.

GEOLOGIC THERMOMETRY

Earl Ingerson of the U. S. Geological Survey very kindly examined on a heating stage a quartz crystal containing liquid inclusions. This crystal is from depth 12,036 feet in Gulf Oil Corporation No. 1 McElroy-State, Upton County. Ingerson (letter of May 28, 1958) stated: "The crystal has numerous liquid inclusions and they all appear to have about the same degree of filling. The ones I studied all became filled with the liquid phase between 71° and 77° C."

The temperature recorded on the gamma ray—neutron log for this well indicates a temperature of about 72° C. at a depth of 12,000 feet. This temperature is about 10° C. too low when compared with the temperature of the other five wells in western Upton County examined during this project. These temperatures are very near to the temperature at which Ingerson found that the vapor phase disappeared.

Ingerson also stated: "The pressure correction, assuming crystallization at about the present depth, would be approximately 50° C., so the best estimate of actual temperature of formation would be 120° to 125° C." (See Ingerson, 1947.) This figure was derived using for pressure a value equivalent to a 12,000-foot rock column, whereas, since the crystal grew in an open fracture, the pressure value probably should be only that equivalent to a 12,000-foot column of saline water. The actual temperature of formation, using this reduced value for pressure, would then be between about 95° and 100° C. It seems unreasonable, however, that a temperature as high as this lower value was ever reached at this level in this well.

It was hoped that examination of liquid inclusions in this crystal would give information on the depth of burial at the time the crystal formed and thus more precise knowledge of the geologic history. This finding is similar to the findings for the Mississippi Valley lead-zinc deposits and some sedimentary salt deposits, where the temperatures determined are not likely to have been attained. Perhaps, as suggested by Kennedy (1950) and seconded by Skinner (1953), our fundamental assumptions in the use of vacuoles in geologic thermometry need revision.

WELL CORRELATION

All available evidence as outlined in the sections on "General Stratigraphy" and "Correlation Techniques and Criteria" (pp. 25–51) was considered in making the well correlation charts (Pls. 1–6). On the graphic logs no distinction is made between sand, clay, and chert which are part of the rock; and sand, clay, and chert in veins and in breccia matrix which possibly may be hundreds of feet out of place. Since many of the logs in the correlation charts were prepared from descriptions of cuttings in which the source of the sand, clay, and chert cannot be determined, it seemed useless to distinguish their source when cores were logged. The core descriptions (Appendix B, pp. 305–691) state whether the sand, clay, and chert are in situ or in the veins and/or breccia matrix, and the reader may plot this information in any way he desires.

Electric and radioactivity logs were useful in correlating a few poorly sampled wells west of the Llano region. Electric logs are also useful in tracing members of the Wilberns and Riley formations beyond the point where they can be recognized by their lithologic composition.

Where the Honeycut and Gorman formations are present, the boundary between the two formations was used as a base line (Pls. 1–4); in areas where this boundary is missing, the top of the sandstone in the San Saba member was used as a base line (Pl. 5) or as a supplementary base line (Pls. 2 and 3); one surface section and one well (Pl. 2) were aligned along the top of the Welge sandstone member of the Wilberns formation.

The correlation of units above the Honeycut formation (C′, B2b′, and B2a′) and the placement of the top of the Honeycut formation are provisional, as the distance between wells is great, and the wells are far from the nearest surface section at Beach Mountain, Culberson County.

Specific comments are needed for a few wells. Beds in cores from Humble Oil & Refining Company No. F-90 Odom, Coke County (Pl. 5), dip 60 degrees. When correction is made for this amount of dip, the units are too thin, and without correction they are too thick. It is likely that in this well, faulting in part compensated for dip.

In G. L. Rowsey No. 2 Fee, Bandera County (Pl. 1), fist-sized granite pebbles are near the top of the Hickory sandstone, indicating the presence of a granite knob nearby. Sandstone beneath this level, however, is surprisingly free of granitic debris. The Johnson City section, Blanco County, starts near the top of such a granite hill, which at its highest point may have reached the top of the Cap Mountain limestone. Shell Oil Company No. 1 Purcell, Williamson County, entered such a buried hill, which reaches at least to the middle of the Morgan Creek limestone.

The Cap Mountain limestone appears to thin much too abruptly between G. L. Rowsey No. 2 Nowlin, Kerr County, and G. L. Rowsey No. 2 Fee, Bandera County (Pl. 1). No appreciable thinning has been noticed in units near buried knobs in the Llano region; therefore it seems likely that the Cap Mountain in G. L. Rowsey No. 2 Fee was thinned about 320 feet by faulting and that another fault of about 230 feet displacement is in the San Saba member.

The correlation of Lower Ordovician rocks in wells in Collin and Grayson counties in northeast Texas is shown on Plate 6, section M-N. Because the rocks are more nearly like the Arbuckle group of Oklahoma than the Ellenburger to the south, Oklahoma names are used. Ham (1955, p. 1) found that the calcitic facies of the Arbuckle group has a thickness of about 6,700 feet and that it changes eastward to a dolomitic facies about 4,000 feet thick. This figure is still larger than the 3,200 feet indicated for essentially equivalent beds of the Ellenburger (Pl. 2). In addition to its greater thickness, the Arbuckle contains more terrigenous material and otherwise does not closely resemble the Ellenburger rocks.

The sample log of Humble Oil & Refining Company No. 1 Miller, Collin County, along with the paleontological data of Cloud (pp. 78–80) were sent to W. E. Ham, of the Oklahoma Geological Survey. In a letter of October 18, 1955, he made the following statement:

> As microgranular dolomites are mostly lacking in the Arbuckle group of the Arbuckle Mountains, the best correlation apparently is to be made on the basis of fossils and insoluble residues. The Miller well is in the limestone facies of the Arbuckle group and corresponds most closely with the outcrop section I measured on the Joins ranch in Ts. 1 and 2 S., R. 1 W., Murray County, Oklahoma, and the following correlations are strongly suggested.
>
> 1. Depth 9,520 to 9,720 feet is equivalent to an interval 475 to 785 feet below the top of the West Spring Creek limestone, the interval being characterized by spicular chert. I am satisfied that the base of this zone is equivalent in the two localities.
> 2. Depth 10,265 feet is equivalent to the base of the West Spring Creek, or 1,375 feet below the top of the Arbuckle group. In the Arbuckle Mountains this mapped rock unit everywhere contains medium to coarse rounded-frosted-pitted sand, and it is invariably approximately 30 feet above the highest occurrence of *Ceratopea tennesseensis*. This would indicate that approximately 250 feet of West Spring Creek has been eroded under Strawn rocks in the Miller well.
> 3. In the Miller well from 10,265 feet to the top of the diabase at 10,725 feet is typical low-residue assemblage of the upper and middle Kindblade.
> 4. In the Miller well the interval from 10,980 to 11,155 feet is typical of the lowest Kindblade, and I would call the base of the Kindblade and top of Cool Creek at 11,160 feet. I have never found spicular cherts in the upper 500 feet of the Cool Creek.
> 5. There must be a fault cutting Kindblade strata, as everywhere in the southern part of the Arbuckle Mountains this formation is approximatly 1,440 feet thick, whereas in the Miller well this interval is only about 900 feet counting the thickness of the diabase. This indicates clearly to me that at least 500 feet of Kindblade, probably the lower middle part, is missing through faulting, and it further seems probable that the diabase is a sill injected along or near the fault.

The two Grayson County wells, as logged by the North Texas Sample Log Service, appear to have a normal Simpson sequence above the Arbuckle. One of the wells—The Superior Oil Company No. 1 S. L. Privette—was closely correlated with the Miller well by Cloud (p. 81) on the basis of fossils. The other well, The Superior Oil Company No. 1 J. E. Henderson, compares closely in every way with the Privette except that Jean M. Berdan (p. 81) reported the presence of Middle Ordovician (Black River) ostracods from 6,405 to 6,406 and from 6,443 to 6,446 feet. This suggests one of two things: either that these ostracods range further than was thought, or that cores foreign to the Arbuckle were inadvertently included.

Deep Rock Oil Corporation No. 1 Moore Estate, Clay County, is a long distance from any other well examined during this project and is nearest to the wells of Collin and Grayson counties. The 258-foot interval cored in this well, except for material in veins and breccia matrix probably leaked from above, is essentially free of insoluble materials and may correlate with the low-residue assemblage in the upper part of Phillips Petroleum Company No. 1-A Bullington, Archer County (Hendricks, 1952, Pl. 3). Discussing Humble Oil & Refining Company No. 1 Miller, Collin County, Ham (point 3) mentioned that the upper and middle Kindblade typically have a low-residue assemblage. The low-residue intervals of the Moore and Bullington wells may therefore correlate with the upper and middle Kindblade of the Arbuckle group, which is approximately equivalent to the upper half of the Honeycut formation of the Ellenburger group.

The three wells in the Texas Panhandle area with sufficient cored intervals to show graphically are included in Plate 6, section K-L. In Phillips Petroleum Company No. 2 Delp, Gray County, several collections of fossils of Honeycut age were identified (p. 81), and on this basis and on the lack of a lithologic break above the highest identified collection, it is assumed that in this well the Honeycut formation continues to the top of the Ellenburger. The lowest Honeycut fossil is just above a grain-size change and not far above a 65-foot shaly interval, suggesting that the grain-size change may indicate a formational boundary. If this is correct, then the Honeycut displays the same characteristics as farther south, that is, a relatively coarser grain size in the lower part and a finer grain size upward.

The other two wells are correlated on the basis of grain size, but since a complete stratigraphic sequence is not available for comparison, such a correlation may be entirely incorrect. For example, the shaly zone in the No. 2 Delp is not present in Gulf Oil Corporation No. 1-E Porter "A," Lipscomb County. The reason for this, other than lateral change, could be that the cored interval in the Porter well belongs either entirely below or entirely above the cored interval in the Delp well.

The intervals sampled in 36 wells are so short that it is not worthwhile to include them in the well-correlation sections (Pls. 1–6). These wells are correlated in table 3 (pp. 70–71).

The rocks overlying the Ellenburger were mostly disregarded, but in two wells south of the Llano region, beds are present which should be mentioned. In G. L. Rowsey No. 2 Nowlin, Kerr County, a 230-foot interval of slightly glauconitic, aphanitic limestone with some sandstone in the lower 40 feet has no counterpart in the Llano region unless it be the basal part of the Stribling formation (Cloud, Barnes, and Hass, 1957).

In the Magnolia Petroleum Company No. 1 Below, Kendall County, depth 3,964 to 3,976.5 feet, a greenish-gray to olive-gray, in part very pyritiferous and shaly siltstone or very fine-grained sandstone was examined for conodonts by W. H. Hass, of the U. S. Geological Survey. In his report of September 24, 1954, he stated that these rocks are "definitely a part of the Devonian and Mississippian black shale sequence" and suggested that they are equivalent to the upper part of the Doublehorn shale (Cloud, Barnes, and Hass, 1957) of the Llano region.

TABLE 3. *Correlation of wells not shown in well-correlation sections (Pls. 1–6).*

County	Company	Well	Depth (feet)	Formation
NEW MEXICO				
Lea	Humble Oil & Refining Co.	#3 "V" N. M. State	7,460– 7,466 7,466– 7,486	Post-Ellenburger Honeycut(?)
TEXAS				
Andrews	Humble Oil & Refining Co.	#18 Cowden	10,026–10,066 10,070–10,120	Honeycut(?) Gorman
Andrews	Magnolia Petroleum Co.	#2–36995 University	13,851–13,876	Honeycut(?)
Coke	E. L. Doheny	#1 Taylor	5,459– 5,471 5,471– 5,525	Carboniferous(?) Tanyard(?)
Coke	Humble Oil & Refining Co.	#10 Odom	5,829– 5,897	Tanyard
Coke	Humble Oil & Refining Co.	#F-91 Odom	5,680– 5,719	Hickory sandstone
Concho	Floyd C. Dodson	#1 Wilson	3,750– 3,848 3,848– 4,009 4,009– 4,035 4,035– 4,102	Carboniferous Tanyard San Saba (calcitic) San Saba (sandstone)
Crane	The Atlantic Refining Co.	#1-W University	10,391–10,445 10,491–10,445	B2b′(?) B2a′(?)
Crane	Humble Oil & Refining Co.	#1-C Jax Cowden	9,024– 9,096 9,096– 9,132	B2b′ B2a′
Crockett	Continental Oil Co.	#E-1 Harris	10,131–10,178	Upper(?) Honeycut
Crockett	Humble Oil & Refining Co.	#1 Alma Cox	8,140– 8,178	Upper(?) Gorman
Crockett	Humble Oil & Refining Co.	#1-E Alma Cox	8,602– 8,668	Lower(?) Honeycut
Crockett	Humble Oil & Refining Co.	#2 Harvick	8,481– 8,505	Upper(?) Honeycut
Crockett	Shell Oil Co.	#5 Chambers County School Land	7,536– 7,602	Lower(?) Honeycut
Crockett	Shell Oil Co.	#9 Chambers County School Land	7,534– 7,586	Lower(?) Honeycut
Crockett	Shell Oil Co.	#10 Chambers County School Land	7,520– 7,584	Lower(?) Honeycut

Crockett	Shell Oil Co.	#12 Chambers County School Land	7,502– 7,553	Lower (?) Honeycut
Ector	Shell Oil Co.	#D-10 University	8,756– 8,795	Upper (?) Honeycut
Gray	Gulf Oil Corp.	#1 E. A. Shackleton	7,898– 7,928	Honeycut (?)
Hansford	Gulf Oil Corp.	#1 J. R. Collard	8,484– 8,494	Ellenburger
Hutchinson	Gulf Oil Corp.	#1 Amarillo National Bank	8,164– 8,180 8,180– 8,284	Post-Ellenburger Ellenburger
Irion	Wilshire Oil Co.	#1-A Brooks	7,231– 7,375	Gorman (?)
Menard	B. A. Duffy	#1 Sol Mayer	3,793– 3,970 3,970– 4,178	Gorman Tanyard
Nolan	General Crude Oil Co.	#1 George Cave	6,223– 6,230 6,230– 6,246 6,246– 6,261	Tanyard San Saba (dolomite) San Saba (sandstone)
Nolan	Skelly Oil Co.	#B-4 Boyd	6,137– 6,185	Tanyard
Nolan	Sun Oil Co. et al.	#1-A B. K. Stone	7,172– 7,173 7,180– 7,246 7,741– 7,753	Carboniferous Tanyard San Saba (sandstone)
Nolan	U. S. Smelting, Refining & Mining Co.	#3 TXL "A"	6,235– 6,262	Point Peak— Morgan Creek
Reagan	Humble Oil & Refining Co.	#1-G Sawyer	10,362–10,405	Gorman (?)
Schleicher	Robert Berry	#1 Thomerson	5,540– 5,572 5,572– 5,630 5,630– 5,750	Carboniferous Tanyard San Saba (sandstone)
Scurry	Humble Oil & Refining Co.	#1-B B. A. Moore	8,196– 8,238	San Saba (dolomite)
Sutton	Humble Oil & Refining Co.	#1 North Branch Unit	5,870– 5,970	High Gorman (?)
Tom Green	Humble Oil & Refining Co.	#1 Washington County School Land	6,079– 6,090 6,090– 6,100	San Saba (dolomite) San Saba (sandstone)
Tom Green	Humble Oil & Refining Co.	#1 J. W. Johnson	5,610– 5,636	San Saba (sandstone)
Upton	C. L. McMahon	#1 Z. Oswalt	11,988–12,064	Lower Honeycut (?)
Upton	Wilshire Oil Co.	#14-117 McElroy	12,373–12,389	Upper Honeycut (?)
Upton	Wilshire Oil Co.	#14-130 McElroy	12,063–12,078 12,078–12,083	Simpson (?) Ellenburger
Ward	Shell Oil Co.	#3 Sealy Smith	10,460–10,484	Upper Honeycut (?)

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PART 2: INDIVIDUAL REPORTS

Paleontologic Data and Age Evaluation for Individual Wells, Pre-Simpson Paleozoic Rocks[2]

PRESTON E. CLOUD, JR., AND ALLISON R. PALMER[3]

ABSTRACT

Fossils were examined from 64 Texas and New Mexico wells for purpose of dating and stratigraphic correlation of Upper Cambrian and Lower Ordovician rocks. Genera of value for correlation and dating include, among others, *Apsotreta, Huenella, Polytoechia, Pomatotrema, Diparelasma, Hormotoma, Euconia, Orospira, Archaeoscyphia, Kinsabia, Labiostria,* and the saukiid trilobites. These and a few other forms are illustrated and briefly described.

UPPER CAMBRIAN FOSSILS

Trilobites, brachiopods, and merostomes are the commonest fossils in the subsurface Upper Cambrian rocks of Texas. Less common forms are spicules of the sponge *Chancelloria* and objects of unknown biologic affinities referred to *Kinsabia*. Some characteristic specimens from surface and subsurface collections are illustrated on Plate 34. In addition, recent publications (Lochman, 1938; Palmer, 1954; Wilson, 1949) include descriptions and illustrations of Cambrian fossils from surface exposures in central Texas and discussions of their stratigraphic significance. Raasch (1939) described and discussed the merostomes.

Trilobites can be located by observing cross sections on the outsides of cores, or on polished and moistened surfaces. Useful material can be obtained only by splitting fossiliferous portions parallel to the bedding. Most identifiable trilobites from the subsurface belong to the *Aphelaspis* and post-*Aphelaspis* faunas of early Late Cambrian age or are saukiid trilobites characteristic of rocks of latest Cambrian age. The early Late Cambrian forms have been seen in limestone lenses in glauconitic sands equivalent in age to the Lion Mountain sandstone member of the Riley formation (example, *Labiostria conveximarginata,* Pl. 34, figs. 15, 16). The latest Cambrian trilobites have been seen in clean white sands from the upper part of the Wilberns formation (example, undet. saukiid trilobite, Pl. 34, figs. 12, 14).

Phosphatic acrotretid brachiopods have been observed in limestone portions of most Cambrian cores. Specimens are abundant in limestones within the Lion Mountain sandstone member of the Riley formation and somewhat less abundant in beds of the Cap Mountain limestone member of the Riley formation and the Morgan Creek limestone member of the Wilberns formation. Some acrotretids have limited ranges and hold great promise for Cambrian subsurface stratigraphy. They are small (1 to 2 mm), distinctive, and easily obtained as free specimens by dissolving limestone cores or cuttings in dilute formic or acetic acid. *Apsotreta expansa* Palmer, a characteristic species from the early Late Cambrian Lion Mountain sandstone member of the Riley formation, is shown on Plate 34, figures 6–8.

Linguloid brachiopods are of little stratigraphic value because of their generally fragmentary nature and lack of diagnostic characteristics. They have been obtained from insoluble residues of limestones and bedding-splits of sandstones throughout the Cambrian section.

Calcareous brachiopods have been observed in the subsurface only in limestones of the Wilberns formation. At the surface

[2] Publication authorized by the Director, U. S. Geological Survey.
[3] Geologists, U. S. Geological Survey.

they are also known, although rarely, from the Riley formation. The calcareous brachiopods are generally difficult to extract from cores in identifiable condition, but they are likely to be significant when found and identified. *Huenella texana* (Walcott), a characteristic middle Late Cambrian form, from the Wilberns formation is illustrated on Plate 34, figures 10, 13.

Merostomes are represented only by fragments. These fragments have been obtained by splitting sandstone portions of cores from the upper part of the Wilberns formation. Their characteristic brown, shiny, strongly pustulose surface (Pl. 34, figs. 9, 11) distinguishes them from linguloid fragments. Merostomes with strongly pustulose surfaces are not known from beds older than middle Late Cambrian—that is, equivalent to the Wilberns formation.

Kinsabia (Pl. 34, figs. 3–5) is a name applied to small (less than 1 mm), white, insoluble objects of uncertain biologic affinities. These objects are conical or cap-shaped, with a smooth undersurface and a pustulose upper surface. The pustules are more or less concentrically arranged. Specimens are known only from beds of earliest Late Cambrian age in the lower portion of the Cap Mountain limestone member of the Riley formation. They are generally observed only in insoluble residues prepared with formic or acetic acid.

Chancelloria (Pl. 34, figs. 1, 2) is a sponge represented by club-shaped spicules that have their thick basal portions beveled in several planes. These fossils are known in central Texas only from insoluble residues of the Cap Mountain limestone member of the Riley formation.

LOWER ORDOVICIAN FOSSILS

Criteria for age assignment and correlation of Lower Ordovician carbonate rocks in the midcontinent region were summarized by Cloud and Barnes in an earlier paper (1948, pp. 22–27, 61–62, 113–118). Some distinctive fossils are illustrated in the same paper, and reference is there made to earlier and supplemental works by others (*loc. cit.*, Pls. 38–43, p. 114). The National Research Council's correlation chart for the Ordovician formations (Dunbar et al., 1954) shows graphically the known stratigraphic distribution of a selection of fossils found useful in correlation to the date of this paper.

For present purposes, therefore, it is sufficient merely to mention the forms found to be most useful in the subsurface, by reason of their abundance, distinctiveness, or propitious occurrence. These include a lithistid sponge resembling *Archaeoscyphia;* the gastropods *Hormotoma, Coelocaulus, Orospira, Ophileta (Ozarkispira),* and *Euconia;* the brachiopods *Archaeorthis, Pomatotrema, Diparelasma,* and *Polytoechia;* and an ostracod provisionally referred to *Eoleperditia* by Jean M. Berdan. *Hormotoma* and *Coelocaulus* are similar slender, high-spired gastropods that differ in the structure of the columella, it being hollow in *Coelocaulus* and solid in *Hormotoma.* Where identification is uncertain the name *Hormotoma* is used in a quotational or queried sense, because its stratigraphic implications are more conservative (younger than the age equivalents of the Tanyard formation of the Ellenburger group, as opposed to a range for *Coelocaulus* from highest Lower Ordovician to Silurian), and because it is the commonest high-spired gastropod of this type in the rocks dealt with.

It is possible to identify some genera of Lower Ordovician gastropods with fair assurance from random sections in well cores, and without detailed knowledge of ornamentation, because the whorl and spire profile are likely to be generically distinctive among the early Paleozoic forms (in contrast to their descendants). Among the brachiopods, both internal structure and external ornamentation are ordinarily necessary for identification. The sponges are identified by spicular arrangement and shape; the ostracods by hingement, musculature, shape, and external ornamentation. Except for a few silicified specimens, all fossils listed were identified on the basis of random sections or specimens obtained by splitting along bedding surfaces and removing sufficient matrix to see the critical features.

Only the best of this generally poor material has been retained in the Federal collections, the figured specimens by the U. S. National Museum and unfigured material by the U. S. Geological Survey. Plate 35 illustrates a selection of the material on which the determinations of Early Ordovician age are based.

TABULATION OF THE DATA AND AGE EVALUATION

In the list below, as in the foregoing discussion, Cloud is responsible for Ordovician and Palmer for Cambrian, except for a few determinations by the late Josiah Bridge of the U. S. Geological Survey and some by W. C. Bell of The University of Texas. Quotations from Bridge and Bell are indicated by the initials J B and W C B at appropriate places. Jean M. Berdan and W. H. Hass of the U. S. Geological Survey also have supplied most helpful identifications and opinions, as quoted at appropriate places below.

To avoid constant repetition in designating inferred equivalence with named formational units the word formation, or the lithic term, is commonly dropped after the geographic term. The lithologic limits of the particular Lower Ordovician formations involved also so nearly correspond with biostratigraphic boundaries that it is sometimes convenient to use the names of the rock units in a time-equivalent sense. To what formations the beds referred to actually belong depends on a consensus of evidence, mainly lithic. We are here concerned primarily with the dating and stratigraphic correlation of collections of fossils.

The location of wells from which Upper Cambrian and Lower Ordovician fossils were obtained is shown in figure 9. Data for individual wells follow.

NEW MEXICO

Eddy County

RICHARDSON & BASS NO. 1 FEDERAL-COBB

Top of Ellenburger—15,973 feet.
16,169—attenuate-spired *Hormotoma.*
16,199—*Ophileta.* This moderately elevated *Ophileta* might be anywhere in the Ellenburger, but it looks a little more like a pre-Honeycut species.
Lower Ordovician—could be all Honeycut, all Gorman, or part Gorman and part Honeycut near the formation boundary.

Lea County

CONTINENTAL OIL COMPANY NO. 1 BURGER B-28

Top of Ellenburger—9,239? feet.
9,242—*Hormotoma?*, *Orospira?*.
9,250—*Hormotoma?*, *Orspira?*.
9,268—*Hormotoma.*
Lower Ordovician—higher than the Tanyard formation, probably equivalent to the Honeycut formation.

HUMBLE OIL & REFINING COMPANY NO. 6 "V" N.M. STATE

Top of Ellenburger—7,525 feet.
7,544, 7,547, and 7,548—attenuated spired *Hormotoma* and small endoceratid cephalopods.
7,553—small, round-whorled, 3 to 5 whorls, moderately high-spired gastropods. The largest 6 mm long, 4 mm diameter on body whorl, not *Coelocaulus.* One fragment of 2 whorls in residue. JB
7,558—rare small gastropods as above. JB
7,558 and 7,559—same as 7,544 to 7,548.
7,565—sections of gastropods similar to those at 7,558 feet, many outlined by a green mineral.
Lower Ordovician—lithology and very attenuated spired *Hormotoma*-like gastropod suggest Honeycut or higher.

SHELL OIL COMPANY NO. 5 STATE

Top of Ellenburger—7,827 feet.
7,828–7,829—*Hormotoma.*
7,878–7,879—*Hormotoma?*.
Lower Ordovician—post-Tanyard, possibly post-Gorman.

TEXAS

Andrews County

GULF OIL CORPORATION NO. 1-E STATE "AM"

Top of Ellenburger—12,588 feet.
12,781, 12,783, 12,793, 12,824, and 12,825—*Hormotoma* sp. abundant.
Lower Ordovician—post-Tanyard, probably post-Gorman.

GULF OIL CORPORATION NO. 1 TEXAS "000"

Top of Ellenburger—12,460 feet.
12,662—*Hormotoma* abundant.
Lower Ordovician—post-Tanyard, possibly post-Gorman.

HUMBLE OIL & REFINING COMPANY NO. 18 COWDEN

Top of Ellenburger—10,014 feet.
10,051—longitudinal sections of slender, many-whorled gastropods. Largest 1 inch long (both ends incomplete), ¼ to ⅜ inch wide, whorls angular, slightly rounded, 6 to 7 visible, apical angle 10° to 15°; possibly *Coelocaulus.* JB
Presumably Lower Ordovician—equivalent to topmost Honeycut or higher than Honeycut.

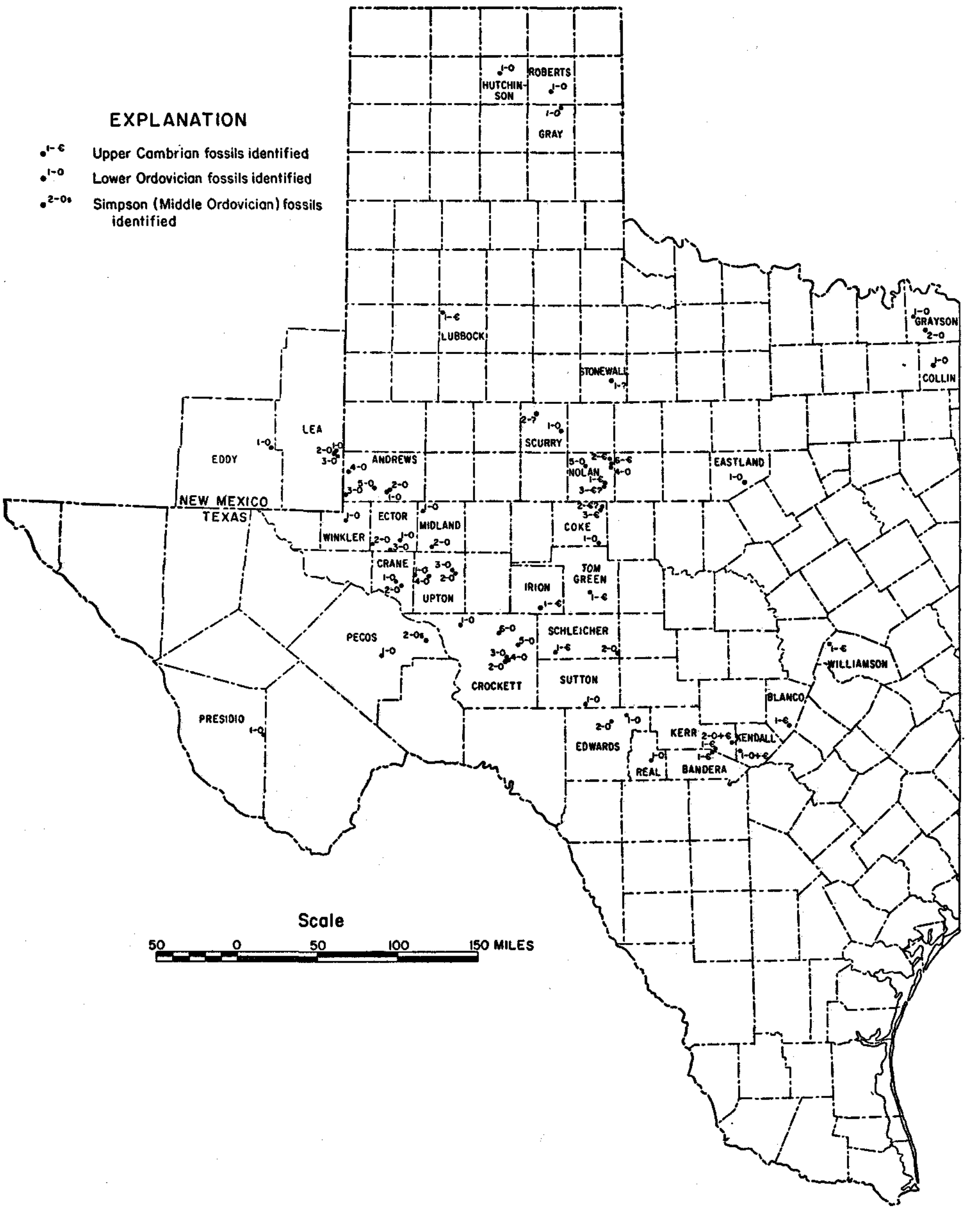

FIG. 9. Map showing wells from which fossils were examined.

Fig. 9, explanation (continued)—

NEW MEXICO

EDDY COUNTY
1. Richardson & Bass #1 Federal-Cobb

LEA COUNTY
1. Continental Oil Co. #1 Burger B-28
2. Humble O. & R. Co. #6 "V" N. M. State
3. Shell Oil Co. #5 State

TEXAS

ANDREWS COUNTY
1. Gulf Oil Corp. #1-E State "AM"
2. Gulf Oil Corp. #1 Texas "000"
3. Humble Oil & Refg. Co. #18 Cowden
4. Humble O. & R. Co. #2 Evelyn Lineberry
5. Shell Oil Co. #12 Lockhart

BANDERA COUNTY
1. G. L. Rowsey #2 Fee

BLANCO COUNTY
1. Roland K. Blumberg #1 Wagner

COKE COUNTY
1. Honolulu Oil Corp. #1 Webb
2. Humble Oil & Refg. Co. #F-90 Odom
3. Humble Oil & Refg. Co. #F-91 Odom

COLLIN COUNTY
1. Humble Oil & Refg. Co. #1 Miller

CRANE COUNTY
1. Humble Oil & Refg. Co. #1-C Jax Cowden
2. Humble Oil & Refg. Co. #3 Jax Cowden

CROCKETT COUNTY
1. Continental Oil Co. #E-1 Harris
2. Humble Oil & Refg. Co. #1 Alma Cox
3. Humble Oil & Refg. Co. #1-C Alma Cox
4. Humble Oil & Refg. Co. #1-D Alma Cox
5. Humble Oil & Refg. Co. #2 Harvick
6. The Superior Oil Co. #1-27 University

EASTLAND COUNTY
1. Luling Oil Co. #1 Blackwell

ECTOR COUNTY
1. Cities Service Oil Co. #1-E Foster
2. Humble Oil & Refg. Co. #22 Yarbrough & Allen
3. Shell Oil Co. #D-10 University

EDWARDS COUNTY
1. Humble Oil & Refg. Co. #1 J. H. Guthrie
2. The Texas Co. #1 Phillips

GRAY COUNTY
1. Phillips Petroleum Co. #2 Delp

GRAYSON COUNTY
1. The Superior Oil Co. #1 J. E. Henderson
2. The Superior Oil Co. #1 S. L. Privette

HUTCHINSON COUNTY
1. Gulf Oil Corp. #1 Amarillo Natl. Bk.

IRION COUNTY
1. The Atlantic Refg. Co. #1 Noelke

KENDALL COUNTY
1. Magnolia Petroleum Co. #1 Below

KERR COUNTY
1. G. L. Rowsey #2 Nowlin
2. Tucker Drilling Co. #1 Dr. Roy E. Perkins

LUBBOCK COUNTY
1. Humble Oil & Refg. Co. #1 Farris

MIDLAND COUNTY
1. Magnolia Petroleum Co. #1 Nobles
2. Magnolia Petroleum Co. #2-A Windham

NOLAN COUNTY
1. General Crude Oil Co. #1 George Cave
2. Honolulu Oil Corp. #2 Whitaker
3. Kilroy Co. of Texas #1 Roberts
4. Seaboard Oil Co. #1 TXL "C"
5. Skelly Oil Co., #1 Ater
6. U. S. Smelt., Rfg. & Min. Co. #3 TXL "A"

PECOS COUNTY
1. Phillips Petroleum Co. #1-C Puckett
2. Standard Oil Co. of Texas #2-1 Claude Owens

PRESIDIO COUNTY
1. Gulf Oil Corp. #1 Mitchell Bros.—State

REAL COUNTY
1. Stanolind Oil & Gas Co. #1 Knippa

ROBERTS COUNTY
1. Gulf Oil Corp. #1 John Haggard

SCHLEICHER COUNTY
1. American Trading & Prod. Corp. #1 Sauer
2. Magnolia Petroleum Co. #1 Mary Ball

SCURRY COUNTY
1. American Tr. & Prod. Corp. #1 E. Howell
2. Humble O. & R. Co. #1-B B. A. Moore

STONEWALL COUNTY
1. Seaboard Oil Co. #4 Upshaw

SUTTON COUNTY
1. Humble Oil & Refg. Co. #1 J. D. Harrison

TOM GREEN COUNTY
1. C. L. McMahon #1 J. W. Johnson

UPTON COUNTY
1. Gulf Oil Corp. #1 McElroy-State
2. Humble Oil & Refg. Co. #1 Z. Oswalt
3. Sohio Petroleum Co. #1 Hill Estate
4. Wilshire Oil Co. #23-118 Windham

WILLIAMSON COUNTY
1. Shell Oil Co. #1 Purcell

WINKLER COUNTY
1. Gulf Oil Corp. #108-E Keystone

HUMBLE OIL & REFINING COMPANY NO. 2 EVELYN LINEBERRY

Top of Ellenburger—4,495 feet.
10,347—fossils very indistinct, apparently small gastropods similar to those in No. 6 "V" N.M. State. JB
10,426—*Hormotoma.*
Lower Ordovician—post-Tanyard, possibly Honeycut.

SHELL OIL COMPANY NO. 12 LOCKHART

Top of Ellenburger—8,655 feet.
8,702—*Hormotoma?.*
8,794—*Hormotoma, Ophileta (Ozarkispira).*
8,795—*Hormotoma.*
8,822 and 8,823—*Hormotoma.*
8,824—*Hormotoma?.*
8,827—*Hormotoma.*
Lower Ordovician—post-Tanyard, possibly post-Gorman.

Bandera County

G. L. ROWSEY NO. 2 FEE

Top of Ellenburger—4,495 feet.
6,268—*Pseudagnostus.*
6,299—small gastropods, small acrotretid brachiopods, linguloid fragments, trilobite fragments.
6,302—trilobite cross sections, *Billingsella, Huenella* cf. *H. texana* (Walcott).
6,311(?)—small gastropods, small acrotretid brachiopods, trilobite fragments, *Huenella* cf. *H. texana* (Walcott).
6,730, 6,741, and 6,796—linguloid fragments.
Upper Cambrian—the presence of *Huenella* cf. *H. texana* at 6,302 and 6,311 feet indicates a Franconia age for these horizons. The small acrotretids resemble some that have been recovered from post-*Elvinia* beds in the Morgan Creek limestone member of the Wilberns formation. The beds from 6,268 to 6,311 feet are probably equivalent in age to the Morgan Creek limestone member of the Wilberns formation. Dating of the lower section of this well, from 6,730 to 6,882 feet, on the basis of fossils cannot be refined beyond Cambrian.

Blanco County

ROLAND K. BLUMBERG NO. 1 WAGNER

Top of Ellenburger—130 feet.
2,565–2,575—*Apsotreta expansa* Palmer.
2,580–2,585—*Apsotreta expansa* Palmer, probably cavings.
Late Cambrian—uppermost Lion Mountain sandstone member of the Riley formation. WCB

Coke County

HONOLULU OIL CORPORATION NO. 1 WEBB

Top of Ellenburger—5,603 feet.
5,626—*Ophileta (Ozarkispira).*
Lower Ordovician—probably Gorman or high Tanyard.

HUMBLE OIL & REFINING COMPANY NO. F-90 ODOM

Top of Ellenburger—5,730 feet.
5,845–5,849 and 6,121–6,239—linguloid brachiopods at several depths. These are not stratigraphically definitive, and on fossil evidence the rock cannot be dated more closely than probably Paleozoic.

HUMBLE OIL & REFINING COMPANY NO. F-91 ODOM

Top of Wilberns—5,672 feet.
5,696—*Dicellomus.*
Upper Cambrian—all known authentic occurrences of *Dicellomus* in outcrop are of Dresbach age (Riley of Llano region). WCB

Collin County

HUMBLE OIL & REFINING COMPANY NO. 1 MILLER

Top of Arbuckle—9,152 feet.
9,160–9,170—ostracod resembling "*Eoleperditia*" in small chip; see discussion below.
9,334–9,337—includes samples at each foot, all about the same. The brachiopods *Pomatotrema* and *Diparelasma* occur in all samples, implying high Lower Ordovician equal to Black Rock formation or Smithville formation of the Ozark Mountains and high West Spring Creek formation of the Arbuckle Mountains. In addition, in samples from 9,336 feet, G. Arthur Cooper of the U. S. National Museum identified *Polytoechia* aff. *P. alabamensis* Ulrich and Cooper, indicating a similar age. The rock also contains several unidentified gastropod fragments, one possible *Lesueurilla;* an asaphid trilobite; and leperditiid ostracods. Conodonts obtained in residues were determined by W. H. Hass of the U. S. Geological Survey as *Scolopodus* and a distacodid type.

Jean Berdan of the U. S. Geological Survey comments as follows on ostracods from 9,334, 9,335, 9,336, 9,344, and 9,348 feet: "All of the collections appear to contain essentially the same ostracode fauna. This consists of leperditiids and small, smooth straight-hinged ostracodes probably referable to the "wastebasket" genus *Aparchites.* Unfortunately the preservation is such that details of hingement and overlap cannot be worked out, and in the case of the leperditiids, the muscle scars are very obscure. As far as can be determined, in the latter an adductor scar only is present, so that they can be referred provisionally to the genus *Eoleperditia.* As far as is known at the present time, *Eoleperditia* is confined to the Ordovician, and I suspect that if present, it is not common in the Upper Ordovician. However, until more studies are made of the leperditiids, this is only a supposition, based in part on the fact that the genus has not been found in the Bighorn dolomite and other Upper Ordovician rocks and is apparently replaced by *Leperditia (Herrmannina).*"

The faunal assemblage from the interval 9,334 to 9,348 feet is of special interest for its good preservation, variety, and unequivocal age significance. It is equivalent to some part of the high West Spring Creek strata of the Arbuckle Mountains, Smithville and Black Rock beds of the Ozark Mountains, the Odenville limestone of Alabama, and the Fort Cassin formation of Whitfield (1890) of Vermont.
9,344, 9,346, 9,347, 9,348, and 9,349—leperditiid ostracods abundant. Smooth, bean-sized ostracods like this have been reported below the highest Lower Ordovician only twice (Palmer, 1954, p. 774, and Frederickson, 1946, p. 578).

They are common in the Middle Ordovician and range upward to the Carboniferous, but these are surely high Lower Ordovician if in normal sequence in the well.

9,355–9,356—brachiopods as from 9,334 to 9,337 feet, but poorer specimens.

9,357—fragment of rather large smooth trilobite, brachiopods as above.

9,358 and 9,359—brachiopods as above.

9,360, 9,375, and 9,376—nothing recognizable, though fragments suggest about same as above.

9,443 and 9,446—poorly preserved orthoid brachiopods, possibly *Diparelasma?*.

9,505—trilobite cross sections and orthoid brachiopods, cf. *Diparelasma?*.

9,568—organic object suggesting *Ceratopea* and thus strata younger than the Cool Creek and Gorman formations.

9,580—cross section of a *Ptychonema*-like gastropod.

9,587—nothing recognizable.

9,696—cross section of straight cephalopod with eccentric siphuncle and annular external ridges centered on camerae. If seen out of context this would suggest post-Lower Ordovician, but overlying fossils invalidate so high a position.

9,705—*Archaeorthis?*; probably younger than the Cool Creek and Gorman formations.

9,711—unidentified long, twig-like sponges up to 5 mm diameter with 3-mm cloacal cavity and extending to lengths of 5 cm without showing any sign of branching. Vaguely resembles a smaller diameter, unbranched *Lissocoelia*, which is found in high beds of the Pogonip group (high Lower Ordovician) in Nevada.

9,734—cross sections of small orthoid brachiopods and gastropods, one of the latter suggesting *Hormotoma?*.

9,745, 9,746, and 9,748—*Diparelasma.*

9,777—*Diparelasma?, Archaeorthis?.*

9,780—*Archaeorthis?*, also the gastropod *Lesueurilla*, which occurs in middle Jefferson City dolomite through Powell dolomite in the Ozarks.

9,796—asaphid trilobite.

9,803—*Archaeorthis?.*

10,441—unidentified nautiloid cephalopod and *Hormotoma?*, presumably at least younger than McKenzie Hill formation.

10,643—something that could be a piloceratid siphuncle, in which case a Cool Creek or Kindblade age might be suggested.

10,649 and 10,656—lithistid sponge resembling *Archaeoscyphia* or *Calathium;* probably equivalent to beds of Kindblade or Cool Creek age.

10,872 and 10,875—lithistid sponge resembling *Archaeoscyphia* or *Calathium.*

10,879—lithistid sponge resembling *Archaeoscyphia* or *Calathium.*

10,883—*Euconia?.*

10,884, 10,885, 10,886, and 10,973—algal pisolites and nodules. Lithistid sponge resembling *Archaeoscyphia* or *Calathium.*

10,992—lithistid sponge resembling *Archaeoscyphia* or *Calathium.* Specimen retained in U.S.G.S. collections.

10,994—lithistid sponge; also macluritid gastropod, possibly *Barnesella?*. Probably Kindblade.

10,997—an unusual *Hormotoma*-like gastropod that suggests *Hormotoma dubia* Cullison of the lower Jefferson City beds and equivalence to the Kindblade formation.

11,008—*Archaeoscyphia?.*

11,011—*Archaeoscyphia?.* Cross section of gastropod that suggests *Orospira?*. Probably Kindblade.

11,012—*Archaeoscyphia?.*

11,020—cf. *Archaeoscyphia?, Hormotoma?.*

11,021—*Ophileta (Ozarkispira?)*; probably Cool Creek.

11,027—*Ophileta;* probably Cool Creek, although by itself it could be McKenzie Hill.

11,038—*Hormotoma.*

11,045—raphistominid gastropod.

11,046—*Euconia?, Ophileta;* probably Cool Creek.

11,060 and 11,078—*Ophileta* sp.

11,111—*Hormotoma.*

11,118 and 11,124—lithistid sponge, probably *Archaeoscyphia.*

11,131—stromatolitic lamination, indicating shoal-water deposition.

11,134—lithistid sponge, cf. *Archaeoscyphia;* post-McKenzie Hill.

11,153—*Hormotoma?.*

11,278—chertified stromatolitic laminae, indicating shoal-water deposition.

The material from this well looks mainly high in the Lower Ordovician and resembles the Arbuckle rather than the Ellenburger sequence.

The *Pomatotrema, Diparelasma,* and *Polytoechia* at 9,334 to 9,337 feet indicate that the top of the sequence is very high Lower Ordovician—about equivalent to Smithville or even Black Rock beds in the Ozark section or high West Spring Creek in the Arbuckles, and much higher than the highest surface Ellenburger. At 9,745 to 9,749 feet *Diparelasma* indicates something above the Kindblade formation (probably post-Cotter of the Ozark section), and *Diparelasma?* is still present at 9,777 feet. Thus at least the top 400 to 450 feet or so of the sequence is post-Ellenburger and, on fossils and lithology, could be called West Spring Creek down to perhaps 9,780 feet or lower, where *Lesueurilla* and *Archaeorthis?* are found.

Lithistid sponges suggesting *Archaeoscyphia* or *Calathium* are common from 10,649 to 11,134 feet. They are associated with gastropod cross sections that suggest *Hormotoma* (several levels), *Barnesella* (10,994 feet), and *Orospira* (11,011 feet), and a *Hormotoma* at 10,997 feet suggests *H. dubia* Cullison, a lower Jefferson City species. This suggests downward transition from West Spring Creek to Kindblade beds somewhere between 9,800 and 10,600 feet, with Kindblade (Honeycut equivalent) beds between 10,649 and 11,134 feet, more or less.

Below 11,134 to 11,153 feet the general complexion of the fossils (all susceptible to misidentification) suggests Cool Creek (Gorman equivalent) beds.

Altogether then the sequence in Humble Oil & Refining Company No. 1 Miller appears to represent beds that range from about upper Cool Creek through most of the West Spring Creek of the Arbuckle section, but in a more magnesian phase than the surface exposures. No evidence of beds lower than Cool Creek (Gorman) was seen, however.

Crane County

Humble Oil & Refining Company No. 1-C Jax Cowden

Top of Ellenburger—9,015 feet.

9,121.5—The following report on material from this level was made by Josiah Bridge: "The long, slender gastropods that are so abundant in the Cowden and Harvick cores and which are present in the Cox core belong to the genus *Coelocaulus*, a genus common to Ordovician and Silurian rocks. It is distinguished from similarly shaped forms commonly referred to as *Hormotoma* by the hollow columella. The earliest described species are from rocks of Chazy age, but Ulrich identified the genus in the Cotter dolomite of Missouri and in the partially equivalent Newala formation of Alabama. A very poor specimen from this latter horizon was figured by Butts, Geol. Alabama, Special Rept. 14, 1926, pl. 17, figs. 5–7. Because of poor preservation and general lack of knowledge of these early Ordovician forms, it has probably often been identified as *Hormotoma*. Fragments of other gastropods, too poor for generic identification, are present in all three cores. *Coelocaulus* is not listed by Cloud and Barnes from the Ellenburger of the Central Hill country. Judging from its occurrence in Missouri and the southern Appalachians, if it does occur in the Ellenburger, it might be found near the top of the Honeycut formation, but it is more likely that it represents a slightly younger horizon, possibly one of the upper "*Hormotoma*" zones of the Beach Mountain section of the El Paso limestone.

"Dr. J. Brookes Knight of the U.S.N.M. and I working independently arrived at the same conclusions: 1. that the same form is represented in all three collections, and that it is a *Coelocaulus;* and 2. that the stratigraphic horizon is probably the same in all three wells, or at least that they are very close to the same horizon.

The speculations regarding age are to be attributed to me alone." JB

Humble Oil & Refining Company No. 3 Jax Cowden

Top of Ellenburger—8,804 feet.

8,913—*Hormotoma?*. Lower Ordovician—post-Tanyard?.

8,919—many fragments of gastropods, one longitudinal section of a small *Hormotoma*-like form, ½-inch long, ¼-inch wide, 5 rounded whorls. JB

Crockett County

Continental Oil Company No. E-1 Harris

Top of Ellenburger—10,025 feet.

10,138—*Hormotoma??*. Suggests post-Tanyard, possibly post-Gorman.

Humble Oil & Refining Company No. 1 Alma Cox

Top of Ellenburger—7,715 feet.

8,139—dolomite, light gray, finely and evenly crystalline, many thin beds of silicified fossils. Fossils are small hormotomids up to 10 mm long, 2 mm wide, with 5 to 6 well-rounded whorls. Suggests the *H. gracilis* bed in the Cotter of Missouri. Residue almost entirely spongy fragments of these shells. JB

(The Ellenburger group of surface outcrop in central Texas is all pre-Cotter. PEC)

Humble Oil & Refining Company No. 1-C Alma Cox

Top of Ellenburger—8,130 feet.

8,387—some fragments *might* be *Hormotoma.*

8,440—*Coelocaulus?;* see Bridge's report for Humble Oil & Refining Company No. 1-C Jax Cowden.

8,448—*Hormotoma?* (or *Coelocaulus?*), *Euconia?*.

8,468—abundant *Hormotoma.*

Lower Ordovician—higher than Tanyard, probably Honeycut.

Humble Oil & Refining Company No. 1-D Alma Cox

Top of Ellenburger—7,293 feet.

7,591, 7,636, 7,637, 7,641, and 7,659—mainly unidentifiable gastropod cross sections, including possible *Hormotoma?*.

7,665 and 7,666—*Hormotoma* abundant.

7,679—*Hormotoma* abundant, possible *Orospira?*, endoceratid cephalopods.

7,685—*Orospira?*. Probably Honeycut.

7,687—*Hormotoma.*

7,688—small hormotomoid gastropods. JB

7,699—*Hormotoma.*

7,709 and 7,735—*Hormotoma.*

7,774—*Hormotoma* abundant, possible *Orospira?*, endoceratid cephalopods. Post-Tanyard and probably post-Gorman.

Lower Ordovician—higher than Tanyard, probably all Honeycut.

Humble Oil & Refining Company No. 2 Harvick

Top of Ellenburger—8,393 feet.

8,493—*Hormotoma.*

8,498—attenuate-spired *Hormotoma* abundant, *Orospira?*, *Archaeoscyphia?*, endoceratid cephalopod.

8,501—small stromatolitic humps.

8,502—unidentified sections of gastropods and cephalopods, some of which might be pieces of *Hormotoma?*.

8,505—*Coelocaulus?*.

Lower Ordovician—post-Tanyard, probably Honeycut.

The Superior Oil Company No. 1-27 University

Top of Ellenburger—7,005 feet.

7,035.5–7,037—*Hormotoma?*.

7,119–7,121.5—*Hormotoma.*

7,242—*Hormotoma?*.

Lower Ordovician—higher than Tanyard, possibly post-Gorman.

Eastland County

Luling Oil Company No. 1 Blackwell

Depth not given—*Hormotoma* sp.
Lower Ordovician—post-Tanyard and probably post-Gorman.

Ector County

Cities Service Oil Company No. 1-E Foster

Top of Ellenburger—12,910 feet.
13,037, 13,085, 13,087, 13,088—*Hormotoma*. Post-Tanyard, probably post-Gorman.

Humble Oil & Refining Company No. 22 Yarbrough & Allen

Top of Ellenburger—10,536 feet.
10,557—many small gastropod fragments. A single longitudinal section of a gastropod 17 mm long, 3½ mm wide, with at least 9 whorls (tip missing probably about 3 whorls), apical angle less than 10°, probably *Coelocaulus*. JB
10,559—a few fragments of fossils, 1 section across a gastropod whorl 6.5 mm across. JB
Probably upper part of Lower Ordovician.

Shell Oil Company No. D-10 University

Top of Ellenburger—8,740 feet.
8,782—*Hormotoma?*.
Lower Ordovician—probably post-Tanyard.

Edwards County

Humble Oil & Refining Company No. 1 J. H. Guthrie

Top of Ellenburger—3,950 feet.
3,963—*Hormotoma* and other gastropod fragments.
3,966–3,969—*Hormotoma?*.
3,969–3,972—*Orospira*.
3,976—*Orospira, Hormotoma*, unidentified gastropods and cephalopod.
3,996–3,997—*Hormotoma*.
4,010—coiled nautiloid cephalopod with diverging living chamber, probably a tarphyceratid.
4,023—*Orospira?*.
4,060—*Orospira*.
Lower Ordovician—equivalent to Honeycut formation.

The Texas Company No. 1 Phillips

Top of Ellenburger—5,091 feet.
5,182, 5,187, and 5,188—*Hormotoma*.
5,189—*Hormotoma, Euconia?, Orospira?, Ceratopea?*, small endoceratid cephalopod.
5,190 and 5,191—*Hormotoma*.
5,225–5,226—*Orospira*. Retained part in U.S.G.S. collections.
5,233—*Ceratopea*, also digitate stromatolites (?) like those at 4,343 to 4,344 feet in Magnolia Petroleum Company No. 1, Below Kendall County.
5,250—*Orospira?*.
5,274—*Hormotoma?*.
Lower Ordovician—Honeycut similar to that in Magnolia Petroleum Company No. 1 Below, Kendall County.

Gray County

Phillips Petroleum Company No. 2 Delp

Top of Ellenburger—11,073 feet.
11,181–11,182—*Hormotoma?*.
11,226–11,227—*Hormotoma*.
11,303–11,314—*Hormotoma?*.
11,335–11,336—*Hormotoma?*.
11,336–11,340—*Hormotoma*, a long slender species.
11,339–11,340—*Hormotoma*.
11,371–11,372—*Euconia*.
11,384–11,385—*Hormotoma?*.
11,408–11,417—*Hormotoma*, large attenuate species.
Lower Ordovician—probably equivalent to the Honeycut formation.

Grayson County

The Superior Oil Company No. 1 J. E. Henderson

Top of Arbuckle—6,095 feet.
6,129–6,130—*Hormotoma*.
6,237–6,250—*Hormotoma?*.
6,405–6,406—leperditiid ostracods which Jean M. Berdan identifies as "of the type of *Isochilina armata* (Walcott), on basis of prominent ventral spine." This type of leperditiid occurs in beds of Black River age, the Simpson equivalent east of the Mississippi.
6,443–6,446—as above.
6,503–6,505—*Hormotoma?*.
6,529–6,533—*Hormotoma?*.
Fossils at 6,405 to 6,446 identified by Jean M. Berdan as Middle Ordovician (Black River) types. Others could be Middle Ordovician, although by themselves they are more suggestive of Lower Ordovician (post-Tanyard).

The Superior Oil Company No. 1 S. L. Privette

Top of Arbuckle—7,708 feet.
7,768–7,769—unidentified small stromatolitic balls.
7,846–7,847—*Hormotoma?*.
7,858–7,861—*Hormotoma?*, unidentifiable orthoid brachiopod.
7,868–7,869—*Pomatotrema, Diparelasma*.
High Lower Ordovician, equivalent to Black Rock, Smithville, or high West Spring Creek beds, roughly equivalent to beds at 9,334–9,337 in Humble Oil & Refining Company No. 1 Miller.
7,903–7,904—Trepostomatous bryozoa—presumably extraneous material of Simpson age.
7,903–7,905—unidentified brachiopod fragments.
All except 7,903–7,904 is Lower Ordovician, equivalent to West Spring Creek beds of Arbuckle group and lithically similar to them.

Hutchinson County

Gulf Oil Corporation No. 1 Amarillo National Bank

Top of Ellenburger—8,180 feet (Gulf).
8,280–8,281—*Hormotoma?*.
Lower Ordovician—probably post-Tanyard.

Irion County

The Atlantic Refining Company No. 1 Noelke

Top of Ellenburger—7,357 feet.
7,769—*Dicellomus*. WCB
7,780, 7,782, and 7,788—linguloid fragments.
7,792—*Dicellomus*.
All known authentic occurrences of *Dicellomus* in outcrop are early Late Cambrian (Dres-

bach), the Riley formation in the Llano region. WCB

Kendall County

MAGNOLIA PETROLEUM COMPANY NO. 1 BELOW

Top of Elenburger—3,977 feet.

4,008—*Hormotoma??*.

4,050, 4,051, 4,096, and 4,114—unidentified cross sections of gastropods and trilobites, one recognizable *Hormotoma* at 4,114 feet.

4,194–4,194.5—much trilobite debris and some gastropod sections, including *Hormotoma*.

4,219 and 4,220—abundant trilobite and gastropod cross sections and *Archaeoscyphia* fragments.

4,220.5—abundant *Archaeoscyphia;* most likely Honeycut. Limestone also contains burrow-like features with wrinkles of agglutinated-looking grains around aphanitic centers, possibly representing the tubes of large marine annelids.

4,221.5—*Archaeoscyphia* bits and unidentified trilobite and gastropod cross sections in limestone.

4,223—*Hormotoma*.

4,252—*Hormotoma, Orospira?*.

4,253.5, 4,256.5, and 4,257—*Archaeoscyphia* sp. in limestone, stromatolitic crusts and fingers, trilobite and gastropod cross sections.

4,272.5, and 4,273—*Archaeoscyphia* in chert.

4,319—*Archaeoscyphia* in chert, *Hormotoma?*.

4,320.5—*Archaeoscyphia* in chert, *Hormotoma?, Orospira?*.

4,323, 4,323.5, and 4,324—*Archaeoscyphia, Hormotoma?, Ophileta (Ozarkispira)??*.

4,335—*Orospira?*.

4,338—*Archaeoscyphia*.

4,343, 4,343.5, and 4,344—digitate sediment-binding types of stromatolites, or very odd borings; also *Hormotoma*.

4,415—*Archaeoscyphia, Hormotoma*.

Beds between 4,415 and 4,008 are all Lower Ordovician and very probably equivalent to the Honeycut formation.

6,338—*Elvinia* sp., *Pterocephalia* cf. *P. occidens* (Walcott), *Linnarssonella*.

6,348—*Pterocephalia* cf. *P. occidens* (Walcott), *Linnarssonella*.

6,363—*Apsotreta expansa* Palmer.

6,379—forms intermediate between *Apostreta expansa* Palmer and *Angulotreta triangularis* Palmer.

6,388—*Angulotreta triangularis* Palmer, *Aphelaspis*.

The material from 6,338 to 6,388 correlates almost entirely with the Lion Mountain sandstone member of the Riley formation. The upper 10 feet may be partly equivalent in age to the basal Welge sandstone member of the Wilberns formation.

Trilobites or phosphatic brachiopods, or both, were recovered from five levels in the core. The most useful fossils were the brachiopods. On the basis of the stratigraphic sequence worked out from surface exposures, it is possible to correlate the well core with the White Creek section in Blanco County. The faunal change from *Angulotreta* to *Apsotreta* is a useful marker level. The correlation of the fossils at 6,379 feet in the Below core with those from beds of the Lion Mountain sandstone member between 779 and 784 feet above the base of the White Creek section on the surface (Palmer, 1954, p. 785) is about as accurate a correlation as can be made.

The dating of the collection at 6,338 feet as Franconia in age is based on the presence of *Linnarssonella* and also of an *Elvinia*. The presence of *Linnarssonella* and *Pterocephalia* cf. *P. occidens* at 6,338 and 6,348 feet, and the fact that the *Elvinia* is not *E. roemeri* but a granular form possibly related to *E. granulosa* Resser from the Dunderberg shale in Nevada support the dating as very early Franconia. *Pterocephalia* cf. *P. occidens* is also present in rocks of late Dresbach age (795 feet above base of White Creek section) and is stratigraphically older than the common Texas form *P. sanctisabae*.

Kerr County

G. L. ROWSEY NO. 2 NOWLIN

Top of Ellenburger—5,320 feet.

7,369—*Tricrepicephalus, Kingstonia*.

7,370—*Tricrepicephalus, Meteoraspis, Kinsabia variegata* Lochman, *Dicellomus?, Protillaenus*.

Upper Cambrian—these two collections represent the lower *Coosella* zone of Dresbach age in the Riley formation. They are probably slightly younger than the fossiliferous beds of Dresbach age in Tucker Drilling Company No. 1 Dr. Roy E. Perkins.

TUCKER DRILLING COMPANY NO. 1 DR. ROY E. PERKINS

Top of Ellenburger—570 feet.

1,573–1,576—*Hormotoma??* or small *Sinuopea?*, unidentified brachiopod sections. Suggests post-Tanyard or even post-Gorman, but stratigraphic position based on such poor fossils is of course very uncertain.

2,540—*Apsotreta expansa?*.

Upper Cambrian—uppermost Lion Mountain sandstone member(?), Riley formation. WCB

2,836—calcareous alga(?) (see Lochman, 1940, Pl. 2, figs. 4–6).

2,839—agnostid, *Apsotreta orifera* Palmer, *Paterina, Opisthotreta?, Chancelloria*-type spicule, linguloid fragments, calcareous alga(?).

2,840—*Apsotreta orifera* Palmer, coosellid trilobite.

2,841—*Syspacheilus, Meteoraspis*, calcareous alga(?).

2,852—coosellid trilobite, *Meteoraspis*.

2,855—*Apsotreta orifera* Palmer, chancelloria-type spicules.

Upper Cambrian—the beds from 2,836 to 2,855 feet belong to the *Cedaria-Cedarina* zone and are approximately equivalent in age to the upper part of the lower limestone unit of the Cap Mountain limestone member of the Riley formation as seen in surface section in the southern part of the Llano region.

Lubbock County

HUMBLE OIL & REFINING COMPANY NO. 1 FARRIS

Top of Ellenburger—11,445 feet.

11,679–11,684—*Dicellomus?*.

Upper Cambrian. WCB

Midland County

Magnolia Petroleum Company No. 1 Nobles

Top of Ellenburger—13,367 feet or higher.
13,367—has sponge spicules that are *not Archeoscyphia*, pseudo-spicular chert that could be mistaken for *Archaeoscyphia*, and a septate structure that might be a piece of a cephalopod, but nothing identifiable.
No opinion is warranted on age or correlation on the basis of these samples.

Magnolia Petroleum Company No. 2-A Windham

Top of Ellenburger—12,571 feet.
13,009.5—*Hormotoma.*
13,009–13,011—*Hormotoma?.*
13,035–13,036.5 and 13,036.5–13,038—*Hormotoma?.*
Lower Ordovician—post-Tanyard, probably post-Gorman.

Nolan County

General Crude Oil Company No. 1 George Cave

6,248—merostome fragments, cf. *Aglaspis.*
6,249—saukiid trilobites.
6,253 and 6,255—merostome fragments?.
6,258, 6,260—linguloids.
The merostome fragments have a pustulose surface, indicating, according to Raasch (1939, pp. 52, 53), either *Aglaspis* or *Aglaspella.* The size and distribution of the pustules on the fragments is more suggestive of *Aglaspis.* Both genera are recorded only from the Late Cambrian, beds of late Franconia and Trempealeau age. The presence of a saukiid trilobite at 6,249 feet that resembles *Saukia* or *Tellerina* suggests that the beds with the merostomes and saukiids in this well are of Trempealeau age.

Honolulu Oil Corporation No. 2 Whitaker

Ellenburger absent. Top of Wilberns—5,521 feet.
5,539–5,540—aglaspid merostome fragment.
5,615–5,616, 5,620–5,621, and 5,621–5,622—*Linnarssonella?.*
5,622–5,623 and 5,631–5,638—linguloid of the *Elvinia* zone type.
Upper Cambrian—below 5,615 feet equivalent to lower part of Morgan Creek limestone member, Wilberns formation. WCB

Kilroy Company of Texas No. 1 Roberts

Ellenburger absent (?). Top of Wilberns—6,038 feet.
6,082–6,083—linguloid scraps.
6,093–6,094—a scrap of a trilobite thoracic segment. It is not possible to determine if the trilobite is a Cambrian form, and although the probabilities are that the trilobite-bearing sand is Cambrian, neither horizon can be dated more closely than Paleozoic on the fossil evidence.

Seaboard Oil Company No. 1 TXL "C"

Top of Ellenburger—6,029 feet.
6,042 and 6,043—in one thin section is a hint of a possible longitudinal section of a dasycladacean alga. The only dasycladaceans seen in the Ellenburger of the Llano region are upper Tanyard; the modern ones live exclusively in shallow tropical or subtropical waters.
6,052 and 6,055—a hint of dasycladacean algae.
This might be about equivalent to the upper Tanyard formation, Lower Ordovician.

Skelly Oil Company No. 1 Ater

Top of Ellenburger—7,087 feet.
7,082—*Hormotoma?*, probably reworked.
7,139—*Hormotoma?.*
Lower Ordovician—probably post-Tanyard.

U. S. Smelting, Refining & Mining Company No. 3 TXL "A"

Top of Ellenburger—5,904 feet.
6,241—linguloids.
6,246—linguloid, "*acuminatus*" type.
6,248—merostome fragment.
6,249—linguloid fragments.
6,257—a scrap of a merostome. It is not possible from this specimen to date more accurately than Upper Cambrian. Not enough of the specimen is preserved to eliminate the only Dresbach genus, *Beckwithia.* As described merostomes are much more common in rocks that correlate with the Wilberns formation, of post-Dresbach age, the chances are that this is the Wilberns or an equivalent unit.
6,261—merostome fragment, cf. *Aglaspis.*
On the basis of the pustulose merostome fragment possibly representing *Aglaspis* in 6,261, this horizon is probably no older than late Franconia in age.

Pecos County

Phillips Petroleum Company No. 1-C Puckett

Top of Ellenburger—13,205 feet.
13,238—stromatolitic laminae, no age significance but implies very shallow water.
13,323—several slices through an object that may be an endoceratid cephalopod.
13,471–13,472 and 13,473—*Hormotoma.*
14,227—a small macluritid-like gastropod such as is characteristic of relatively high Lower Ordovician beds.
14,239—unrecognizable gastropod cross sections, one of which suggests *Euconia.*
14,299, 14,318, and 14,342—unrecognizable gastropod sections, some suggest *Hormotoma??* and *Euconia??.*
14,478—*Hormotoma?* and cross section of unidentifiable endoceratid cephalopod.
14,505—cross sections of unidentifiable gastropods, one of which suggests *Euconia, Hormotoma?.*
Lower Ordovician—post-Tanyard, probably Honeycut, and perhaps post-Honeycut above 14,500 feet or so.

Standard Oil Company of Texas No. 2-1 Claude Owens

Top of Ellenburger—9,408 feet.
9,354—*Receptaculites.*
Post-Lower Ordovician and pre-Carboniferous. Probably Simpson and possibly high Simpson.

Presidio County

Gulf Oil Corporation No. 1 Mitchell Bros.—State

Top of Ellenburger—15,230 feet.
15,372—cross section possibly *Ceratopea?*, thus Honeycut (?) or higher.
15,703—*Hormotoma.*
15,708—*Hormotoma.*
Lower Ordovician—post-Tanyard, probably Honeycut or younger.

Real County

Stanolind Oil & Gas Company No. 1 Knippa

Top of Ellenburger—7,224 feet.
7,412—partial cross sections suggest incomplete *Orospira?.*
Lower Ordovician—Honeycut if suggested identification is correct.

Roberts County

Gulf Oil Corporation No. 1 John Haggard

Top of Ellenburger—12,207 feet (Gulf).
12,262–12,263—*Hormotoma* (sample retained in U.S.G.S. collections).
12,290–12,299—*Hormotoma?.*
12,365–12,366—*Orospira?.*
Lower Ordovician—possibly equivalent to Honeycut formation.

Schleicher County

American Trading & Production Corporation No. 1 Sauer

Top of Ellenburger—7,136 feet.
7,649—linguloid fragments, *Hyolithes,* saukiid trilobites, high-spired gastropod.
7,650—a small, subspherical gastropod and a probable merostome fragment.
As gastropods of this form are not known from rocks older than latest Cambrian and merostomes are not known from post-Cambrian rocks, this horizon is most probably in the upper part of the Wilberns formation or an equivalent unit.
7,655—merostome fragments, cf. *Aglaspis.*
The similarity in lithology and fauna between the material from 7,649 to 7,655 feet and the fossiliferous levels in General Crude Oil Company No. 1 George Cave suggests that they are correlative and of latest Cambrian, Trempealeau, age.

Magnolia Petroleum Company No. 1 Mary Ball

Top of Ellenburger—4,408 feet.
4,455–4,456—*Orospira?.*
4,457—lithistid sponge, cf. *Archaeoscyphia, Hormotoma?,* coiled nautiloid cephalopod, "cannonball chert."
4,457–4,458—*Archaeoscyphia, Ophileta.*
4,458—*Archaeoscyphia.*
4,464—small *Ophileta*-like gastropods, *Hormotoma?.*
4,468–4,471—*Hormotoma;* also, at 4,469, a small *Ophileta* or *Liospira*-like gastropod resembling, except in size, *Liospira? depressa* Cullison.
4,484—lithistid sponge, cf. *Archaeoscyphia.*
4,485—*Orospira, Hormotoma.*
4,499—*Hormotoma?.*
4,514—*Hormotoma, Orospira?.*
4,515—*Hormotoma, Orospira?, Ophileta.*
4,516—*Hormotoma?.*
4,517—*Raphistomina?.*
4,518—*Hormotoma?.*
4,543—*Hormotoma?.*
4,547–4,548—*Hormotoma, Orospira?.*
4,548—*Orospira?, Raphistomina?.*
4,550—*Hormotoma, Orospira?, Raphistomina?.*
4,554—*Orospira?.*
4,555—*Orospira.*
4,578—*Orospira?, Hormotoma,* "cannonball chert."
4,580—*Hormotoma.*
4,581—*Hormotoma, Raphistomina?.*
4,581–4,582—*Hormotoma,* "cannonball chert"?
4,595—*Hormotoma.*
4,596—*Hormotoma?.*
4,618—*Hormotoma, Ophileta.*
4,657—*Hormotoma?.*
Lower Ordovician—probably equivalent to Honeycut formation from highest samples studied down through 4,596 and perhaps lower. However, 4,618 and 4,657 *could* be equivalent to top of Gorman formation or bottom of Honeycut formation.

Scurry County

American Trading & Production Corporation No. 1 Elmer Howell

Top of Ellenburger—7,380 feet.
7,400—*Hormotoma.*
Probably Lower Ordovician—higher than the Tanyard formation and probably higher than the Gorman formation of the Ellenburger group.

Humble Oil & Refining Company No. 1-B B. A. Moore

Top of Wilberns—8,196 feet or higher.
8,210—nothing organic recognizable, but the dolomitic rock contains tiny green grains suggesting glauconite and looks clastic textured.
8,216—an obscure structure *might* prove to be *Sinuopea if* it were determinable.
Position uncertain, although weak evidence hints it might be Cambrian or basal Ordovician.

Stonewall County

Seaboard Oil Company No. 4 Upshaw

Top of Ellenburger—5,885 feet.
6,144, 6,146, 6,149, 6,156, 6,160, 6,164, 6,190—no recognizable fossils in any sample. Interstitial glauconite (and pyrite) and color and texture of dolomite resemble upper Wilberns (Upper Cambrian).

Sutton County

Humble Oil & Refining Company No. 1 J. D. Harrison

Top of Ellenburger—6,790? feet.
6,872—*Orospira* sp.
6,875—*Hormotoma?, Orospira?.*
6,879, 6,880, 6,881, 6,886, and 6,888—*Hormotoma* abundant.
6,916—*Hormotoma* abundant.
Lower Ordovician—entire interval is probably of Honeycut age.

Tom Green County

C. L. McMahon No. 1 J. W. Johnson

Ellenburger absent. Top of Wilberns—5,529 feet.
5,600—saukiinid trilobites (see Appendix B, p. 631).
5,610–5,636—unidentified trilobite, aglaspid merostome fragments, bellerophontid snail.
Upper Cambrian—upper Wilberns. WCB

Upton County

Gulf Oil Corporation No. 1 McElroy-State

Top of Ellenburger—11,602 feet.
12,150–12,152—gastropod cross sections that suggest a large, high-spired, strongly keeled, many-whorled *Orospira* of the type of *O. gainesvillensis* Cullison or a small high-spired *Ophileta* of the type of *Ophileta (Ozarkispira)* cf. *O. rotuliformis* (Meek). A post-Tanyard age is certain, and *O. gainesvillensis* is a form in the upper part of the Jefferson City dolomite in Missouri. Probably high Honeycut.
12,298—*Orospira?*.
12,346—*Orospira?*.
12,419—unidentified endoceratid cephalopod.
12,620—*Hormotoma?*.
12,668—*Hormotoma?*.
Lower Ordovician—whole sequence probably Honeycut or higher, but this is not based on any *sure* identification.

Humble Oil & Refining Company No. 1 Z. Oswalt

Top of Ellenburger—11,906 feet.
12,012.5—etched surfaces show wavy stromatolitic structure, small *Hormotoma* on corner of one piece suggests Honeycut formation or higher in the Lower Ordovician.

Sohio Petroleum Company No. 1 Hill Estate

12,396—fossils include both high- and low-spired forms, the former suggesting *Hormotoma* or *Coelocaulus*. Lithology and fossils strongly resemble those from the Humble Oil & Refining Company No. 1-C and No. 3 Jax Cowden wells in Crane County and suggest a correlation, with all of high Lower Ordovician age.

Wilshire Oil Company No. 23-118 Windham

Top of Ellenburger—12,293 feet.
12,329—possibly *Hormotoma?*.
Possibly post-Tanyard.

Williamson County

Shell Oil Company No. 1 Purcell

Top of Ellenburger—6,940 feet.
9,394–9,410 and 9,450–9,460—"*Dicellomus*" *mosaica* (*Conaspis* zone).
Upper Cambrian—upper part of Morgan Creek limestone member, Wilberns formation. WCB

Winkler County

Gulf Oil Corporation No. 108-E Keystone

Top of Ellenburger—8,875 feet.
8,951 and 8,959—dolomitized pelmatozoan debris probably younger than Ellenburger, but no identifiable fossils found.
9,244 and 9,245—*Hormotoma.*
9,277—gastropod cross sections suggest a post-Tanyard form.
9,602—many cross sections of a small gastropod suggest tiny *Sinuopea* or individual whorls of *Hormotoma.* If this were a *Sinuopea* a Tanyard (or Late Cambrian) age would be implied, but data from other wells in this area suggest that the Tanyard is missing so it is probably *Hormotoma.*
Probably post-Ellenburger from 8,951 to 8,959 feet. Ellenburger from 9,244 feet down through samples studied. From 9,277 feet up, at least, suggests post-Tanyard and possibly post-Gorman.

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Examination of Pre-Simpson Paleozoic Rocks for Insoluble Fossils

EUGENE J. TYNAN[5]

ABSTRACT

Four hundred sixty-one samples from twenty-one localities, both surface and subsurface, were examined for insoluble fossil content. The samples were mostly from the Lower Ordovician, some from the Upper Cambrian, and a few from immediately overlying rocks of the Middle Ordovician Simpson group. All of the samples are essentially barren of insoluble fossils.

INTRODUCTION

The search for insoluble fossils in pre-Simpson rocks was carried out at the University of Massachusetts under the direction of Dr. L. R. Wilson, Chairman of the Department of Geology. Ten-gram cuts of crushed samples prepared as described on page 90 were used in this study; location of wells examined for insoluble fossil content is shown in figure 10.

Preliminary examination of a few samples indicated the presence of organic objects which could be assigned to the Hystrichosphaerida. By the time the study was completed, it was concluded that no insoluble organic remains were present which could be assigned to any known or problematic fossil group.

The fossils insoluble in hydrochloric and hydrofluoric acid most likely to be present in lower Paleozoic rocks are the chitinozoans and the hystrichosphaerids, the latter being probably the more important of the two groups. The hystrichosphaerids are single-celled microscopic organisms whose general shape is spherical, angular, or elliptical. The central body may be very thin, may have a variable number of appendages arranged in a radial manner, or may be smooth. The appendages may be spines, simple and bifurcated processes, cilia, or tubes. The size of the central capsule and the number, size, and type of appendages permit distinction between groups, although the size and shape of the appendages may vary in the same individual. The wall of the hystrichosphaerids varies generally from colorless to amber and black.

HISTORY OF INSOLUBLE-FOSSIL RESEARCH

Fossils which are now placed in the order Hystrichosphaerida were first reported by Ehrenberg (1836) from the Cretaceous flints of Europe. Ehrenberg described these organisms as a species of *Xanthidium*, zygospores of a desmid genus. In North America, White (1862) applied the name *Xanthidium* to microfossils found in mid-Devonian hornstones of New York. In Europe, Rothpletz (1880) described similar fossils from the Saxony (Cretaceous) cherts under the name of *Sphaerosomatites*. Wetzel (1933) proposed the name *Hystrichosphaera* to include all microfossils formerly called *Xanthidium*. Wetzel did not believe these organisms were algae but that they were related to the dinoflagellates of the phylum Protozoa. Deflandre (1937) described numerous new species and several new genera from Cretaceous flints of Europe. Eisenack (1938) and Deflandre (1945) have described an abundant hystrichosphaerid fauna from Silurian rocks of France and Germany. Both Deflandre and Eisenack were in accord with the classification of the hystrichosphaerids established by Wetzel (1933).

Bashnagel (1942) described a hystrichosphaerid fauna from the Onondaga chert of central New York. He considered

[5] Department of Geology, University of Oklahoma.

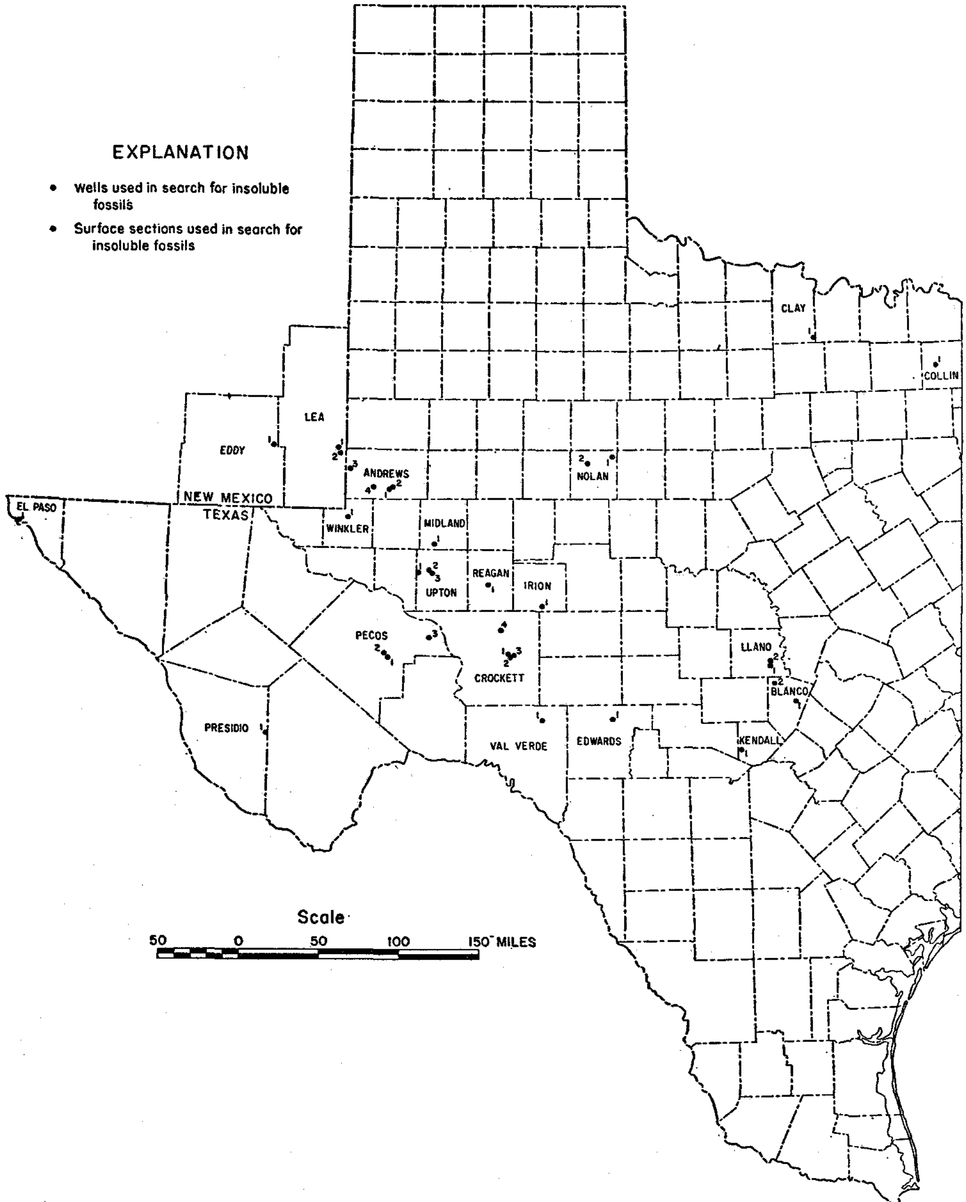

FIG. 10. Map showing wells and surface sections used in search for insoluble fossils.

Fig. 10, explanation (continued)—

NEW MEXICO

ANDREWS COUNTY

1. Richardson & Bass #1 Federal-Cobb

LEA COUNTY

1. Continental Oil Co. #1 Burger B-28
2. Shell Oil Co. #5 State

TEXAS

ANDREWS COUNTY

1. Gulf Oil Corp. #1-E State "AM"
2. Gulf Oil Corp. #1 Texas "000"
3. Humble Oil & Rfg. Co. #2 Evelyn Lineberry
4. Humble Oil & Rfg. Co. #37 Parker

BLANCO COUNTY

1. Honeycut Bend section
2. White Creek section

CLAY COUNTY

1. Deep Rock Oil Corp. #1 Moore Estate

COLLIN COUNTY

1. Humble Oil & Rfg. Co. #1 Miller

CROCKETT COUNTY

1. Humble Oil & Rfg. Co. #1-C Alma Cox
2. Humble Oil & Rfg. Co. #1-D Alma Cox
3. Humble Oil & Rfg. Co. #1-E Alma Cox
4. The Superior Oil Co. #1-27 University

EDWARDS COUNTY

1. The Texas Co. #1 Phillips

EL PASO COUNTY

1. Franklin Mountains section

IRION COUNTY

1. The Atlantic Rfg. Co. #1 Noelke

KENDALL COUNTY

1. Magnolia Petroleum Co. #1 Below

LLANO COUNTY

1. Moore Hollow section
2. Warren Spring section

MIDLAND COUNTY

1. Magnolia Petroleum Co. #2-A Windham

NOLAN COUNTY

1. Honolulu Oil Corp. #5 Whitaker
2. Skelly Oil Co. #1 Ater

PECOS COUNTY

1. Phillips Petroleum Co. #1 Glenna
2. Phillips Petroleum Co. #1-C Puckett
3. Standard Oil Co. of Texas #2-1 Claude Owens

PRESIDIO COUNTY

1. Gulf Oil Corp. #1 Mitchell Bros.—State

REAGAN COUNTY

1. Humble Oil & Rfg. Co. #1-M University

UPTON COUNTY

1. Gulf Oil Corp. #1 McElroy-State
2. Sinclair Oil & Gas Co. #9 McElroy
3. Wilshire Oil Co. #23-118 Windham

VAL VERDE COUNTY

1. Phillips Petroleum Co. #1 Wilson

WINKLER COUNTY

1. Gulf Oil Corp. #108-E Keystone

them fresh-water algae and related to the Desmidacea found in modern fresh-water lakes. Rotan (1952) described 100 types from 21 formations ranging in age from Precambrian to lower Mississippian. D. W. Fisher (1953) has described a number of hystrichosphaerid fossils from the Clinton group (Silurian) of New York State and disagreed with previous work as to the phylogenetic affinity of the hystrichosphaerids. He stated that these microfossils may represent the zygospores of the brown algae, but Dr. L. R. Wilson (personal oral communication) points out that no brown algae produce spores similar to the hystrichospaerids. J. Fisher (1955) found that changes in species population within the Clinton group of New York State are of great enough significance to make stratigraphic zonation possible.

PROCEDURE

Preparation of samples.—The method used to recover hystrichosphaerids depends upon the composition of the rock. Carbonate rocks, such as those reported on here, are first dissolved in hydrochloric acid before being treated with hydrofluoric acid in order to prevent the formation of calcium fluoride crystals. The hydrochloric treatment is omitted for noncarbonate rocks.

Because hydrofluoric acid is very corrosive and toxic, extreme caution must be used and equipment must be sound. The fume hood in particular must be designed to carry away all fumes. The use of face shield, gloves, and apron is essential to personal safety.

All equipment should be rinsed with distilled water just before being used and should be thoroughly washed after each usage. The use of tap water is not recommended as it may be contaminated by plant and animal micro-organisms. Samples should be covered when not in the fume hood.

The samples may be processed in either of two ways. The first method described below is used where speed in obtaining results is desired or where only a few samples are digested. The preparation of samples using this method can be accomplished in about 30 minutes. The other method, the one used for this study, requires about 20 hours and should be used where a large number of samples are to be studied and where the results are not immediately needed. With the slower method all the samples receive the same treatment and the results should be more nearly uniform.

For the faster method, place about 10 grams of sample, crushed to fragments several millimeters in size, in a glass beaker, add hydrochloric acid, boil in the fume hood until reaction stops, dilute with distilled water, centrifuge, and discard the liquid. Be sure all carbonate is removed. Place the residue in a copper beaker, cover with 52% hydrofluoric acid, boil in fume hood for about 5 minutes, if sample is very siliceous add more hydrofluoric acid and continue boiling, dilute with distilled water, centrifuge, discard liquid, wash sample several times by centrifuging, and place residue in homeopathic vial until ready for examination.

For the slower method, place about 10 grams of sample, crushed to fragments several millimeters in size, in a glass beaker, cover with hydrochloric acid in a fume hood, if reaction is violent allow to set for about half an hour before boiling, boil about 2 minutes and if sample still effervesces add more hydrochloric acid until all carbonate is removed, dilute with distilled water, allow to settle for about 3 hours keeping sample covered, then decant liquid. Place residue in copper beaker in fume hood, cover with 52% hydrofluoric acid, leave sample in acid 15 hours, bring to boil, remove from flame, and immediately dilute with about 4 volumes of distilled water. Allow to settle for about 3 hours, decant, repeat this process until sample has been washed three times with distilled water, and place in homeopathic vial until ready for examination.

Examination of residues.—Wet mounts are prepared by placing one drop of residue on a glass microscope slide, adding one drop of glycerol, and covering with a cover glass. In most cases, it is first advisable to stain the residue with several cubic centimeters of concentrated Safranin Y for about 5 minutes, or longer if required. The staining is useful for distinguishing fossils from the contaminants. The latter mostly stain pink or bright red and the fossils remain uncolored.

Two wet mounts are scanned closely and if no fossils are found the sample is considered to be barren. If the wet-mount examination reveals the presence of fossils, the residue from the homeopathic vial is centrifuged 5 minutes or more in a glass centrifuge tube to remove as much moisture as possible. To the residue in the centrifuge tube add glycerine jelly, melted by placing container in hot water, and in amount proportional to the amount of residue so that all slides will have the same density, stir thoroughly, return to homeopathic vial, and place in dehydrating jar for 24 hours to remove excess moisture.

To prepare permanent slides, wash slides and cover glasses in alcohol, dry with lintless cloth, heat homeopathic vial, stir residue thoroughly, place one drop on warm slide, cover with warm cover glass, adjust cover glass properly, invert slide, warm slightly by passing through flame of alcohol lamp, and place in slide rack in inverted position to harden. Clean around cover glass using knife and alcohol, center slide on ringing table, rotate table as small camel's hair brush dipped in asphaltum is touched to the edge of the cover glass, store slides horizontally in appropriate containers. Do not store on edge as glycerine will melt during warm weather, allowing the residue to shift.

Scan the slides systematically using a compound binocular microscope equipped with mechanical stage, ring and number each fossil found, record each number on a 5- by 8-inch card along with description of fossil, using one card to each fossil. Description of fossils should be accompanied by illustrations which may be photographs, free hand or camera lucida sketches, or a combination of photography and sketching. The generally accepted basis for classification of the hystrichosphaerids is outlined by Wetzel (1933), Deflandre (1935a, 1935b, and 1937), Eisenack (1938), and Lejuene-Carpentier (1941).

Photography.—For photomicrography, perfect optical alignment and freedom from vibration are necessary. The use of non-color-corrected (chromatic) lenses in the microscope seems to bring out certain diagnostic features useful in identification. An emulsion is needed with low graininess, high resolving power, and balanced color sensitivity. Kodak plus-X film meets these requirements and is available in 35-millimeter size. Since negatives of moderately high contrast with a minimum of grain are desired, a fine-grain developer should be used. The length of exposure is determined by trial and error. Development and printing are the same as for other photographic processes except that a more rigid standardization is needed.

RESULTS OF EXAMINATION OF PRE-SIMPSON PALEOZOIC ROCKS

During the summer of 1954, 593 surface and subsurface samples were prepared by the longer method outlined above (Appendix E). Ten-gram samples were used; for those having little residue larger samples would have been better. Ten samples per day were processed, and part of the wet-mount examination was carried on concurrently.

The first 143 samples examined were from the following 7 wells:

- Continental Oil Company No. 1 Burger B-28, Lea County, New Mexico
- Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas
- Gulf Oil Corporation No. 1 McElroy-State, Upton County, Texas
- Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas
- Gulf Oil Corporation No. 1 Texas "000", Andrews County, Texas
- Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County, Texas
- Magnolia Petroleum Company No. 1 Below, Kendall County, Texas

The amount of the organic residue was very small and no structures unquestionably hystrichosphaerids were found. The forms questionably assigned to the hystrichosphaerids were so few—one or two to a sample—that a correlation even if attempted would be invalid.

Since wells selected at random failed to yield positive results, surface sections of known stratigraphic position were examined, namely, the Moore Hollow, Warren Springs, and Honeycut Bend sections (Cloud and Barnes, 1948). As these samples were barren, only a wet-mount examination was made of samples from the White Creek section (Bridge, Barnes, and Cloud, 1947) and from the Franklin Mountains section (Cloud and Barnes, 1948). These also were barren.

To give stratigraphic and geographic coverage, samples were examined from the following 9 wells, which were also barren:

The Atlantic Refining Company No. 1 Noelke, Irion County, Texas
Deep Rock Oil Corporation No. 1 Moore Estate, Clay County, Texas
Honolulu Oil Corporation No. 5 Whitaker, Nolan County, Texas
Humble Oil & Refining Company No. 1 Miller, Collin County, Texas
Phillips Petroleum Company No. 1 Glenna, Pecos County, Texas
Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas
Phillips Petroleum Company No. 1 Wilson, Val Verde County, Texas
Richardson & Bass No. 1 Federal-Cobb, Eddy County, New Mexico
Skelly Oil Company No. 1 Ater, Nolan County, Texas

Of the 593 samples digested, 132 from the following 13 wells were not examined:

Gulf Oil Corporation No. 1-E State "AM", Andrews County, Texas
Humble Oil & Refining Company No. 1-C Alma Cox, Crockett County, Texas
Humble Oil & Refining Company No. 1-E Alma Cox, Crockett County, Texas
Humble Oil & Refining Company No. 2 Evelyn Lineberry, Andrews County, Texas
Humble Oil & Refining Company No. 37 Parker, Andrews County, Texas
Humble Oil & Refining Company No. 1-M University, Reagan County, Texas
Magnolia Petroleum Company No. 2-A Windham, Midland County, Texas
Shell Oil Company No. 5 State, Lea County, New Mexico
Sinclair Oil & Gas Company No. 9 McElroy, Upton County, Texas
Standard Oil Company of Texas No. 2-1 Claude Owens, Pecos County, Texas
The Superior Oil Company No. 1-27 University, Crockett County, Texas
The Texas Company No. 1 Phillips, Edwards County, Texas
Wilshire Oil Company No. 23-118 Windham, Upton County, Texas

No organic remains were found in the samples examined that could be assigned to any known or problematic fossil group. Contamination by present-day pollen was common with these genera recognized: *Pinus, Acer, Quercus, Chenopodium,* and *Fagus.* The alga *Protococcus* was found in all outcrop samples. This is probably a living form as none was found in the well samples.

All of the residues prepared for this study and all the permanent slides are on file and available for examination at the Department of Geology, University of Massachusetts, Amherst. Untreated samples and depth records for all samples examined are on file at the Bureau of Economic Geology, The University of Texas.

CONCLUSIONS

Insoluble fossils are essentially absent in the pre-Simpson rocks and therefore are of no value for correlating these rocks. It is concluded that either the Upper Cambrian and Lower Ordovician were not periods of abundant insoluble fossil population, or the environment of deposition of these rocks in the Texas-New Mexico area was not compatible with the growth of insoluble fossils.

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Thin-Section Examination of Pre-Simpson Paleozoic Rocks

ROBERT L. FOLK[6]

ABSTRACT

The Ellenburger group in the area studied consists largely of dolomite, with limestone present in the eastern part. There is very little terrigenous material; this consists of a trimodal mixture of well-rounded medium sand, coarse silt, and clay. Throughout most of the area, sands are supermature orthoquartzites, but in certain horizons in west Texas and New Mexico immature arkoses are present. This indicates that the source for the sand was probably a warm and humid linear granitic upland between Lea County, New Mexico, and Pecos County, Texas. The high degree of rounding of the supermature sands was all accomplished during Ellenburger deposition.

The Ellenburger carbonates contain abundant intraclasts (grains of reworked semiconsolidated lime sediment), oolites, fecal(?) pellets, and few fossils. A very large amount of microcrystalline calcite is present as an original matrix between the transported carbonates and also forms a rock in its own right. Sparry calcite (clear) was formed as a pore-filling cement in those sediments which consisted of relatively winnowed carbonate sands; there appears to be little or no recrystallization of calcite in the Ellenburger limestones. Nearly all the dolomite in the Ellenburger has formed by replacement of limestone, probably shortly after deposition. All the chert nodules are of replacement origin, but replacement occurred shortly after deposition while the lime sediment was still soft. It is found that chert can replace both limestone and dolomite, dolomite can replace both limestone and chert, and calcite can (rarely) replace both chert and dolomite.

A new classification of limestones is introduced and discussed at some length. Limestones are divided into three basic families depending on the proportion of (1) allochems — transported carbonate grains, analogous to the sand grains of a sandstone; (2) microcrystalline ooze, analogous to the clay matrix of a sandstone; and (3) sparry calcite cement, analogous to the pore-filling cement that occurs in well-winnowed sandstones. These families are subdivided depending on the dominant allochem (intraclasts, oolites, fossils, or pellets). The rock name is then compounded of these two elements, for example, intrasparite or biomicrite. The Ellenburger is largely intrasparite, pelsparite, and micrite.

The Ellenburger sediments are believed to have formed in a calm, shallow warm sea that was more saline to the west, resulting in the formation of dolomite and some evaporites in that area, while limestone formed farther to the east as a result of influx of fresher water from a postulated series of welts that lay far southeast of the area of study.

INTRODUCTION

This paper is concerned with the petrography of the pre-Simpson rocks with emphasis on those from the Ellenburger group and is based on description of 850 thin sections from 48 wells and one surface section examined from July 1954 through September 1955. The location of these wells and surface section is shown in figure 11.

The chief aim of the petrographic

[6] Associate Professor, Department of Geology, The University of Texas.

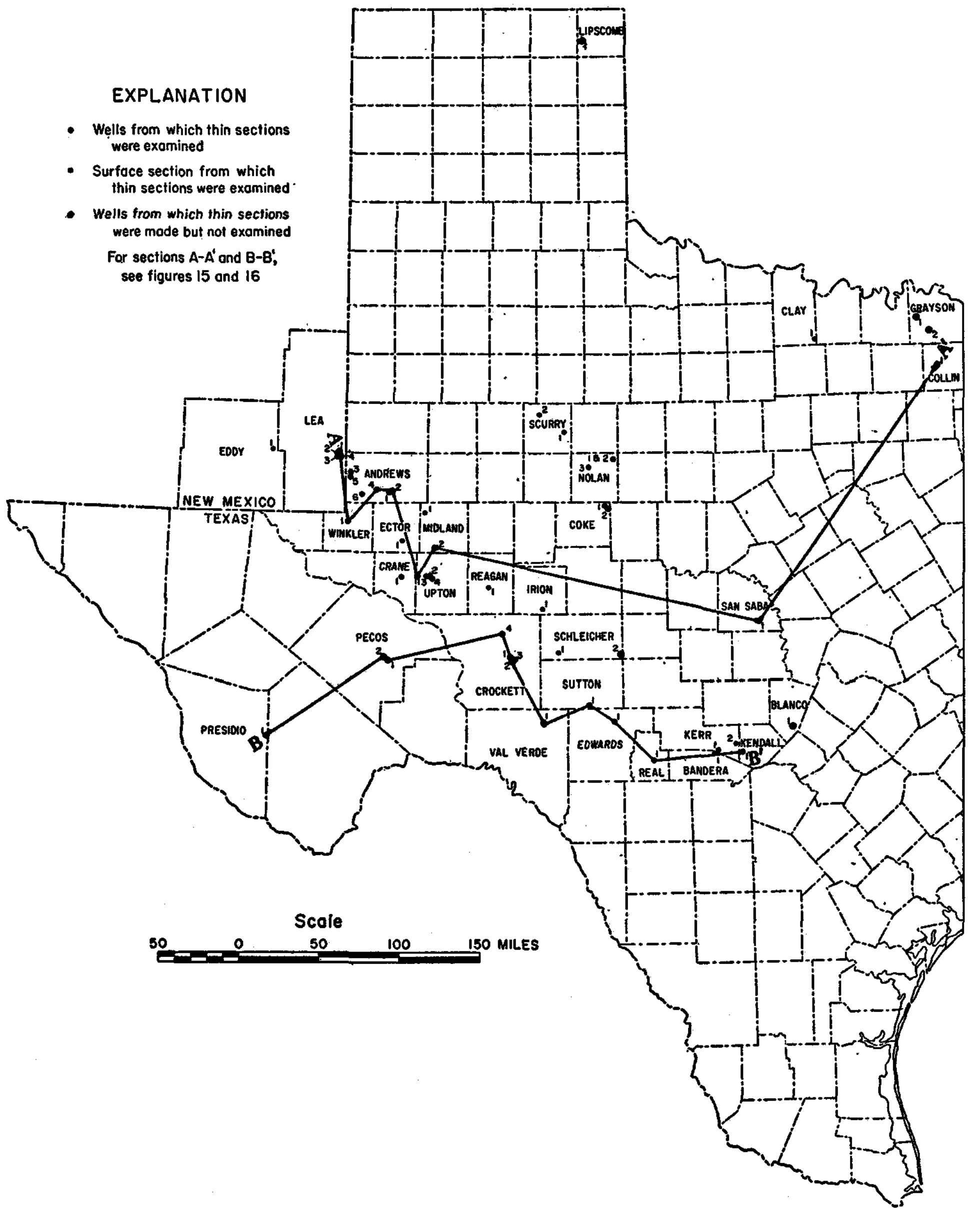

FIG. 11. Map showing wells and surface section from which thin sections were examined and lines of sections. [A few thin sections received too late to be examined by Folk are described in Appendix B.]

Fig. 11, explanation (continued)—

	Number of thin sections
NEW MEXICO	
EDDY COUNTY	
1. Richardson & Bass #1 Federal-Cobb	4
LEA COUNTY	
1. Continental Oil Co. #1 Burger B-28	13
2. Humble Oil & Rfg. Co. #3 "V" N. M. State	1
3. Humble Oil & Rfg. Co. #6 "V" N. M. State	3
4. Shell Oil Co. #5 State	5
TEXAS	
ANDREWS COUNTY	
1. Gulf Oil Corp. #1-E State "AM"	3
2. Gulf Oil Corp. #1 Texas "000"	31
3. Humble Oil & Rfg. Co. #2 Evelyn Lineberry	2
4. Shell Oil Co. #12 Lockhart	7
5. Shell Oil Co. #1 Pinson	1
6. Shell Oil Co. #7 Ratliff & Bedford	2
BANDERA COUNTY	
1. G. L. Rowsey #2 Fee	6
BLANCO COUNTY	
1. Roland K. Blumberg #1 Wagner	2
CLAY COUNTY	
1. Deep Rock Oil Corp. #1 Moore Estate	3
COKE COUNTY	
1. Humble Oil & Rfg. Co. #10 Odom	2
2. Humble Oil & Rfg. Co. #F-90 Odom	9
COLLIN COUNTY	
1. Humble Oil & Rfg. Co. #1 Miller	33
CRANE COUNTY	
1. The Atlantic Rfg. Co. #1-W University	1
CROCKETT COUNTY	
1. Humble Oil & Rfg. Co. #1-C Alma Cox	7
2. Humble Oil & Rfg. Co. #1-D Alma Cox	52
3. Humble Oil & Rfg. Co. #1-E Alma Cox	1
4. The Superior Oil Co. #1-27 University	28
ECTOR COUNTY	
1. Cities Service Oil Co. #1-E Foster	1
EDWARDS COUNTY	
1. The Texas Co. #1 Phillips	7
GRAYSON COUNTY	
1. The Superior Oil Co. #1. J. E. Henderson	3
2. The Superior Oil Co. #1 S. L. Privette	4
IRION COUNTY	
1. The Atlantic Rfg. Co. #1 Noelke	3

	Number of thin sections
KENDALL COUNTY	
1. Magnolia Petroleum Co. #1 Below	45
KERR COUNTY	
1. G. L. Rowsey #2 Nowlin	2
2. Tucker Drilling Co. #1 Dr. Roy E. Perkins	3
LIPSCOMB COUNTY	
1. Gulf Oil Corp. #1-E Porter "A"	1
MIDLAND COUNTY	
1. Magnolia Petroleum Co. #1 Nobles	1
2. Magnolia Petroleum Co. #2-A Windham	41
NOLAN COUNTY	
1. Honolulu Oil Corp. #2 Whitaker	14
2. Honolulu Oil Corp. #5 Whitaker	5
3. Skelly Oil Company #1 Ater	10
PECOS COUNTY	
1. Phillips Petroleum Co. #1 Glenna	16
2. Phillips Petroleum Co. #1-C Puckett	39
PRESIDIO COUNTY	
1. Gulf Oil Corp. #1 Mitchell Bros.—State	52
REAGAN COUNTY	
1. Humble Oil & Rfg. Co. #1-M University	3
REAL COUNTY	
1. Stanolind Oil & Gas Co. #1 Knippa	7
SAN SABA COUNTY	
1. Cherokee Creek section	132
SCHLEICHER COUNTY	
1. American Trading & Prod. Corp. #1 Sauer	2
2. Magnolia Petroleum Co. #1 Mary Ball	6
SCURRY COUNTY	
1. American Trading & Production Corp. #1 Elmer Howell	1
2. Humble Oil & Rfg. Co. #1-B B. A. Moore	2
SUTTON COUNTY	
1. Humble Oil & Rfg. Co. #1 J. D. Harrison	5
UPTON COUNTY	
1. Gulf Oil Corp. #1 McElroy-State	73
2. Sinclair Oil & Gas Co. #9 McElroy	10
3. Wilshire Oil Co. #14-130 McElroy	7
4. Wilshire Oil Co. #23-118 Windham	10
VAL VERDE COUNTY	
1. Phillips Petroleum Co. #1 Wilson	85
WINKLER COUNTY	
1. Gulf Oil Corp. #108-E Keystone	60

study was to determine the properties and origin of pre-Simpson rock types and to attempt to shed some light on the depositional conditions. An important part of the study was the determination of the paragenetic sequence: the time and mode of formation of calcite, dolomite, chert, and other chemical minerals. Another aim was to find, if possible, a stratigraphic zonation that might be traceable over an extended area. Since sampling of cores was done chiefly with the first aim in mind, the samples examined are not statistically representative of the entire Ellenburger but are heavily weighted with unusual or complex rock types.

In order to find if a stratigraphic zonation exists, it would have been best to sample on a rigid, closely-spaced grid (for example, one sample per 10 feet in each well). As it is, however, in some wells long gaps are unrepresented by samples whereas in other wells, samples are very closely spaced. In the summary discussion of each well, an attempt is made to give the general characteristics of each part of the stratigraphic sequence encountered, even though this is rendered somewhat uncertain because of the irregular sampling interval and the prevalence of unusual rocks.

The order of presentation of the work on thin sections is as follows:

(1) Description of minerals present and their paragenesis.
(2) Formulation of a carbonate rock classification.
(3) Placement of pre-Simpson rocks in this classification.
(4) Stratigraphic and regional characteristics of pre-Simpson rocks.
(5) Summary of rock types and zonation for each well with detailed petrographic description of selected thin sections (Appendix F).

The writer wishes to express his appreciation to Fred A. Schindler, who took the photomicrographs.

MINERALOGY AND PETROLOGY

General Statement

The Ellenburger part of the pre-Simpson sequence consists chiefly of dolomite with subordinate limestone and very little terrigenous material. Although sand, silt, and clay are lacking or present only in traces in most thin sections, some thin sections do contain considerable amounts and a few true sandstones and shales are present. Most of the sandstones are medium grained (Wentworth, 1922); over most of the region studied they are supermature orthoquartzites, but in a belt from Lea County, New Mexico, through Pecos County, Texas, they consist in part of immature to submature arkoses.[7]

Dolomite is the most abundant orthochemical mineral in the Ellenburger group and occurs in a variety of forms which have proved useful in stratigraphic zonation. Calcite is abundant only in the eastern part of the area. Chert is common both as nodules and as interstitial fillings between dolomite crystals. Quartz forms replacement spherulites, vein and geode fillings, and in the sandstones occurs as overgrowths on terrigenous quartz grains. Minor orthochemical minerals are pyrite, anhydrite, and barite.

Transported carbonates (here termed allochems) are readily visible in most thin sections that are still calcitic, but throughout much of the Ellenburger sequence they have been obscured or destroyed by dolomitization. Intraclasts and pellets are quite abundant; fossils and oolites are much less frequent.

The paragenetic relationships of orthochemical silica, calcite, and dolomite are very complex; each of these has been observed to occur as directly precipitated cavity fillings, and each of these has been observed replacing the other two minerals. Some replacements occurred while the rock was still a porous aggregate of transported carbonate particles; other replacements occurred after cementation; and still others occurred during or after tectonic deformation.

After the individual minerals and mineral aggregates in the Ellenburger group have been discussed, the rock types which these minerals form are considered; here it is desirable to introduce a rock classification scheme for carbonate sediments, based chiefly (1) on the relative proportions of microcrystalline carbonate ooze, sparry (more coarsely crystalline) carbonate cement, and allochems; and (2) on the nature of the allochems.

Finally, the interrelationship of rock types (as shown by bedding and sedimentary structures) is discussed, and the origin and significance of later features such as stylolites and veins are covered.

With regard to the general petrology of the Ellenburger rocks and the depositional conditions of the original sediments, the writer is in almost complete accord with the work done by Cloud and Barnes (1948), with only minor differences.

Terminology for Rock Description

In discussing the petrography of the pre-Simpson rocks, the writer has introduced a few new terms. This was done in order to eliminate some of the confusion that is nowadays attached to such terms as "detrital" or "clastic," which are used differently by many geologists. The basic constituents of all sedimentary rocks are divided into three main categories and several subcategories as shown in the outline below:

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[7] Terminology after Folk (1954). Sandstones are classified compositionally on the mineralogy of the silt-sand-gravel fraction, ignoring clay content, sorting, rounding, or cementation. An orthoquartzite contains under 5 percent feldspar, under 5 percent mica, metamorphic rock fragments, and metaquartzite fragments, and over 90 percent quartz and/or chert; it may have any degree of sorting or rounding and any type of cement (or even none). An arkose contains over 25 percent feldspar or igneous rock fragments of any type and under 10 percent mica, metamorphic rock fragments, and metaquartzite; it also may have any degree of sorting and rounding and any type of cement. A subarkose is intermediate between an orthoquartzite and an arkose, containing 5 to 25 percent feldspar and igneous rock fragments.

Texturally immature rocks contain more than 5 percent clay and are usually poorly sorted and angular. Submature rocks contain less than 5 percent clay but are still poorly sorted and angular. Mature rocks contain little or no clay, are well sorted (σ under 0.5), but still not well rounded. Supermature rocks contain no clay, are well sorted, and well rounded.

I. Terrigenous constituents, or "terrigens." Includes all materials derived from erosion of source lands outside of the basin of deposition and contributed as solids to the sediment. Examples: quartz sand and silt, feldspar, clay minerals, heavy minerals.

II. Allochemical constituents, or "allochems." Includes all materials that have formed chemically *within* the basin of deposition but which are organized into discrete aggregated bodies and for the most part have suffered some transportation ("allo" is from the Greek meaning "out of the ordinary," in the sense that these are not just simple, unmodified chemical precipitates). Allochems are subdivided into the following four classes:[8]

A. Intraclasts—includes all materials that have been reworked into the present rock by penecontemporaneous erosion of weakly to moderately consolidated carbonate sediments within the same basin. Intraclasts commonly range from very fine sand to cobble size and may be composed of any type of limestone or dolomite. Example: limestone pebbles in intraformational conglomerate.

B. Oolites—these inorganic particles must have either radial or concentric structure (commonly they have both). Pisolites may also be included in this category.

C. Fossils—for practical purposes, both sedentary and transported fossils are grouped here as allochems because of the difficulty of telling them apart with any certainty.

D. Pellets—rounded, spherical to ellipsoidal aggregates of microcrystalline carbonate ooze, devoid of internal structure and ranging in size between 0.05 mm and 0.2 mm (larger particles are nearly always intraclasts). They are interpreted as invertebrate fecal pellets, although some may possibly form in other ways.

III. Orthochemical constituents or "orthochems." Includes all "normal" chemical precipitates, formed within either the basin of deposition or the rock itself, and essentially suffering little or no evident transportation ("ortho" is from the Greek meaning "true" or "proper"). Orthochems are divisible into four groups:

A. Microcrystalline ooze—includes microcrystalline calcite or dolomite in grains 1 to 5 microns in diameter, conceived as forming by chemical or biochemical precipitation in sea water, settling to the bottom, and in most cases suffering some later drifting by weak currents, analogous to the deposition of snow. It is considered as an orthochemical constituent because it is a normal chemical precipitate, despite the fact that it may be drifted somewhat by currents; furthermore, some of it may form in situ. Conceivably some 1- to 5-micron calcite may be "dust" produced by abrasion of shell debris, hence would not be a "simple" chemical precipitate; yet the writer thinks that this dust is quantitatively negligible and in any case behaves hydraulically as ordinary ooze. As yet no criteria are known whereby it might be identified in thin section; therefore, it is included with ordinary microcrystalline ooze in this classification.

B. Syngenetic direct precipitates—as used in this paper, "syngenetic" minerals are defined as those which are precipitated from either sea water or its local connate modification, prior to or during the consolidation of the rock and before the introduction of far-traveled connate, juvenile, or meteoric waters. Direct precipitates may form either by (1) precipitation into open pore space or (2) by physically displacing adjoining soft sediment without dissolving it. Examples: sparry calcite cement in clear crystals generally larger than 10 microns, sparry dolomite pore-fillings, some types of authigenic silica.

C. Syngenetic replacements—produced by precipitation of one mineral in the place of another one which simultaneously dissolves, the guest and host remaining essentially in contact with each other. Examples: most dolomite, chert, authigenic quartz, authigenic feldspar, and pyrite.

D. Epigenetic minerals—as used in this paper, "epigenetic" refers to those minerals which form after consolidation of the rock and are precipitated from far-traveled waters of connate, juvenile, or meteoric origin. Examples: epigenetic quartz, later pore- and vein-filling carbonates, travertine crusts, and hematite derived from weathering of pyrite.

Terrigenous Constituents

Terrigenous minerals are defined as those minerals derived from erosion of a land area outside of the basin of deposition and contributed to the basin as solids.

Most Ellenburger thin sections contain little or no visible terrigenous material. Many contain scattered grains of sand or silt or stringers and nests of clay, but there are only a few samples of what might legitimately be classed as terrigenous rocks such as sandstones or clay shales. Most of the terrigenous material is well-rounded, medium-grained, and rather well-sorted sand consisting almost entirely of quartz (Pl. 36, A, B), but there are also

[8] This classification assumes that allochems (except for certain fossils) are transported constituents, a rule which holds true for most carbonate rocks. Some limestones, however, may be made up of pseudo-allochems, that is, *objects that simulate* the appearance of intraclasts, oolites, or pellets but which have formed in place by recrystallization processes. These have not been recognized in pre-Simpson samples.

some angular, poorly sorted, arkosic beds (Pl. 36, C, D).

MINERALS

Quartz is by far the most abundant constituent of the silt-sand fraction, comprising over 95 percent of the grains. Over nine-tenths of the quartz grains, a remarkably high proportion, have straight extinction and few inclusions except for bubble trains (Pl. 36, E). A few have slightly undulose extinction, but grains with strong undulose extinction are rather rare. Nearly all of the grains are single-crystal units, but there are a few composite ones. Only a few grains have the abundant fluid inclusions diagnostic of a hydrothermal source. Thus, following Krynine (1940), the quartz came almost entirely from a plutonic granite or granite-gneiss source, with only minor contributions from pegmatites, veins, and stressed metamorphic rocks. In local areas, however, the proportion of strained quartz or composite quartz grains is higher, and these were apparently near more cataclastic gneissic or schistose source regions.

Quartz grains embedded in a carbonate matrix generally lack overgrowths. Sandstones, or pure sandy or silty laminae in the carbonate rocks, contain quartz grains with conspicuous overgrowths. Apparently these overgrowths have grown by direct precipitation into pore spaces between the sand grains in these well-sorted layers, because the overgrowths lack carbonate inclusions and show no evidence of any replacement of the carbonate matrix. The overgrowths consequently developed early in the history of the sediment, before any carbonate minerals had a chance to fill the available pore space.

Detrital chert is a very rare constituent but has been noted in amounts of one or two grains in each of several dozen thin sections. These grains tend to be elongated and subround to subangular, although some angular grains have been encountered. One chert pebble 5 mm long was found in Gulf Oil Corporation No. 108-E Keystone, Winkler County. The chert grains are composed of typical microcrystalline quartz with a grain size of 1 to 5 microns and show no evidence of metamorphism, hence must have come from older unmetamorphosed sediments. These chert grains are more angular than the quartz grains with which they are associated, and inasmuch as sand-size chert apparently rounds more rapidly than sand-size quartz (Folk and Ward, 1957), this indicates that the chert has had considerably less abrasion and did not come from the same source as the quartz. Consequently, the writer believes that these chert grains came from reworking of Ellenburger chert-bearing beds only slightly older than the sands in which these grains are found and may be an indicator of minor diastems or local penecontemporaneous erosion within the Ellenburger group.

Many thin sections superficially appear to contain detrital chert grains, but in reality these grains are simply chertified intraclasts, that is, sand-sized bits of carbonate ooze that have been replaced by chert after deposition. Careful examination usually brings forth evidence of post-depositional replacement, and these at-first-sight-confusing cases can be recognized.

Feldspar shows great variation in abundance. Throughout most of the area studied, it is entirely absent or present in mere traces, with the exception of some of the basal sands where it may form as much as 5 percent of the detritus (Pl. 36, F). But in a belt extending from Lea County, New Mexico, to Pecos County, Texas, feldspar is abundant, sometimes forming over 50 percent of the terrigenous material (Pl. 36, C, D). Even in this belt, though, there are some sandy beds where feldspar is scarce to absent. The controlling factor in feldspar percentage is the amount of abrasion which the sand has undergone: feldspars are abundant where the associated quartz sand is subangular and rare to absent where the associated quartz sand is well rounded. In the richly arkosic beds the feldspar grains themselves are usually angular to subround and have the same size range and shape as the associated quartz. Over half of the feldspar shows no visible twinning in sand-size grains and is hence called orthoclase. The orthoclase is commonly slightly to moderately altered by *vacuolization* (Folk, 1955) but ranges from perfectly clear to heavily altered; no sericite or kaolin alteration was observed. Less than one-half of the sand-size feldspar grains show grid twinning, and these are classed as microcline. Microcline is considerably fresher than orthoclase, although some vacuolization occurs. Sodic plagioclase is only rarely encountered, forming at most perhaps 2 percent of the feldspar and occurring in fresh, subround grains; it is more abundant in the basement rocks (P. T. Flawn, personal communication) and may have been destroyed during weathering in the source area. Perthite occurs rather frequently, and occasional large grains of graphic granite have been found. In well-sorted sandy beds, the feldspar grains often have small clear hypidiomorphic and untwinned overgrowths, but where a clay or carbonate matrix is present there are no overgrowths.

Mica is an exceedingly rare constituent in the Ellenburger thin sections. Mostly it occurs only in the form of small shreds up to 0.05 mm long, but rare flakes up to 0.5 mm or even 1 mm long have been observed in the arkosic sand beds near the base of the section in the Lea-Pecos County belt. Muscovite is almost the only type present, although there are some shreds of chlorite and very rarely biotite. Mica is notably uncommon even in the fine siltstones where one might expect it to be abundant because of its hydraulic properties.

Metamorphic rock fragments are represented only by metaquartzite aggregates and fragments of metamorphosed and sutured vein quartz; they form less than 2 percent of the silt-sand fraction. Even in beds consisting of poorly sorted, angular sand, evincing a low energy expenditure and consequent slight abrasion, no fragments of schist, phyllite, slate, or other soft, low-rank, micaceous rock fragments were found.

Heavy minerals are unusually scarce, with only an occasional grain of zircon or tourmaline being noted.

Clay minerals occur in numerous ways: as matrix in poorly sorted arkosic sandstones (Pl. 36, D), as thin stringers interbedded in the carbonate rocks (Pl. 36, G; Pl. 39, F), as interstitial wisps between dolomite rhombs (Pl. 37, A), as inclusions in chert nodules, and as stylolite fillings. There are even a few thin beds of clay shale. Inherently the color is pale greenish, but most of the clay areas have been stained brownish by oxidation of associated pyrite. Masses give illite-like birefringence (strong yellows and blues in oriented aggregates when the gypsum plate is inserted) and have an index slightly higher than balsam. The material is dominantly illite and chlorite; X-ray analysis by Jonas has given more complete data (pp. 131–143).

GRAIN SIZE

There are three distinct modes in the size distribution of the terrigenous minerals. One mode is in the clay range, one in the coarse silt grade, and one in the medium sand grade. These modes remain of nearly constant grain size throughout the vertical and lateral extent of this study; most samples consist almost entirely of one or the other of these modes, and only a few samples contain conspicuous amounts of two or more modes.

The silt mode is the one most commonly encountered. The silt averages 0.04 to 0.06 mm, although extreme examples ranging from 0.03 to 0.10 mm (actually in the very fine sand grade) have been observed. Wherever it occurs, the silt is well sorted with σ about 0.5 ϕ (Folk and Ward, 1957). The silt mode occurs in four ways: (1) most frequently as scattered isolated grains embedded in a "sea" of carbonate; (2) frequently as distinct well-sorted laminae in the carbonate rocks containing little clay and no sand; (3) more rarely as scattered grains in large masses of clay; or (4) as a matrix to coarser sand grains.

The clay mode has been discussed under "Minerals" (p. 102); in review it occurs chiefly as relatively pure stringers within the carbonate rock, as interstitial material between dolomite crystals, and sometimes as beds of clay shale.

The medium sand mode is usually rather well sorted (σ about 0.4 to 0.7 ϕ) and the average diameter is 0.30 to 0.35 mm, although extreme thin sections may have an average grain size ranging from 0.25 to 0.45 mm. Individual grains of sand as large as 0.70 mm are common, and occasional pebbles (of graphic granite, vein quartz, chert, and metaquartzite) as large as 10 mm have been seen.

When the sand and silt fractions occur together, the sediment is strikingly bimodal with a "gap" at about 0.10 to 0.20 mm (Pl. 37, C). This peculiar bimodality is a characteristic feature of Ordovician sands in such widely separated areas as Texas, Pennsylvania, Idaho, and Wyoming. Its significance is not surely known; elsewhere the writer (Folk, 1952) has explained this extreme and persistent bimodality as being due to aeolian action, with the silt being the material continually blown out to sea by the "normal" winds of the region, while the sand fraction occurred in coastal dunes and possibly deserts and was contributed to the sediment only when minor uplifts, migrating shore lines, or exceptional storms occurred.

GRAIN SHAPE

Throughout almost the entire area, the sands are superbly rounded, but there is a tendency for the rounding to decrease in the fine sizes; it is common to find rounded grains as small as 0.20 mm, but rounded grains smaller than 0.10 mm are uncommon (Pl. 37, B). The roundness sorting is very good—that is, all the grains in any one thin section show about the same degree of rounding, and there is usually no mixture of rounded with angular grains. This indicates that the grains *were being rounded during Ellenburger deposition,* and that the high roundness is not a characteristic inherited from reworking of older rounded sands. It is important to note that although most of the sand is rounded, some horizons consist of medium- to coarse-grained, uniformly subangular quartz; the fact that even *in the same well* some beds of uniformly subangular sand alternate with some beds of uniformly well-rounded sand of similar size confirms the important point that the rounding of the quartz in these beds was accomplished in Ellenburger environments, and that conditions were such that angular grains coming directly from granite or gneiss were able to become rounded to an extreme degree by transportational processes during the formation of these sediments. (One frequently reads in the literature that well-rounded grains must have passed through many cycles of abrasion—implying many different formations—in order to attain such high roundness; here is strong evidence that it may be accomplished in only *one* cycle.)

CHARACTER OF SOURCE AREA

Because of the presence of occasional beds of angular, little abraded detritus, one can postulate rather efficiently about the lithologic character of the source area inasmuch as the softer constituents have not been removed by abrasion in these beds. The composition of the sands indicates that the source area was composed chiefly of granites and granite gneisses, rich in orthoclase and microcline with very little plagioclase. Cutting this country rock were only minor amounts of hydrothermal veins and pegmatites, together with occasional more intensely sheared zones. Low-rank metamorphic rocks such as slates, phyllites, or schists were almost completely lacking, judging by the absence of fragments of these rocks even in the most angular sand, where these soft fragments should have been best preserved from abrasion. This is confirmed by the surprising paucity of micaceous material and sericite even in silt beds wherein they should have accumulated because of their hydraulic properties. This source area may have been covered by small patches of older sediments, but these apparently made very little contribution to Ellenburger deposits. Of course, there was a little penecontemporaneous erosion of Ellenburger sediments, such that some older Ellenburger sands and chert beds have apparently been reworked to higher levels within the Ellenburger group, but such occurrences were probably minor.

Tectonically, the area was probably a rather stable shelf, judging by the paucity of terrigenous material in the pre-Simpson sequence, the supreme degree of rounding of the quartz, the excellent sorting, and the supermature orthoquartzite nature of most of the sands. Near the Lea-Pecos County belt, however, there probably existed a linear granitic highland or island chain of moderate relief which periodically shed immature arkosic sediment into the surrounding area.

These conclusions, arrived at independently, agree quite well with the data of Flawn (1956), who has made an intensive study of basement rock petrography in the area. Most of the area described in the present paper is underlain by the Texas craton, largely granite and granodiorite. The two most outstanding basement "highs," the Central Basin Platform and the Fort Stockton high, underlie exactly those Ellenburger wells in which the coarsest and most arkosic sand appears in the area here loosely termed the Lea-Pecos County belt.

The climate of the Lea-Pecos County land or island chain is believed to have been humid and warm, indicated by the presence of occasional arkose beds consisting of a mixture of fresh with much altered feldspars (following the evidence used by Krynine, 1950). Confirmatory evidence arises when the Ellenburger sands are compared with sands in the Lower Ordovician Beekmantown carbonate sequence of Pennsylvania (Folk, 1952). In the Ellenburger sediments, feldspar is almost totally lacking where the sands are well rounded, and feldspar is abundant only where the sands are subangular. In Beekmantown sediments, the sand is just as well rounded as Ellenburger sand, but feldspar is abundant (10 to 30 percent) and perfectly fresh and clear. Both sediments were derived from a granitic and gneissic source area and are remarkably similar with regard to quartz types, feldspar composition, and heavy minerals. The fact that in one area beautifully rounded sands contain abundant fresh feldspar, while in the other area sands no better rounded contain none, indicates that another factor besides abrasion is destroying the feldspar, namely, a humid climate in the source area of the Ellenburger sediments. Where the time available for weathering is brief (as in the angular Ellenburger sands), the feldspar is not completely destroyed, and one finds arkosic sands containing weathered feldspar.

The reason for the alternation of well-rounded, orthoquartzite sands with angular, poorly sorted arkosic sands is not known. It may be due to depositional environment, with the orthoquartzite sands going through a protracted period of beach-dune action; it may be due to tectonic pulses alternating with long periods of quiescence; or it may be due to distance from the source area, although the latter cannot serve as the entire explanation because both types of sands are found alternating even within the same well. Probably during a period of tectonic uplift erosion is rapid, sediments pass through a beach phase rapidly or not at all, and immature arkoses result. During tectonic quiescence, seas transgress and regress over large areas very slowly, and wide beaches and sand flats with attendant dunes are spread out. During these inactive periods the rate of erosion slows down considerably, *increasing the length of time that* any one grain is exposed to the effects of weathering. Thus feldspar has adequate time to be destroyed completely by the humid climate, and supermature orthoquartzites develop.

LOCATION OF SOURCE AREA

From this limited petrographic study, it is exceedingly difficult to determine accurately the source area of the Ellenburger quartz-feldspar sands. The sandy beds occur only at scattered zones within the sequence, and with sporadic thin-section coverage it is impossible to obtain an accurate estimate of the relative sandiness of each core. Sandiness estimates can be much better done by binocular logging of the section, as has been done by Barnes (pp. 305–691). No significant regional trends in sandiness have been established through thin-section data, but such changes might easily have been missed.

Petrographic evidence on the source of the sand must therefore come from data other than sandiness percentages. The only other reliable criteria appear to be grain shape and mineralogy. Angular, arkosic sands rich in potash feldspar occur only along the Lea-Pecos County belt, which is also the area where the coarsest sands appear. Throughout the rest of the region studied, the sands are perfectly rounded, supermature orthoquartzites containing little or no feldspar, and they are of nearly constant grain size throughout this area. Hence the writer believes the most likely source area for the terrigenous material is in or near the Lea-Pecos County belt, although, of course, basal sands from all localities are probably of more local derivation.

Cloud and Barnes (1948) postulated that the source of the sands in the middle of the outcropping Ellenburger sequence lay to the south or east of the Llano uplift, because these rocks become more sandy to the southeast in the Llano area. In the opinion of this writer, the Ellenburger probably shows many local fluctuations in sand content, and the increase noted by Cloud and Barnes represents an approach to a local area of increased sandiness, which is not of regional (that is, statewide) significance and is rather a minor irregularity in the "sandiness" distribution.

Allochemical Constituents

Allochems are defined as those constituents which formed by chemical precipitation within the basin of deposition but are organized into discrete aggregates and usually suffered some movement by current action (or, in the case of some animals, moved under their own power). There are four types of allochems: intraclasts, oolites, fossils, and pellets.

Allochems are visible in nearly all the limestone thin sections and are well preserved in some of the dolomites. However, in most dolomites only vague allochem ghosts remain, and in some the allochems have been completely obliterated. Intraclasts and pellets are the most common type, although oolites and fossils occur frequently. Ghosts of these allochems are recognizable in the dolomite by the presence of a "dusty" brownish-appearing area within the transecting mosaic of dolomite crystals or chert, and often the chert or dolomite replacing the allochem is finer grained than similar material in the spaces between allochems. The brownish appearance is in part due to organic matter but in most thin sections is due to an abundance of liquid- and gas-filled vacuoles in the replacing dolomite. It is easy to determine the nature of the inclusions by using reflected light; liquid or gaseous inclusions then appear milky or silvery, while organic matter remains a smoky gray or brown.

Intraclasts (Pl. 37, D-F; Pl. 38, A) occur throughout the Ellenburger group and average 0.3 to 1 mm long, although some as large as 10 mm occur. They are subelongated as a rule but vary from equant to extremely flat and discoidal; almost without exception their corners are well rounded because of their ease of abrasion. They must have been fairly rigid at the time of deposition because none appear to be bent or squashed-in by adjoining grains. Some intraclasts are made up of structureless, homogeneous, microcrystalline calcite or dolomite, but more commonly the intraclasts are made up of pellet limestone. Other intraclasts may possibly represent broken-up algal structures. All of the intraclasts appear to be of destructional origin (because many possess bedding); there seem to be no accretionary "intraclasts" like the "grapestone" of Illing (1954).

Oolites (Pl. 38, B-D) are very common in some horizons and form correlatable zones over much of the area studied. Where oolites occur, they generally form almost the entire rock, although sometimes considerable well-rounded quartz sand occurs with them. Oolites are always well sorted and average about 0.4 mm in diameter but range from 0.25 to 0.6 mm; most are spherical but some are slightly elongated, and a few thin sections show strangely collapsed and contorted oolites (Pl. 40, C). They show both radial and concentric structure if made out of calcite or chert; oolites replaced by dolomite show little or no structure. Most have no evident nucleus except possibly a fecal pellet. Chert oolites usually have the slow ray vibration direction lying tangential to the oolite surface.

Pellets are common throughout the sequence and form spherical to elliptical or ovoid grains 0.05 to 0.20 mm in diameter, composed of structureless microcrystalline calcite (Pl. 38, E, F; Pl. 39, A). They are often visible as near-circular brownish ghosts in the centers of small dolomite rhombs. They are believed to be invertebrate fecal pellets and are distinguished from intraclasts because of their uniform lack of internal structure, nearly constant shape, small size, and excellent degree of sorting. Most of the objects described by Cloud and Barnes (1948) as pellets are termed intraclasts in this paper; as a rule, the pellets as described herein cannot be seen with binocular microscope.

Fossils occur as scattered individuals in many thin sections but almost never make up a significant volumetric proportion of the specimen as they do in Carboniferous rocks from this area (Pl. 39, B, C). Brachiopods appear to be most common, with gastropods and Pelmatozoa less so. Occasional thin sections of algal(?) mound structures have been encountered. These appear as gently scalloped or irregularly curving, concentric bands of differently sized calcite crystals which cross the entire thin section and often have elongated filled or open pores parallel with the banding (Pl. 39, D, E).

Orthochemical Constituents

Orthochemical constituents are here defined as those substances which are formed by chemical precipitation within the basin of deposition but which show no evidence of important movement after formation, thus differing from allochems. Orthochemical constituents include microcrystalline calcite and dolomite ooze; all cementing minerals, such as sparry calcite or quartz overgrowths; and all replacements, such as dolomite, chert, and pyrite.

CALCITE

Calcite, which was originally the chief carbonate mineral over the entire area of study, is now present in significant quantities only in the eastern part of the region; elsewhere it has been almost entirely replaced by dolomite. Where still present, calcite occurs in three forms: (1) as a constituent of allochems, that is, intraclasts, oolites, fossils, or pellets; (2) as microcrystalline ooze, either forming a clay-size matrix in allochemical rocks or else forming a rock in its own right ("lithographic limestone"); and (3) as sparry calcite cement, a pore-filling precipitate developed after deposition of transported material.

Microcrystalline ooze occurs in grains under 5 microns in diameter, usually averaging about 2 or 3 microns; grains are irregularly rounded and appear brownish or nearly opaque in thin section chiefly because of their fine grain size and high relief, although this type of calcite also usually contains included or interstitial organic matter (Pl. 39, F; Pl. 40, A, B). It is considered to form as a snowlike precipitate in sea water, then settle slowly to the bottom where it may undergo some drifting by currents. Some of it may be then reworked to form intraclasts; some may pass through animalian digestive tracts and emerge as pellets; and some may be disturbed by soft-sediment slumping or the boring activities of organisms. It is not known how this ooze is produced; presumably it may form either inorganically by agitation and heating of sea water (which drives off carbon dioxide, allowing precipitation of calcium carbonate), or it may form by reactions set off in the metabolism of plants and animals, particularly algae or bacteria. Nevertheless, it appears to settle only in areas of rather calm water, where it may form the matrix to allochem rocks (corresponding to a clay matrix in a sandstone) or may form a "lithographic" limestone made up entirely of this ooze (corresponding to a terrigenous claystone).

Sparry calcite is here used for that clear variety of calcite which forms crystals over 0.010 mm in diameter. It is usually very easy to distinguish from microcrystalline ooze because of its clarity and coarser crystallinity (Pl. 40, B, C; Pl. 37, E), but there are some transitional cases. In the pre-Simpson rocks, this type of calcite is believed to form by direct chemical precipitation inside empty pore spaces after deposition of the allochem framework of the rock. The larger the pore spaces, the coarser the calcite (although some large pore spaces may have very fine calcite). In the Ellenburger, sparry calcite crystals usually range between 0.01 to 0.2 mm in diameter, with the average somewhere around 0.05 mm (medium to finely crystalline; see table 4).

In the Ellenburger sequence, virtually none of this type of calcite forms by recrystallization of a finer-grained calcite ooze. Evidence for this is seen in the fact that sparry calcite occurs in well-sorted rocks much more commonly than in poorly sorted ones; it never forms a rock in its own right; and in all the thin sections examined, only one specimen showed a bed of microcrystalline ooze with splotches of recrystallizing sparry calcite in it. Sparry calcite is here a simple pore-filling precipitate just like the cement in sandstones.

Although recrystallization in the Ellenburger is in general an exceedingly insignificant process, several thin sections (Pl. 38, B; Pl. 40, D) show some evidence that a small amount of recrystallization may take place. These thin sections consist of oolites which at one time were composed in part of concentrically banded microcrystalline carbonate, but this was partially replaced by radial sparry calcite crystals which tended to obliterate the structure. The oolites are now composed of alternating narrow radiating sectors of (1) original microcrystalline calcite showing concentric structure by slight grain-size variations and (2) radial crystals of clear, sparry calcite, which extend as single units from the center to the edge of the oolite. Possibly even this is not a case of recrystallization (where a coarser-grained mineral grows in place of finer crystals of the same mineral) but may represent calcite replacing an original aragonite oolite.

DOLOMITE

Dolomite now forms the great bulk of the Ellenburger. Crystals range from 0.004 mm or less (recognizable in thin section as dolomite only because some of the tiny crystals preserve good rhombic angles) up to individuals of 4 mm or even more. The average size of the crystals throughout the entire area studied is 0.10 to 0.15 mm. The following tabulation shows the percentage of Ellenburger that is occupied by dolomite *zones* having the specified average crystal size:

Crystal Size	*Millimeters*	*Percent*
Aphano-crystalline	Less than 0.004	0
Very finely crystalline	0.004–0.016	1–2
Finely crystalline	0.016–0.062	About 25
Medium crystalline	0.062–0.25	45–50
Coarsely crystalline	0.25–1.0	About 25
Very coarsely crystalline	1.0–4.0	1–2

In rocks consisting entirely of dolomite, the crystals tend to be hypidiomorphic (Pl. 39, A; Pl. 40, E, F; Pl. 41, A). Where the dolomite crystals are embedded in chert, limestone, clay (or even where an essentially pure dolomite rock has a little interstitial porosity. Crystals tend to be idiomorphic (Pl. 37, A; Pl. 41, B, C). A peculiar type of ragged, composite dolomite crystal (Pl. 41, D, E) occurs in several stratigraphic zones. This type of dolomite occurs only in crystals larger than about 0.25 mm and is best developed when crystal size attains about 0.5 to 0.7 mm. The composite nature is not strictly a function of size, however, because other dolomite crystals in this same size range show normal idiomorphic to hypidiomorphic shapes. These peculiar dolomite crystals have the following characteristics: (1) Crystals in any one thin section show a great range in average diameter, in contrast to ordinary dolomite which is usually fairly uniform in size; (2) crystals have ragged, highly irregular edges devoid of crystal faces and looking somewhat like the irregular edge of a jig-saw puzzle; (3) each crystal when turned nearly to the position of extinction appears to be made up of a large number (say about a dozen) of crystal units or blocks each in slightly different orientation, their extinction positions differing by 5 degrees or less from that of their neighbors. Consequently, it is often difficult to tell where one large composite crystal stops and its neighboring composite crystal begins.

Inclusions are frequently abundant in dolomite, giving it a common cloudy appearance and hence responsible for its milky color in hand specimen. Usually these inclusions are fluid or gaseous and appear as brownish "dust" in transmitted light and as a silvery or milky clouding in reflected light. Gaseous inclusions appear as black, almost opaque bodies and maintain their extreme relief as the dolomite is rotated, but liquid inclusions or irregular areas filled with Canada balsam change relief markedly on rotation. Organic matter appears as a brown, smoky haze in reflected light but is not as common as gaseous or liquid inclusions. Calcite inclusions are abundant in some dolomite crystals; these tiny, irregularly rounded grains average only a few microns in diameter and show up under crossed nicols when the host dolomite is turned to extinction. One must make sure that these are really inclusions, and not grinding debris, by moving the fine focus to ascertain that they are actually inside the grain, not plastered on its ground surface. These microcrystalline calcite inclusions usually occur in a rhombic-shaped central zone in the dolomite crystals and presumably represent undigested remnants of microcrystalline calcite preserved from replacement.

Many nearly idiomorphic crystals of dolomite are zoned. By far the most common type of zoning consists of a brownish central rhombic-shaped area (Pl. 41, B, F), usually occupying about half the diameter of the crystal and surrounded by a clearer rim. The central zone is "pleochroic" because of the change in relief of the fluid and gaseous inclusions against the host dolomite crystal as it is rotated. Less commonly, the rhombic zoning is shown by a series of parallel rhomb-shaped lines of inclusions (Pl. 42, A), and, very rarely, a clear central rhombic zone is surrounded by a cloudy rim. The origin of this rhombic zoning is not clear, unless it be that the portion loaded with inclusions grew most rapidly, then after growth slowed down, the clear rim developed. In a second type of zoning, brownish inclusions are arranged along two intersecting lines connecting the corners of the dolomite rhombs (Pl. 42, B), hence forming a cross in the middle of the crystal. Calcite inclusions frequently occur in these crosses. Perhaps the dolomite grew rapidly along these axes (to form a hopper-shaped crystal), then when growth slowed down, the clearer areas between developed. "Hollow" dolomite crystals, with insides filled and apparently replaced with chert, have been rarely observed and their significance is unknown. It is probable that they represent dolomite zonally replaced by chert.

Nearly all of the Ellenburger dolomite has originated by replacement of limestone (Pl. 47, A, B). In fact, the writer has seen less than a dozen thin sections which he would consider as being possible primary dolomite, although such primary dolomites are abundant in the equivalent-age Beekmantown carbonates of Pennsylvania. There are numerous thin sections of very finely crystalline dolomite (0.004 to 0.016 mm) which are devoid of any recognizable allochem ghosts (Pl. 40, E, F); these may be primary but the writer hesitates to say so definitely.

Most of the more coarsely crystalline thin sections show excellent evidence of replacement in the presence of ghost oolites, fossils, intraclasts, or fecal pellets which are transected by the mosaic of dolomite crystals and are visible only by virtue of the fact that these ghost areas have more inclusions than the areas outside (Pl. 38, A, D; Pl. 39, A; Pl. 41, A, E). Why these ghosts have more *fluid* inclusions is not known, although it is fairly easy to understand why they might have more calcitic or organic inclusions.

Some of these allochem structures are preserved on replacement, but others are obliterated, especially if the replacing crystals are finely to very finely crystalline. This may happen even within the very same thin section, where one large intraclast may be visible as a ghost in a group of medium to coarsely crystalline dolomite but disappears completely when traced into an adjoining mass of smaller crystals (Pl. 42, C, D). It may even happen within one single dolomite crystal, where an inner rhombic zone of the crystal preserves excellent allochem ghosts and an outer zone of the same crystal is devoid of them and the ghosts are severed as by a knife at the edge of the zone within the crystal (Pl. 42, E, F; Pl. 43, A).

The time of dolomitization is not certain. It happened after deposition of the allochems and prior to tectonic jointing, but beyond that little definite can be said. The lack of reworked pebbles consisting of obvious replacement dolomite (although reworked limestone pebbles and very finely crystalline dolomite pebbles are fairly common) may indicate that replacement dolomite forms at a depth where it is safe from reworking by normal penecontemporaneous erosion. Thus dolomite probably forms while the sediment is still fairly soft and buried perhaps 10 to 100 feet below the surface, although this is a sheer guess. Presumably, dolomite forms in more saline waters than does limestone (Stout, 1944; Folk, 1952); this would indicate that the Ellenburger sea was more saline to the west, while east of the Llano uplift waters were freshened by influx of fresh rain water.

Cloud and Barnes (1948, pp. 94, 102) have postulated that the dolomite formed in the shallower waters of the Ellenburger sea, while the deeper-water sediments remained calcitic. This writer, however, feels that both limestones and dolomites show evidence of equally shallow water, with essentially similar proportions of intraclasts, oolites, and pellets (or their ghosts), and the intraclasts and oolites seem to have the same grain size and internal structure. Therefore, he believes that both accumulated under essentially similar depths, and that the regional westward increase in dolomite is due to a climate-controlled change in salinity.

The large crystals of composite dolomite also originated by replacement of limestone, as evidenced by the observation that they often preserve pellet and intraclast ghosts. In some limestones partially replaced by these composite crystals, it is clear that they develop by adding a series of small rhombohedrons in parallel orientation to the mother crystal, leaving large re-entrants still consisting of unreplaced limestone. Later the re-entrants are filled in, but the irregular manner of addition results in the peculiar composite extinction and ragged edges of the final crystal.

Why these composite crystals occur in rather persistent stratigraphic zones is not certain. Obviously, it must be due to some original depositional feature of these beds which were spread over considerable areas. Because the crystals are so large, one might assume that they grew much more slowly than the usual type of replacement dolomite. Therefore, they probably formed at a greater depth in the sediment. For a zone so deep in the sediment to be replaced over such a wide area means it must have been exceptionally permeable, more so than the beds above or below it; a connate-water aquifer, so to speak. Thus the writer offers as a possibility the idea that a composite dolomite zone may represent a bed of unconsolidated lime gravel, composed of intraclasts; for some reason, the bed became buried under a considerable thickness of sediments without ever becoming cemented. Much later, Mg^{++}-bearing saline solutions migrated along this buried, porous lime gravel and replaced the bed with composite dolomite which grew very slowly. This hypothesis is supported by the fact that most composite dolomite thin sections show intraclast ghosts.

AUTHIGENIC SILICA

Authigenic silica occurs in three forms: (1) microcrystalline quartz, forming equant grains ranging up to about 5 microns and giving typical "pin-point" birefringence; (2) chalcedonic quartz, forming radiating bundles of fibers or fibrous crusts with the fibers perpendicular to the encrusted surface; and (3) normal quartz (or megaquartz), arbitrarily classed as non-fibrous quartz coarser than 20 microns in particle size (Folk and Weaver, 1952). Chert is considered as an authigenic, essentially monomineralic rock composed chiefly of microcrystalline or chalcedonic quartz, with minor quantities of megaquartz and other impurities such as carbonates, pyrite, clay, silt, and organic matter.

Chert nodules in the Ellenburger group are composed almost entirely of relatively pure microcrystalline quartz which varies in grain size from less than 1 micron (such cherts look pseudo-isotropic) to over 5 microns. The average is about 2 to 3 microns. Former cavities, veins, or fossil tests within the nodule are sometimes filled with chalcedony or megaquartz which is coarser and clearer than the bulk of the material and has formed as a cavity-filling. Almost all the chert nodules examined show definite evidence that they have formed by replacement of limestone because they preserve perfectly such allochem structures as oolites, intraclasts, pellets, and fossils (Pl. 43, B-F). The allochems are usually brownish (due to fluid and organic inclusions) and more finely crystalline than the matrix. In some allochem limestones, the smoothly elliptical, knife-edge boundary of the chert nodule cuts right through intraclasts or pellets, so that half of the intraclast or pellet is chert while the other half is still limestone (Pl. 37, D). Some oolitic limestones (Pl. 38, C) are also transected by replacement chert nodules. Occasionally, the cherts show a series of vacuole bands concentric with the elliptical outer margin of the chert; these are a feature developed after the chert nodule formed, probably by some diffusion process (Pl. 44, A). It might be thought that they developed these bands by rolling on the sea floor in the manner of a snowball, but this is not the case because allochem ghosts within the chert nodule are all oriented parallel with the present bedding direction. Furthermore, scattered clay flakes within the chert nodule preserve horizontal orientation, even where they approach the curving side of the chert nodule. These facts indicate that the chert nodules formed in place after the sediment was buried and that no compaction of the nodule occurred, or else the orientation of the allochems and clay flakes would have been disturbed. A few chert nodules show no allochems, and these may be directly deposited (non-replacement) cherts, but there is no direct evidence for this mode of origin, and the writer feels strongly that they are replacements of homogeneous "lithographic" limestone. Some chert nodules may be pseudomorphous after gypsum (Pl. 61, E, F; Pl. 62, B).

Chert nodules are cut by joints and therefore formed prior to tectonic deformation. As discussed later under paragenesis, sometimes they grew before cementation by calcite and sometimes afterwards; usually before dolomitization but sometimes afterwards.

Spherulites composed of very irregular

flamboyant quartz or chalcedony occur in many of the dolomites (Pl. 44, B-F; Pl. 45, A-C). The spherulites average 1 to 2 mm in diameter and are rudely circular with very irregularly scalloped but sharp margins. The flamboyant quartz is arranged radially, but concentric bands of bubbles indicate growth stages. That these have grown by replacement of the dolomite is indicated by the scalloped margin of the spherulite which cuts into dolomite crystals leaving isolated inclusions which extinguish in continuity with the dolomite. In these spherulites no allochem structures are preserved, and no trace of rhombic pseudomorphs of quartz after dolomite are found; previous structures and textures are completely destroyed. Rarely, these scalloped spherulites are composed of microcrystalline quartz (Pl. 45, D-F).

OTHER MINERALS

In the east-central part of the area studied a little glauconite occurs as brilliant green pellets (or occasionally interstitial wisps) averaging 0.10 to 0.30 mm in diameter. Usually small amounts of nearly isotropic, brown collophane appear in the same thin sections as the glauconite; the collophane possibly represents shells or other organic materials. Glauconite and collophane are virtually restricted to Cambrian rocks in the thin sections examined.

Pyrite is common in many Ellenburger thin sections, mostly in small grains 0.01 to 0.05 mm in diameter but occasionally in larger stringers and masses or along fractures, veins, and stylolites. Sphalerite occurs in some of the vein fillings. Tabular barite crystals (Pl. 46, A) also occur in some veins and pore space fillings. Anhydrite is fairly common in the southwestern part of the area as pore fillings and vein fillings intergrown with calcite and dolomite (Pl. 46, B, C). The time of origin of these minerals is certainly after deposition of the surrounding rock, and probably most of them are associated with movement of water along veins and brecciated zones.

Pseudomorphs of some unknown orthorhombic mineral (Pl. 46, D-F) are present in Gulf Oil Corporation No. 108-E Keystone, Winkler County. Similar pseudomorphs have been encountered in other wells, and the original mineral is uncertain; it may have been barite. The replacing mineral is usually dolomite or quartz. In Humble Oil & Refining Company No. 6 "V" N. M. State, Lea County, New Mexico, chert nodules have a felted, fibrous structure indicating that the chert is pseudomorphous after some fibrous mineral, probably gypsum or anhydrite (Pl. 61, E, F; Pl. 62, B).

Paragenetic Relationships of Calcite, Dolomite and Silica

The paragenetic relationships of calcite, dolomite, microcrystalline quartz, chalcedonic quartz, and megaquartz are quite complex. All of these Ellenburger constituents (with the probable exception of microcrystalline quartz) can be precipitated directly from solution at any time from the first deposition of the sediment on the sea bottom to the time when the rock becomes fractured tectonically. Any of these may form by replacement at the expense of the others; dolomite can replace calcite, and calcite can replace dolomite; chert and quartz can replace calcite, and calcite can replace chert; chert and quartz can replace dolomite, and dolomite can replace chert. These replacements also have a wide time range, some occurring while the sediment was still unconsolidated, others happening after tectonic fracturing late in rock history. Thus no pat rule can be set up, and each specimen must be studied individually because the same two minerals may have entirely different paragenetic relations in two adjoining specimens, or even within the same thin section. In the following discussion the writer has attempted to give an idea of the relative abundance of each relationship, and also has given the criteria used in determining the sequence in the hope that these criteria might prove useful in studying other carbonate rocks.

Calcite-dolomite relationships. — Dolomite that was developed as a replacement of calcite probably constitutes over two-thirds of the Ellenburger rocks. The opposite situation of calcite replacing dolomite has been observed in only a half dozen thin sections but is well established.

The evidence for dolomite replacing calcite has been reviewed earlier in the section on dolomite; to recapitulate, the chief evidence is the presence of allochem ghosts in the dolomite mosaic or transection of bedding and allochem structures in partially dolomitized limestones. Thin sections consisting of dolomite crystals larger than about 0.05 mm nearly always show some allochem ghosts, but rocks finer grained than this show few or none. To some extent this may be a real absence; that is, some of the more finely crystalline dolomites may be primary, but to a large extent this is also due to the fact that finely crystalline dolomite obliterates allochem structures that may be clearly visible in more coarsely crystalline dolomite within the very same bed of one thin section.

Almost indisputable evidence of calcite replacing dolomite has been observed in several thin sections. In one typical thin section, the bulk of the rock consists of microcrystalline calcite. At one end of the thin section there are abundant normal dolomite crystals embedded in the calcite; but as one traverses the thin section the dolomite rhombs gradually come to contain more and more calcite inclusions, so many that the enclosing dolomite crystal becomes a virtual sponge and is scarcely visible. In the final stage, the entire dolomite rhomb is replaced by a mosaic of fine-grained xenomorphic calcite, coarser and clearer than the surrounding microcrystalline calcite (Pl. 47, C-E). The external rhombic form of the pseudomorph remains sharply defined, however, even when calcitization is complete. When this specimen is etched, one can see the solid white dolomite crystals at one end of the rock; in the center of the specimen the dolomite crystals become more and more spongy as the calcite inclusions are dissolved, and at last at the other end of the rock there is no trace of dolomite remaining. The replacing calcite has typical mosaic form and lacks twinning, and the grain size is about one-fifth to one-tenth the grain size of the dolomite rhombs replaced. At first the writer thought that these features might have resulted from complete solution of dolomite crystals and their infilling at some later time with sparry calcite, but the presence of calcite inclusions locked within the dolomite rhomb denies this idea. Next, he thought that the feature might be due to growth of skeletal dolomite crystals only partially replacing limestone, but this is negated by the fact that many of the rhomb-shaped calcite pseudomorphs after dolomite now contain no dolomite at all (shown by etching). The only evident possibility is that calcite can progressively replace dolomite under some conditions now not understood.

Calcite-silica relationships.—Nearly all of the Ellenburger chert nodules have grown by replacing calcite (not dolomite). The contrary relation of calcite replacing chert is much less common but by no means rare.

The evidence for chert replacing limestone is simply the presence of allochem ghosts in the chert nodule, as previously discussed (Pl. 47, F). Sometimes replacement of the limestone took place before the pore spaces had been cemented with calcite; for example, in some intraclast rocks the intraclasts themselves are replaced by microcrystalline quartz, but they have a radially-oriented crust of nearly idiomorphic quartz crystals or else the inter-intraclast areas are filled with chalcedonic quart or mosaic megaquartz, both of which form as cavity fillings (Pl. 48, A, B). This demonstrates that the intraclasts were replaced by chert first, then the open pores were infilled with chalcedonic quartz or megaquartz. In other specimens, chertification took place after the pores had been cemented by calcite; in these rocks, the inter-intraclast areas are filled with microcrystalline quartz (or very fine chalcedonic quartz) because these types form by replacement of a previous solid (in this case, calcite cement).

Insofar as observed, calcite replacements of chert nodules occur almost only along fractures which probably represent joints formed during structural deformation of the Ellenburger sequence (Pl. 48, C, D). Here the calcite forms large crystals up to 1.0 mm or more in diameter, often arranged in parallel groups straddling the fracture and, as Cloud and Barnes (1948) have said, simulating rock candy crystals on a string. If the chert nodule contains dolomite inclusions, these dolomite crystals are unaffected by calcite replacement and remain as indigestible inclusions in the calcite (Pl. 48, C).

In a few interesting thin sections, both quartz and calcite have formed in the very same pore as directly precipitated cements or cavity fillings with no replacement (Pl. 48, E, F). Either quartz or calcite may come first. If quartz is early, it encrusts the allochems with radial crystals showing very smooth geometrical faces and lacking carbonate inclusions, while the sparry calcite filling the rest of the pore has typical mosaic appearance. One might postulate that quartz is growing perfect crystals by replacing calcite, but in all other carbonate sequences examined by the writer such replacement quartz has pitted, irregular crystal faces and numerous undigested calcite inclusions. Clear quartz with smooth crystal faces is consequently regarded as good evidence of a direct precipitation origin of the quartz.

It might be apropos to mention here that detrital quartz is seldom if ever seen replaced by calcite in the Ellenburger sequence. In many thin sections calcite at first glance appears to have eaten into the edge of the sand grains, but under high magnification it is seen that this is merely the effect of overlap due to the thickness of the thin section.

Dolomite-silica relationships.—Chert can be replaced by dolomite, and dolomite can in turn be replaced by chert and flamboyant quartz spherulites, but none of these relationships are of much importance volumetrically. Sometimes chert nodules are replaced by dolomite rhombs growing in parallel position strung out along fractures (Pl. 49, A, B). More commonly, though, the chert nodules are replaced by isolated dolomite crystals 0.1 to 0.3 mm in length which occur scattered more or less uniformly throughout. In the Ellenburger rocks, nearly all such replacement dolomite can be recognized by a very peculiar, extremely intense "pleochroism"; as the thin section is rotated with only the lower, polarizing nicol in use, the dolomite crystal will change from nearly invisible to almost solid black (Pl. 49, C, D). When thin edges of the dolomite crystals are examined under high magnification the reason for this is seen to be that the dolomite crystals, although showing good crystal form, are veritable spongy networks thoroughly crammed with subspherical undigested chert inclusions a few microns in diameter. It is the high relief of the dolomite against these myriad swarms of minute chert inclusions that is responsible for the "pleochroism." Sometimes allochem structures, especially oolites, are preserved through initial replacement by chert and later replacement of the same area by dolomite. When chert replaces the oolites, the concentric banding is preserved by differences in crystal size and inclusions in the chert; these differences are then retained when the chert is later replaced by dolomite (Pl. 49, E, F).

Chert occasionally replaces dolomite leaving behind excellent evidence in the form of chalcedony or quartz pseudomorphs after dolomite rhombs (Pl. 50, A, B). The material comprising these replaced rhombs is much more coarse grained and clearer than the surrounding chert. Commonly, undigested remnants of the dolomite crystal are left behind either as scattered 1- to 3-micron grains, physically separated but optically continuous, or as partial to complete rhombic zones, appearing like a series of nested walls or hollow rhombs (Pl. 50, C, D). Apparently some growth bands in the dolomite crystal were more resistant to silicification.

In other specimens, spherulites made up of radial flamboyant quartz, chalcedonic quartz, or more rarely microcrystalline quartz replace dolomite rock, but here the texture of the rhombs is completely destroyed and the spherulite shows no evidence of the rock that formerly existed in its place. A replacement origin is proven, however, because the edges of the spherulites are highly irregular but have a strong tendency to be convexly scalloped, eating into the dolomite (Pl. 45, D-F). Furthermore, single dolomite crystals become intricately "motheaten" by the advancing siliceous wave, some rhombs almost appearing as if they had been bored into by minute worms (Pl. 50, E, F). Undigested remnants of the dolomite crystal, physically isolated but in optical parallelism, are left behind and surrounded by silica.

Commonly limestone is replaced by both chert and dolomite and the question arises, which came first? Apparently both situations can happen. If an elliptical chert nodule is embedded in a replacement dolomite rock, the chert nodule usually preserves the finest details of the allochem structures of the original limestone, while the dolomite crystals preserve only vague ghosts of the larger structures and none of the finer details. Hence it is unlikely that the chert nodule could have formed by replacing dolomite, after that same dolomite had previously replaced limestone, because the structures would certainly not be preserved through this two-stage replacement (obliteration of the fine details by dolomite would make it impossible for these details to be "exhumed" by chert replacement). Therefore, we can here assume two alternate hypotheses: Either (1) the chert came in first, replacing an elliptical area of limestone, and then the dolomite came in and replaced all the surrounding limestone; or (2) the dolomite came in first, replacing all the limestone except for an elliptical area which remained limestone, and later, chert came in and replaced the residual elliptical area. Possibility (1) seems much more likely; therefore, the writer feels that replacement by chert usually happens prior to dolomitization. In a few specimens, the opposite relation occurs; the limestone contains scattered bands of dolomite crystals, and a chert nodule within the limestone contains similar dolomite crystals in similar amounts and in bands continuous with the dolomitic bands of the limestone. Here it seems that the dolomite came in first; then the chert nodule replaced the limestone but retained the dolomite as indigestible inclusions.

Thus, in Ellenburger rocks, there is no set paragenetic order and each thin section must be analyzed carefully on its own merits. It is hoped the criteria given above may prove useful.

Following is a summary of most of the observed relationships, arranged in probable time sequence:

(1) Mechanical deposition of allochems and microcrystalline ooze (if any).
(2) Cementation of pore space by sparry calcite.
(3) Chert replaces calcite; allochem structures always preserved (usually happens after (2), sometimes before; usually before (4), sometimes after).
(4) Dolomite replaces calcite; allochem structures usually faintly preserved but very often obliterated (usually happens after (2), sometimes before; usually after (3), sometimes before).
(5) Chert and quartz replace dolomite; if silica is in the form of spherulites, texture of dolomite is destroyed; if chert occurs as nodules, rhomb pseudomorphs remain (happens after (4), may be before or after (7)).
(6) Dolomite replaces chert; intensely "pleochroic" crystals form, may or may not preserve structures of chert (happens after (3), may be before or after (7)).
(7) Fracturing (probably during tectonism); veinlets filled with calcite, dolomite, megaquartz, or rarely sulfides.
(8) Calcite replaces chert; crystals "spill out" from fractures, thus happens after (7). Dolomite may also replace chert in the same way.

Structures

Bedding.—Most thin sections show some evidence of bedding, either because of the presence of laminae of different-sized transported particles or because of the parallel orientation of elongated allochems. In many dolomites the bedding is obscure and shown only as layers of dolomite crystals of differing size (Pl. 51, A). Some are finely laminated, with layers of the order of a millimeter thick or less. In some specimens bedding is "curdled" or badly disturbed by slumping (Pl. 51, B).

Veins.—Several types of veins are present. The most common type consists of nearly straight veins averaging 0.05 to 0.2 mm wide, filled with finely crystalline dolomite or calcite, depending on the nature of the surrounding rock. These are presumably fillings of tectonic joints. In places finely crystalline megaquartz or pyrite grains occur along these fractures.

Some probable tectonic veins are up to several millimeters wide and may be filled with either (a) large crystals of calcite, dolomite, or quartz, the latter often showing zoning (Pl. 51, C, D) or (b) a brecciated mass of carbonate rock fragments (Pl. 51, E), occasional angular fragments of chert (Pl. 51, F), broken individual dolomite crystals, and clay. Occasionally shear zones are encountered, in which the two sides of the fracture have moved past each other but remained tightly shut.

A few of the thin sections show probable clastic dikes, apparently formed while the sediment was fairly soft. Many taper and may be filled with fine-grained dolomite, abraded dolomite rhombs, sand grains, and other materials usually set in a clayey matrix (Pl. 52, A, B). A few large clear dolomite crystals jut out into the clayey filling from the sides of the cavity (Pl. 52, C, D). Some of these clastic dikes are cut by small tectonic joints (Pl. 52, E).

Stylolites.—Stylolites (Pl. 52, F; Pl. 53, A) appear to be equally common at all levels in the Ellenburger. Usually they are parallel with the bedding, but some transect it. They vary from slightly undulating seams which could hardly be called stylolites to tremendously jagged lines with fluted vertical columns up to 1 centimeter long. They are usually lined with black, opaque material (probably tightly compressed clay and organic matter, possibly together with some dead oil) which contains tiny specks of pyrite. Other stylolites are lined chiefly with pale brownish clay; still others are filled with fibrous carbonate or fibrous quartz oriented perpendicular with the general trend of the seam. In these types it is possible that the stylolite was reopened by tectonic forces after its initial formation, then infilled with authigenic minerals.

There is no doubt that Ellenburger stylolites have formed by solution after the rock was lithified, because the stylolites cut oolites, intraclasts, fossils, pellets, carbonate ooze, dolomite rhombs, chert nodules, quartz sand grains, and calcite cement indiscriminately, and it is obvious that the dissolved portions have been removed. It is interesting to note the frequency with which rounded quartz sand grains and carbonate rocks interfinger along stylolites, indicating no apparent difference in the rate of solution of carbonate and quartz (Pl. 53, B, D). One sandstone sample showed detrital quartz grains sutured and interpenetrating along stylolitic contacts (Pl. 53, C).

Stylolites generally cut veins, and the veins abut against the stylolites. This seems to indicate that the stylolites formed after veining, although some reversals have occurred.

Porosity

No intensive study of Ellenburger porosity was made. Nevertheless, a few obvious facts were noted during description of the thin sections.

As a rule, most specimens show little or no evidence of porosity in the thin sections, although a few are quite porous. The types of porosity fall into three categories: (1) interstitial porosity, (2) solution porosity, and (3) tabular porosity.

Interstitial porosity occurs only in medium to coarsely crystalline dolomites. The pores are found in spaces between dolomite rhombs and sometimes contain dead oil (Pl. 41, A). This type of porosity probably developed early, for these dolomites are formed by replacement of limestone, and the pores probably represent what had been unreplaced residual areas of calcite. The residual calcite may have been dissolved during replacement (because the replacement of calcite by dolomite entails solution of the calcite), or it may have been dissolved somewhat later. No evidence bearing on the time of solution was found.

Solution porosity may occur in either limestone or dolomite. In limestone, it develops either by (1) preferential solution of allochems, such as fossils or oolites, leaving the surrounding cement of matrix almost unaffected, or by (2) solution of irregular areas often transecting allochems and cement indiscriminately (Pl. 53, E, F). The time of solution is not known. Some of the pores have been partially to completely closed by later precipitation of calcite or other minerals, such as anhydrite or barite; and in some, filling may have accompanied oil migration because some of the cavity-filling minerals have inclusions which look like dead oil (Pl. 55, A). Solution porosity in dolomite is less common and develops by removal of either allochems (Pl. 54, A, B) or irregular areas which may also be filled in later (Pl. 54, C-F; Pl. 55, B). In most thin sections of algal(?) reefs, large pores occur parallel with the banding.

Tabular porosity (named from the shape of the pores) is sometimes found along veins, stylolites, or bedding planes. It is a late development in the history of the rock.

In discussing the petrography of the Ellenburger group, the writer has used a modification of an earlier carbonate classification scheme (Folk, 1952), which scheme is presented here. A classification is not an end in itself but merely serves as an economical shorthand which can be used to describe the essential characters of a rock in one concise phrase. Such a shorthand is just as desirable in the study of carbonate rocks as it is in the study of igneous rocks, where the brief term "granite" refers to a phanerocrystalline, light-colored rock consisting chiefly of potash feldspar with considerable quartz and a small amount of micas, amphiboles, and other minerals.

Classification of carbonate rocks is made complex because of the great diversity of constituents present; yet a classification that does not allow for all the variations (or whose classes are so broad that significant differences are not brought out) is of very little use. At the very outset one has the problem of distinguishing between mineral composition (relative proportions of calcite, dolomite, or silica) and textural composition (relative proportions of oolites, fossils, microcrystalline ooze, and other textural elements). Thus, even at the simplest, the classification must be a binary one.

Almost all carbonate rocks contain more than one type of material; one may be a mixture of oolites, fossils, and sparry calcite cement while another may consist of quartz silt, pellets, and microcrystalline ooze partially replaced by dolomite and chert. The problem of classification is largely one in systematizing these variations in composition and drawing significant limits between types. Carbonate rocks are so complex that it is usually necessary to make a thin-section study in order to pigeonhole a specimen properly, although in some cases binocular-microscope examination of the etched surface will suffice.

Disregarding for a moment the content of terrigenous material, it is possible to base a practical limestone classification on the relative proportions of three end-members: (1) allochems, (2) microcrystalline ooze, and (3) sparry calcite cement.

Allochems represent the framework of the rock: the shells, oolites, carbonate pebbles or pellets that make up the bulk of most limestones, analogous to the quartz sand of a sandstone or the pebbles of a conglomerate. Microcrystalline ooze represents a clay-size "matrix" whose presence signifies lack of vigorous currents, just as the presence of a clay-mineral matrix in a sandstone indicates poor washing. Sparry calcite cement simply fills up pore spaces in the rock where microcrystalline ooze has been washed out, just as porous, nonclayey sandstones frequently become cemented with chemical precipitates. Thus the relative proportions of microcrystalline ooze and sparry calcite cement are an important feature of the rock, inasmuch as they show the degree of "sorting" or current strength of the environment. If we plot these two constituents and the allochemical "framework" as three poles of a triangular diagram (fig. 12), the field in which limestones occur is shown by the shaded area; divisions between the three major textural types of limestone are also shown in this diagram. A similar field would appear if one plotted terrigenous rocks on a triangle with the three poles of sand and silt, clay, and chemical cement (fig. 12).

This classification is predicated on the assumption that the sparry calcite and microcrystalline calcite now visible in the rock are the original inter-allochem constituents—that is, that sparry calcite has not formed by recrystallization of a fine calcite ooze, and that microcrystalline calcite has not formed by degenerative recrystallization[9] of coarser calcite. In the Ellenburger rocks and most other carbon-

[9] Term suggested in personal communication by R. J. Dunham, Shell Development Company, Houston, Texas.

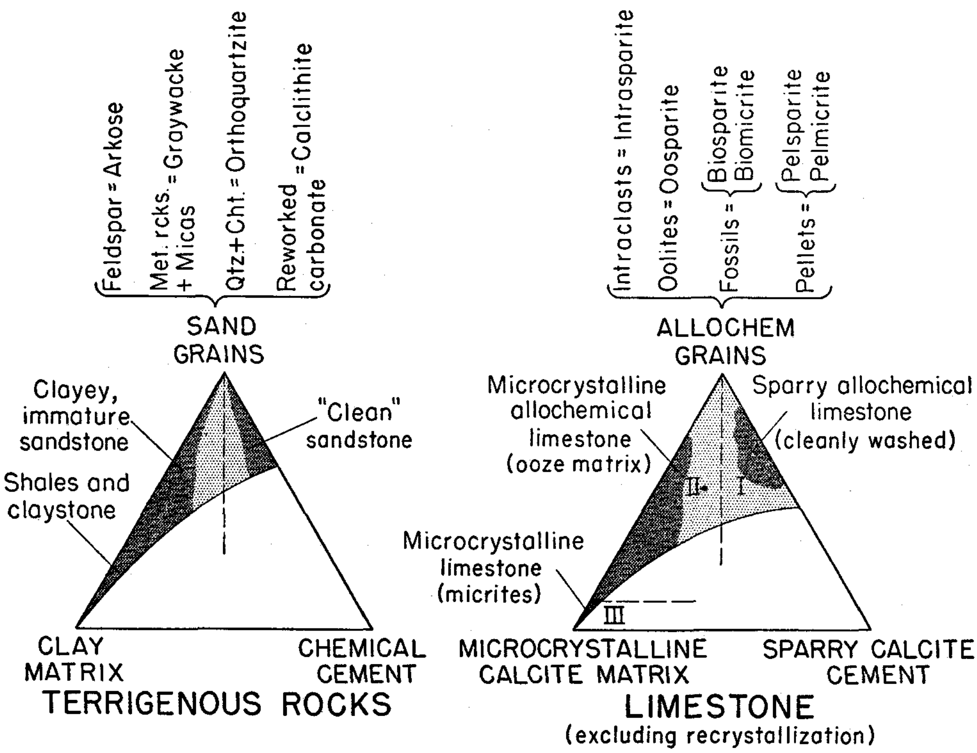

FIG. 12. Diagram comparing the limestone classification given in present paper with an analogous classification of terrigenous rocks. Shaded areas are those parts of the composition triangle which occur most commonly.

Terrigenous rocks could be classified using the proportion of sand grains (structural framework fraction), clay matrix, and chemical cement, the proportions of the latter two being an index to the degree of sorting.

Non-recrystallized limestone can be classified using the proportion of allochems (structural framework fraction), microcrystalline calcite matrix, and sparry calcite cement, the proportions of the latter two also being an index of sorting.

Three basic limestone families are proposed: sparry allochemical limestone (Type I), representing good sorting; microcrystalline allochemical limestone (Type II), representing poorly winnowed sediments; and microcrystalline limestone (Type III), analogous to claystone in the terrigenous triangle. Just as one uses the composition of sand grains to further classify terrigenous rocks into arkose, graywacke, orthoquartzite, and calclithite—each ranging from clayey to nonclayey—so one uses the composition of the allochems to divide limestone into subvarieties, such as intrasparite or biomicrite.

ates the writer has worked on, this assumption is believed to be very largely true. Nevertheless, the writer agrees that recrystallization is a very important process in some other limestone formations, and the classification proposed here does not apply to recrystallized rocks.

Type I limestones (designated as *sparry allochemical rocks*) consist chiefly of allochemical constituents cemented by sparry calcite cement. These rocks are equivalent to the well-sorted terrigenous conglomerates or sandstones in that solid particles (in this case intraclasts, oolites, fossils, or pellets) have been heaped together by currents powerful or persistent enough to winnow away any microcrystalline ooze that otherwise might have accumulated as a matrix, and the interstitial pores have been filled by directly precipitated sparry calcite cement. The relative proportion of sparry calcite cement and allochems varies within rather restricted limits because of the limitations of packing: (1) There is a limit to the tightness with which allochems may be packed; thus there will always be

TABLE 4. *Classification of carbonate rocks.* Asterisk (*) designates rare rock types.

VOLUMETRIC ALLOCHEM COMPOSITION	LIMESTONE, PARTIALLY DOLOMITIZED LIMESTONE, AND PRIMARY DOLOMITE[1–6]: > 10% Allochems ALLOCHEMICAL ROCKS — Sparry calcite cement > Microcrystalline ooze matrix: SPARRY ALLOCHEMICAL ROCKS[6] (I)	> 10% Allochems ALLOCHEMICAL ROCKS — Microcrystalline ooze matrix > Sparry calcite cement: MICROCRYSTALLINE ALLOCHEMICAL ROCKS (II)	< 10% Allochems MICROCRYSTALLINE ROCKS (III) — 1–10% Allochems (Most abundant allochem)	< 10% Allochems MICROCRYSTALLINE ROCKS (III) — < 1% Allochems (IIIm)	BIOHERMAL ROCKS, UNDISTURBED ORGANISMS IN GROWTH POSITION (IV)	REPLACEMENT DOLOMITE[7] (V) — Allochem ghosts (Evident allochem)	REPLACEMENT DOLOMITE[7] (V) — No allochem ghosts
> 25% Intraclasts (i)	Intrasparrudite (Ii:Lr) Intrasparite (Ii:La)	Intramicrudite* (IIi:Lr) Intramicrite* (IIi:La)	Intraclasts: Intraclast-bearing micrite (IIIi:Lr or La)	Micrite (IIIm:L) If disturbed, Dismicrite (IIImX:L) If primary dolomite, Dolomicrite (IIIm:D)	Biolithite (IV:L) (Specified as coral biolithite, algal biolithite, etc.)	Finely crystalline intraclastic dolomite (Vi:D3), etc.	
< 25% Intraclasts; > 25% Oolites (o)	Oosparrudite* (Io:Lr) Oosparite (Io:La)	Oomicrudite* (IIo:Lr) Oomicrite* (IIo:La)	Oolites: Oolite-bearing micrite* (IIIo:Lr or La)			Coarsely crystalline oolitic dolomite (Vo:D5), etc.	Medium crystalline dolomite (V:D4)
< 25% Intraclasts; < 25% Oolites; Volume ratio of fossils to pellets > 3:1 (b)	Biosparrudite (Ib:Lr) Biosparite (Ib:La)	Biomicrudite (IIb:Lr) Biomicrite (IIb:La)	Fossils: Fossiliferous micrite (IIIb:Lr, La, or Ll)			Aphanocrystalline biogenic dolomite (Vb:D1), etc.	
< 25% Intraclasts; < 25% Oolites; Volume ratio of fossils to pellets 3:1 to 1:3 (bp)	Biopelsparrudite* (Ibp:Lr) Biopelsparite (Ibp:La)	Biopelmicrudite* (IIbp:Lr) Biopelmicrite (IIbp:La)					Finely crystalline dolomite (V:D3), etc.
< 25% Intraclasts; < 25% Oolites; Volume ratio of fossils to pellets < 1:3 (p)	Pelsparite (Ip:La)	Pelmicrite (IIp:La)	Pellets: Pelletiferous micrite (IIIp:La)			Very finely crystalline pellet dolomite (Vp:D2), etc.	

1. Names and symbols refer to limestone. If the rock contains over 10 percent replacement dolomite, prefix the term "dolomitized" to the rock name and use "DLr" or "DLa" for the symbol (*e.g.*, dolomitized intrasparite, Ii:DLa). If the rock contains over 10 percent dolomite of uncertain origin, prefix the term "dolomitic" to the rock name and use "dLr" or "dLa" for the symbol (*e.g.*, dolomitic pelsparite, Ip:dLa). If the rock consists of primary dolomite, prefix the term "primary dolomite" to the rock name and use "Dr" or "Da" for the symbol (*e.g.*, primary dolomite intramicrite, IIi:Da). Instead of "primary dolomite micrite" (IIIm:D), the term "dolomicrite" may be used.

2. Upper name in each box refers to calcirudites (median allochem size larger than 1.0 mm) and lower name refers to all rocks with median allochem size smaller than 1.0 mm. Grain size and quantity of ooze matrix, cements, or terrigenous grains are ignored.

3. If the rock contains over 10 percent terrigenous material, prefix "sandy," "silty," or "clayey" to the rock name and "Ts," "Tz," or "Tc" to the symbol, depending on which is dominant (*e.g.*, sandy biosparite, TsIb:La, or silty dolomitized pelmicrite, TzIIp:DLa). Glauconite, collophane, chert, pyrite, or other modifiers may also be prefixed.

4. If the rock contains other allochems in significant quantities that are not mentioned in the main rock name, these should be prefixed as qualifiers immediately before the main rock name (*e.g.*, fossiliferous intrasparite, oolitic pelmicrite, pelletiferous oosparite, or intraclastic biomicrudite). This can be shown symbolically as Ii(b), Io(p), IIb(i), respectively.

5. If the fossils are of rather uniform type, this fact should be shown in the rock name (*e.g.*, pelecypod biosparrudite, crinoid biomicrite).

6. If the rock was originally microcrystalline and can be shown to have recrystallized to microspar (5- to 10-micron, clear calcite), the terms "microsparite," "biomicrosparite," etc., can be used instead of "micrite" or "biomicrite."

7. Specify crystal size as shown on the examples (see table 5).

some pore space available for cement to fill; and (2) there must be a certain minimum amount of allochems present in order to support the structure—sparry calcite cement grows only in pore spaces and cannot form a rock in its own right (except where recrystallization has occurred). It may be noted that carbonate rocks on deposition often have porosity much greater than sandstones or conglomerates of equivalent size because of the irregular shapes of fossils and other allochems.

Type II limestones (designated as *microcrystalline allochemical rocks*) consist also of a considerable proportion of allochems, but here currents were not strong enough or persistent enough to winnow away the microcrystalline ooze, which remains as a matrix; sparry calcite cement is very subordinate or lacking simply because no pore space was available for it to occupy. These rocks are equivalent texturally to the clayey sandstones or conglomerates, which also tend to have little cement. In these rocks the restrictions of packing impose a certain maximum on the amount of allochems; yet there is no minimum, and microcrystalline allochemical rocks are found with percentages of allochems (interclasts, oolites, fossils, or pellets) varying from about 80 percent down to almost nothing. The reason for this is that microcrystalline ooze can form a rock in its own right (comparable with a claystone in the terrigenous rock series) and can accept any amount of allochem material that becomes mixed with it. Thus the boundary line between microcrystalline allochemical rocks and microcrystalline rocks is entirely arbitrary and has been set at 10 percent allochems.

Type I limestones indicate strong or persistent currents; Type II limestones indicate weak, short-lived currents or a rapid rate of formation of microcrystalline ooze; and most limestones can be assigned readily to one or the other of these two classes because usually either sparry calcite or microcrystalline ooze is clearly dominant. In some rocks there are transitions, however, either because (1) washing is incomplete and the ooze is only partially removed, or (2) in some very fine-grained pellet limestones, the pore spaces between pellets are so tiny that sparry calcite crystals are very minute and can only with great difficulty be told from microcrystalline ooze. These transitional types can be designated by the symbol I-II. Again this classification applies only to those rocks in which no significant recrystallization has occurred.

Type III limestones (the *microcrystalline rocks*) represent the opposite extreme from Type I, inasmuch as they consist almost entirely of microcrystalline ooze with little or no allochem material and no sparry calcite. This implies both a rapid rate of precipitation of microcrystalline ooze together with lack of strong currents. Texturally, they correspond to the claystones among the terrigenous rocks.

Some microcrystalline rocks have been disturbed by either boring organisms, shrinkage, or soft-sediment deformation, and the resulting openings are filled with irregular "eyes," nests, or stringers of sparry calcite. Other beds of microcrystalline ooze have been partially torn up by bottom currents and rapidly redeposited but without the production of distinct intraclasts. These are considered as *disturbed microcrystalline rocks*, and a special symbol and rock term ("dismicrite") is used for them (table 4).

Bioherm rocks (Cummings and Shrock, 1928), made up of organic structures growing in situ and forming a mound, are unique and placed in a special class, Type IV. Of course, if these bioherms are broken up and redeposited the resulting rock is considered to be made up of intraclasts or biogenic debris and falls in Type I or Type II, depending on the interstitial material.

After the main division of limestones into Types I, II, or III, it is essential to determine whether the allochemical portion consists of intraclasts, oolites, fossils, or pellets. The scheme for classification is presented in table 4. The division lines between the groups are set at levels believed to reflect the significance of the constituent; for example, intraclasts are so important genetically, evidencing erosion of previously deposited limestone and possibly indicating tectonic uplift, that a rock is called an intraclastic rock if it contains only 25 percent intraclasts, although it may have 60 or 70 percent fossils or oolites. Whether a rock is intraclastic, oolitic, biogenic, or pelletiferous is indicated by adding "i", "o", "b", or "p" to the symbol I or II or III, as in sparry intraclastic rocks (Ii) or microcrystalline biogenic rocks (IIb).

So far, gross texture (whether sparry allochemical, microcrystalline allochemical, or microcrystalline) and composition of allochems (whether intraclasts, oolites, fossils, or pellets) have been included in the classification, but nothing has been said about grain size of the allochems. If the allochems average coarser than 1 mm, the rock is a calcirudite (or dolorudite); if they lie between 0.0625 and 1 mm, the rock is calcarenite or dolarenite; and if the allochems average finer than 0.0625 mm, the rock is a calcilutite or dololutite (table 5). In determining the grain-size name, only the size of the allochems is considered; percentage or crystal size of microcrystalline ooze or sparry calcite and grain size of terrigenous material are ignored. Thus a rock consisting of 20 percent brachiopod shells embedded in microcrystalline ooze and quartz sand is here called a calcirudite, just as much as a rock consisting of 80 percent limestone pebbles cemented by sparry calcite.

In theory, the threefold size classification just given is valid; but in practice, rocks with *allochems* averaging in the calcilutite

TABLE 5. *Grain-size scale for carbonate rocks.*

Carbonate rocks contain both physically transported particles (oolites, intraclasts, fossils, and pellets) and chemically precipitated minerals (either as pore-filling cement, primary ooze, or as products of recrystallization and replacement). Therefore, the size scale must be a double one, so that one can distinguish which constituent is being considered (for example, coarse calcirudites may be cemented with very finely crystalline dolomite, and fine calcarenites may be cemented with coarsely crystalline calcite). For obviously allochemical dolomites, the terms "dolorudite," "dolarenite," and "dololutite" are substituted for those shown. The authigenic size scale is most useful for dolomites, where transported particles are usually obliterated by replacement, and crystal size is one of the few describable characteristics. Most dolomites fall in the medium crystalline range.

Boundary values	Transported constituents	Authigenic constituents	Boundary values
	Very coarse calcirudite	Extremely coarsely crystalline	
64 mm			
	Coarse calcirudite		
16 mm			
	Medium calcirudite		
4 mm			4 mm
	Fine calcirudite	Very coarsely crystalline	
1 mm			1 mm
	Coarse calcarenite	Coarsely crystalline	
0.5 mm			
	Medium calcarenite		
0.25 mm			0.25 mm
	Fine calcarenite	Medium crystalline	
0.125 mm			
	Very fine calcarenite		
0.062 mm			0.062 mm
	Coarse calcilutite	Finely crystalline	
0.031 mm			
	Medium calcilutite		
0.016 mm			0.016 mm
	Fine calcilutite	Very finely crystalline	
0.008 mm			
	Very fine calcilutite		
			0.004 mm
		Aphanocrystalline	

range are very rare. The only allochem rock types with representatives in this size class are pellet rocks or biogenic rocks, and in both of these the pellets or fossil fragments scarcely ever average smaller than 0.04 or 0.05 mm, just barely under the limit of calcarenite. Setting a new textural rock class apart on such an artificial and insignificant boundary seems to be an unnecessary complication; hence the writer has lumped these rare allochem calcilutites together with the calcarenites in the classification scheme. If the need arises, one can always add "lutite" to the word in the same manner as "rudite": for example, biomiclutite and pelsparlutite. The only common calcilutites are the "pure" microcrystalline oozes, although in the field and under a binocular microscope many pellet rocks appear as calcilutites.

All the rock characteristics discussed above are combined in single names, shown in table 4 and diagrammatically in figure 13. At first the writer used such cumbersome terms as "sparry intraclastic calcarenite" for intrasparite and "microcrystalline biogenic calcirudite" for biomicrudite, but these names, although self-explanatory, were felt to be too awkward to use in descriptions. As an alternative he thought of introducing locality terms, but the localities would be difficult to choose and the terms in themselves would be entirely meaningless and difficult to memorize. Finally, the writer decided to use composite words, each portion of which referred to a specific rock characteristic: thus "intra" for intraclastic rocks, "oo" for oolitic rocks, "bio" for biogenic types, and "pel" for pellet rocks. Whether the rocks are Type I or Type II is shown by the second part of the name, "spar" for those with sparry calcite cement and "micr" (pronounced with a short "i," as in "mick") for

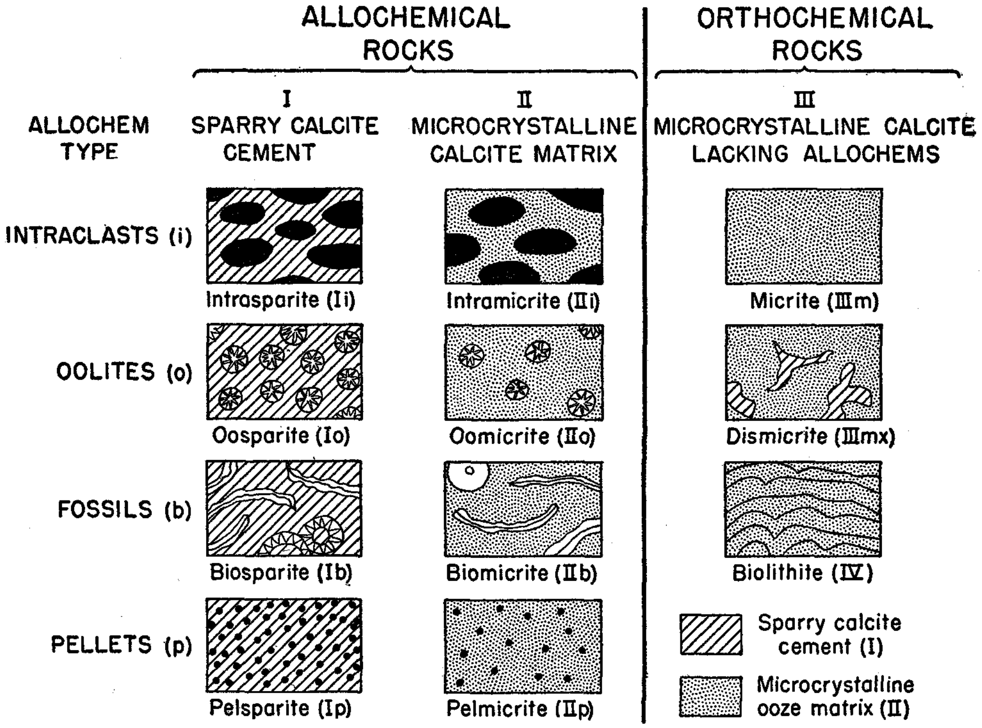

FIG. 13. Diagram showing the eleven fundamental limestone types. Allochemical rocks are first divided on the basis of predominance of sparry calcite cement (Type I) or microcrystalline calcite ooze matrix (Type II). Further division is made by determining the amount of the various allochems. Orthochemical rocks fall into three groups: homogenous microcrystalline ooze (micrite), disturbed microcrystalline ooze (dismicrite), or biohermal rocks (biolithite).

those with microcrystalline ooze matrix. Type III limestones, almost entirely ooze, are designated "micrite" (pronounced "mick-rite") without any allochem prefix. Inasmuch as most limestones are calcarenites, no further syllable is added if the size falls in that category, and, as explained above, the rare and somewhat artificial calcilutites are lumped together with the calcarenites in this table. If it is felt important to differentiate the calcirudites, though, the word segment "rudite" is added if the size falls in that class. Examples, together with the symbols used, are presented in the table.

Some rocks classified as oosparite, intramicrudite, and others may have significant amounts of other allochems which do not appear in the name. These may be specified at the discretion of the worker, such as fossiliferous oosparite or oolitic intramicrudite. Biogenic rocks, if composed largely of one type of organism, should also be described as brachiopod biomicrudite, gastropod biosparite, depending on what type of fossil is dominant. If desirable (and if differentiation is possible), rocks containing fossils in growth positions may be specially designated as "autochthonous brachiopod biomicrite," etc.

The writer has not yet adapted this classification to rocks in which recrystallization has been important; any such attempt would be quite premature until these rocks have been better studied and their importance evaluated. One recrystallized rock type appears to be of rather frequent occurrence in limestones, however (although the writer has seen none in the Ellenburger specimens). These rocks would be classified as micrites, Type III, or biomicrites, Type IIb (that is, nearly pure microcrystalline ooze or fossils in an ooze matrix, respectively), were it not for the fact that the microcrystalline calcite is coarser than normal—the grains are still equidimensional and uniform in size but average 5 to 10 microns instead of 2 to 5 microns. Because this relatively coarser material occupies large areas or makes up the entire specimen, it cannot have formed as a cement and probably represents aggrading recrystallization of a "normal" microcrystalline ooze matrix. These rocks the writer has tentatively designated as microsparite (corresponding to micrite) and biomicrosparite (corresponding to biomicrite), with symbols RIIIm and RIIb, respectively.

Carbonate Content

All of the rock types described above and listed in table 4 can occur either as limestone or as dolomitized limestone, and some may occur as primary dolomite. Overall texture is combined with carbonate composition in a double symbol linked with a colon, as shown in the table. If the rock is a limestone, the rock name (for example, oosparite or pelmicrite) is used unmodified and the symbol applied is Lr or La (for calcirudites and calcarenites, respectively). For example, an intrasparrudite would be designated as Ii:Lr. If the rock contains over 10 percent replacement dolomite, the term "dolomitized" is prefixed to the main rock name and the symbols DLa or DLr are used (for example, dolomitized oosparite, Io:DLa, or dolomitized pelmicrite, IIp:DLa). If the dolomite is of uncertain origin, the term "dolomitic" and the symbols dLr and dLa are suggested. If the rock is primary dolomite (syngenetic, non-replacement), this term is prefixed to the rock name and Dr or Da is used for the symbol (for example, primary dolomite intramicrudite, IIi:Dr). For primary microcrystalline dolomite ooze, the term dolomicrite may be used (term suggested by T. W. Todd, Department of Geology, The University of Texas).

Limestones that have been completely replaced by dolomite offer considerable difficulty because in many cases the original structure is partly obliterated. Fine-grained clastic particles, such as pellets or finely broken fossils, are especially prone to vanish. Likewise, one does not know the original proportion of microcrystalline ooze versus sparry calcite cement. In such examples it is very difficult if not impossible to allot a dolomite to either Types I, II, or III, and it seems best to lump arbitrarily all such completely metasomatized rocks into a distinct class, Type V; if ghost oolites, fossils, intraclasts, or pellets are present, that fact can be indicated by a symbol such as Vo, Vb, Vi, or Vp, respectively, and if no allochem ghosts are recognizable it should simply be listed as Type V. The crystal size of these rocks is a very important characteristic and should be shown by the following terms and symbols:[10]

	Symbol	*Millimeters*
Aphanocrystalline	D1	Under 0.0039
Very finely crystalline	D2	0.0039–0.0156
Finely crystalline	D3	0.0156–0.0625
Medium crystalline	D4	0.0625–0.25
Coarsely crystalline	D5	0.25–1.00
Very coarsely crystalline	D6	1.00–4.00
Extremely coarsely crystalline	D7	over 4.00

Examples of rock names in Type V are medium crystalline intraclastic dolomite (Vi:D4), finely crystalline biogenic dolomite (Vb:D3), and for a rock with no visible allochems, coarsely crystalline dolomite (V:D5).

Terrigenous Content

So far we have ignored the content of terrigenous particles. If the rock contains over 50 perecent terrigenous material, it is a terrigenous rock and not further considered here. If it contains less than 10 percent terrigenous material, it is a pure chemical rock and the terrigenous content is so low that it is not mentioned in this classification.

However, if the rock contains between 10 and 50 percent terrigenous material, that is regarded as important enough to be mentioned in the name and in the classification symbol. These rocks as a class are known as impure chemical rocks; a specimen of this type is classified just as previously described (biomicrite, oosparite, etc.), but to identify it as an impure chemical rock the following letters are prefixed to the symbol: Ts for rocks in which the terrigenous (T) material is dominantly sand, Tz for those in which silt prevails, and Tc for rocks with clay as the most important terrigenous constituent.

Following are some examples of this usage:

Clayey biopelmicrite, TcIIbp:La
Silty coarsely crystalline dolomite, TzV:D5
Sandy dolomicrite, TsIIIm:D
Sandy dolomitized intrasparite, TsIi:DLa.

The classification used here necessarily is determined only by *relative* rates of formation of each constituent, not on absolute rates. Thus an abundance of terrigenous material in a limestone may mean that (1) uplift or proximity of the source area caused a more rapid influx of detritus; (2) a change of conditions in the depositional basin suppressed chemical activity, so that terrigenous minerals accumulated by default; or (3) current velocities were such as to concentrate terrigenous material of a certain size in preference to allochemical material of different size.

Relative Abundance of Rock Types

Some remarks may be made as to the relative abundance of these various rock types in the stratigraphic sequence as a whole. These observations are based on this writer's examination of several thousand thin sections of carbonate rocks from many regions.

Intraclastic rocks commonly have a sparry calcite cement, inasmuch as currents that are strong enough to transport fairly large carbonate rock fragments are also usually capable of washing away any microcrystalline ooze matrix. Thus rocks of Type Ii (intrasparite, Pl. 55, C) are common, whereas Type IIi (intramicrite) is relatively rare. Texturally, intraclastic rocks are about equally divided between calcirudites and calcarenites.

Oolitic rocks with their high degree of sorting imply fairly vigorous current action; therefore oosparite (Type Io, Pl. 55, D) is much more abundant than oomicrite (Type IIo). Texturally these rocks are nearly always calcarenites, although in

[10] The grain-size scale used here for crystal sizes (table 5) differs from the one used by Cloud and Barnes (1948) primarily because their scale is intended for field examination with a hand lens, while the scale used in this paper is intended for petrographic microscope studies.

some specimens the oolites may reach an average diameter larger than 1 mm, in which case the rock would be a calcirudite. Pisolite rocks should be classified as oosparrudites (or, if necessary, they might be designated pisosparites).

Biogenic rocks may occur just as frequently with a microcrystalline ooze matrix (biomicrite, Type IIb, Pl. 55, E) as with a sparry calcite cement (biosparite, Type Ib, Pl. 55, F). Type IIb rocks indicate either that the animals from which the fossils originated were sedentary or else that currents were calm in the depositional area and the microcrystalline ooze did not get winnowed out from the shell material. Type Ib rocks indicate deposition under vigorous current action where the microcrystalline material was washed away (or else no ooze was being produced). Both intraclastic rocks and oolitic rocks require vigorous current action in order to form, while biogenic rocks do not; hence the latter may have either microcrystalline matrix or sparry calcite cement. Biogenic rocks are most commonly calcirudites or calcarenites, although calcilutites occur sometimes if the fossils are very fine-grained foraminifera.

Pellet rocks are quite common but in the field or even under binocular microscope are often mistaken for microcrystalline rocks. Usually they have a sparry calcite cement and thus belong in Type Ip (pelsparite, Pl. 56, A), although sometimes they have a microcrystalline matrix (Type IIp, pelmicrite). Texturally they are borderline between very fine calcarenites or coarse calcilutites, but they are all of such uniform size that the writer designates them all as pelsparite or pelmicrite regardless of the precise average diameter of the allochems. Often they contain quartz silt and are finely laminated, and in many edgewise conglomerates the pebbles consist of silty pelsparite.

Microcrystalline rocks (micrites, Type IIIm, or dismicrites, Type IIImX, Pl. 56, B, C) occur frequently. They quite often contain more than 10 percent clay; thus Type TcIII (clayey micrite) is common; fossiliferous micrite (IIIb) is another rather frequent type.

Distribution of Rock Types in Ellenburger

When first deposited, nearly all the Ellenburger sediments were calcitic. Over three-fourths of this great volume of potential limestone was replaced by dolomite (or in some instances chert) within a short time after deposition. Thus it is difficult to estimate the original abundance of the several petrographic types of limestone because so much of the texture has been destroyed or obscured by replacement. Furthermore, replacement probably occurs more easily in some rock types, and these are selectively removed from the record. Nevertheless, the writer has made a tabulation of the petrographic types occurring in the small amount of limestone that remains, and these are presented (table 6) as a crude estimate of the original petrographic composition of the Ellenburger group. Any attempt to give a quantitative estimate of the proportionate lithology is, of course, dependent upon the nature of the sampling, and the tabulation below can only show the number of thin sections representing each rock type, that is, one thin section may represent a 6-inch bed and another a 10-foot unit, but both are counted equally. Furthermore, unusual beds or rock types are probably represented by a disproportionately large number of thin sections.

Fundamentally, sparry allochemical rocks (Type I) comprise about 60 percent of the thin sections, microcrystalline allochemical rocks (Type II) form about 10 percent, and microcrystalline rocks (Type III) make up about 30 percent. Reefs growing in situ (Type IV) comprise about 3 percent of the thin sections. A more detailed breakdown is given in table 6.

It is evident from the above tabulation that over 70 percent of the Ellenburger limestones are made up of one of three rock types: intrasparite, micrite, and pelsparite. Oosparite, biomicrite, and dismicrite make up most of the remainder. The abundance

TABLE 6. *Estimated original composition of limestone in Ellenburger group, from petrographic examination.*

- I. Sparry allochemical rocks (total, about 60%).
  - Ii. Intraclastic rocks, about 35%; three-fourths of these are intrasparite, one-fourth are intrasparrudite.
  - Io. Oosparite, about 10%.
  - Ib. Biosparite, trace.
  - Ibp. Biopelsparite, trace.
  - Ip. Pelsparite, about 15%.
- II. Microcrystalline allochemical rocks (total, about 10%).
  - IIi. Intramicrite, about 1%.
  - IIo. Oomicrite, none observed.
  - IIb. Biomicrite, about 5%.
  - IIbp. Biopelmicrite, about 2%.
  - IIp. Pelmicrite, about 1%.
- III. Microcrystalline rocks (total, about 30%).
  - IIIi. Intraclast-bearing micrite, none observed.
  - IIIo. Oolite-bearing micrite, none observed.
  - IIIb. Fossiliferous micrite, about 2%.
  - IIIp. Pelletiferous micrite, about 1%.
  - IIIm. Micrite, about 20%.
  - IIImX. Dismicrite, about 5%.
- IV. Biolithite (algal reefs), about 3%.

of these rock types is shown diagrammatically in figure 14. The few Cambrian rocks examined consist chiefly of biosparite with some pelsparite.

What conclusions can be drawn from this distribution of Ellenburger rock types? It is at once evident that diagrams showing proportionate lithologies (fig. 14) can be of considerable aid in tracing lateral environmental changes in a formation and probably also in examining vertical changes as

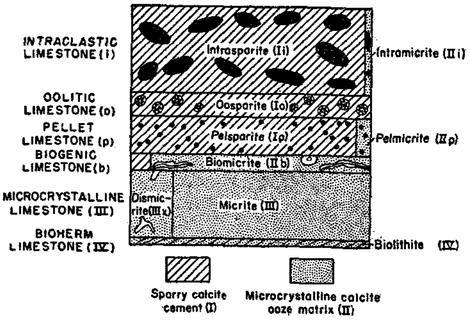

FIG. 14. Diagrammatic representation by proportional areas showing the amount of various limestone types composing the Ellenburger, excluding dolomitized limestone. Intrasparite is the most abundant limestone type, followed by micrite and pelsparite.

an aid in correlation. Not enough samples were studied for this paper to make any certain statements about consistent vertical changes in the Ellenburger, but more detailed study should reveal such changes in proportionate lithology.

Our present knowledge of limestone deposition is inadequate to determine with certainty the environmental significance of given rock types; we can make good guesses but not positive statements. From the large amount of micrite and dismicrite, one can postulate that the Ellenburger sea was a warm, shallow body of water, generally without strong or persistent currents, somewhat like the Bahama region today (Cloud and Barnes, 1948). Precipitation of microcrystalline calcite ooze occurred abundantly, either through inorganic processes or by the agency of algae or bacteria. The beds of oosparite, which are stratigraphically persistent (although repeated through the Ellenburger) presumably were deposited during times of strengthened tidal(?) current activity, as shown by Illing (1954). The stratigraphic change from a time of micrite deposition to a time of oolite deposition might be the result of physiographic changes; perhaps by the development of a more irregular bottom topography with emergent cays, which would funnel tidal currents thereby making them more rapid and forming oolites by their more vigorous activity. Impermanence or systematic migration in the position of cays would allow beds of oolites to be spread rather widely. Or perhaps a change in the physico-chemical environment, possibly a slowdown in the rate of precipitation of calcite or lessened algal or bacterial activity, might make the calcium in solution available for production of oolites by slower crystallization, instead of microcrystalline ooze.

The significance of intrasparite and pelsparite, which are very abundant in the Ellenburger, has not yet been mentioned. But these are directly dependent upon micrite and can become abundant only when micrite is itself abundant. Pelsparite is formed from micrite passed (probably) through digestive tracts of animals, and intrasparite is made up of fragments of micrite or pelsparite, torn up, rounded off, and redeposited by a sudden increase in current or wave action over the normal regimen. Stratigraphic sequences without much micrite seldom contain intrasparite or pelsparite. Thus it appears that there may be at least two super-assemblages of limestones: the micrite-pelsparite-intrasparite assemblage (formed if micrite is abundant and occasional strong currents operate) and the biosparite-oosparite assemblage (formed if micrite is scarce). The Ellenburger group is a member of the first super-assemblage, and the underlying rocks of the Cambrian appear from very preliminary work to be made up largely of the second super-assemblage. Thus the presence of abundant micrite and pelsparite shows that the generally calm, shallow Ellenburger sea had occasional storms and times of stronger current activity, which served to tear up the bottom. Animals (probably of a type that does not leave recognizable fossils) burrowed extensively through this calcite mud bottom to produce the large amount of pelsparite. Shelled animals were uncommon; therefore biomicrite and biosparite are rare, possibly because the bottom was too soft for shelled animals to flourish, as is the case in the Bahamas today. A third super-assemblage, not represented in rocks studied for this pre-Simpson project, may be the biomicrite-micrite assemblage as exemplified by the Cretaceous chalks. These may result (1) when currents are almost uniformly weak, either because the water is too deep or strong currents or waves almost never occur, or (2) when the microcrystalline calcite ooze is not cohesive; a certain degree of coherence is required for pellets or intraclasts to survive current action; hence this would explain the usual lack of intraclasts or pellets in the chalks and possibly also their incoherence in the field.

STRATIGRAPHIC CORRELATION AND REGIONAL CHANGES

Thin-section study revealed no stratigraphic zones traceable over the entire area. In the region of Winkler to Upton counties, a zone characterized by oolitic beds and composite dolomite occurs near the Honeycut-Gorman contact, but in other localities similar oolitic and composite dolomite zones appear at other places in the stratigraphic sequence (fig. 16).

All well data were plotted and examined to see if there were any other consistent trends in dolomite crystal size or characteristics, but none emerged. There is no persistent difference in average crystal size between the upper and lower portions of the Ellenburger, nor is there any consistent geographic trend.

Limestone vs. dolomite.—The proportion of limestone generally increases eastward (figs. 15, 16, 17). From Val Verde and Nolan counties westward there is little or no limestone; east of here limestone increases (tending to come in first at the top of the sequence) until in Edwards, Kendall, and Collin counties the part of the Ellenburger sampled is mostly limestone. The westward increase in evaporite tendency indicated by the abundance of dolomite (figs. 15, 16, 17) is confirmed by the presence of such sulfates as anhydrite in Presidio, Upton, and Crockett counties and barite in Andrews and Winkler counties. Pseudomorphs of dolomite or chert apparently after barite, gypsum, or anhydrite also occur only in this more evaporitic area. Although sampling is sporadic, algal reefs were also noted chiefly in the Andrews to Crockett County belt, following the evaporitic trend and flanking the highland of the Lea-Pecos County belt on the east, although there are not enough samples to make this statement much more than a hint. Calcite pseudomorphs after dolomite seem to occur only in the Crockett-Edwards-Real County area.

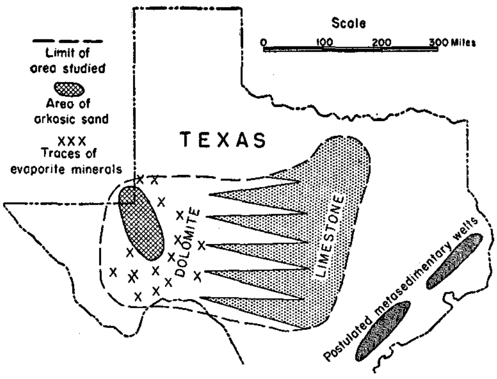

FIG. 15. Map showing areal distribution of Ellenburger lithologic types as deduced from a limited number of thin sections. Limestone increases relative to dolomite eastward, and traces of evaporites occur toward the western margin. An area of arkosic sand, presumably indicating nearness to a warm, humid, rather rugged granitic highland, occurs also in the western part of the area. There is no direct evidence for the existence and location of the metasedimentary welts; they are postulated to be present by analogy with conditions of deposition of the equivalent Beekmantown carbonates of the northern Appalachians.

It may at first sight seem contradictory that the writer has postulated more evaporitic conditions in the western part of the area studied, while at the same time he states that a linear highland with a warm, humid climate existed in the Lea-Pecos County belt, which is right in the middle of the most evaporitic part of the Ellenburger sea. This is not at all inconsistent, though, because a chain of highlands in the middle of a warm, shallow sea is bound to pick up a considerable amount of orographic rainfall, which will affect the weathering processes taking place; yet if the highlands are of limited area, the rainfall will not be enough to provide any significant freshening of the surrounding waters, especially if the climate is warm and the evaporation rate rapid.

The reason for the eastward increase in limestone is believed due to freshening of the sea water as a consequence of rainfall on a postulated more extensive series of highlands and island arcs present southeast, perhaps far southeast, of the area studied. This is suggested by the parallelism of

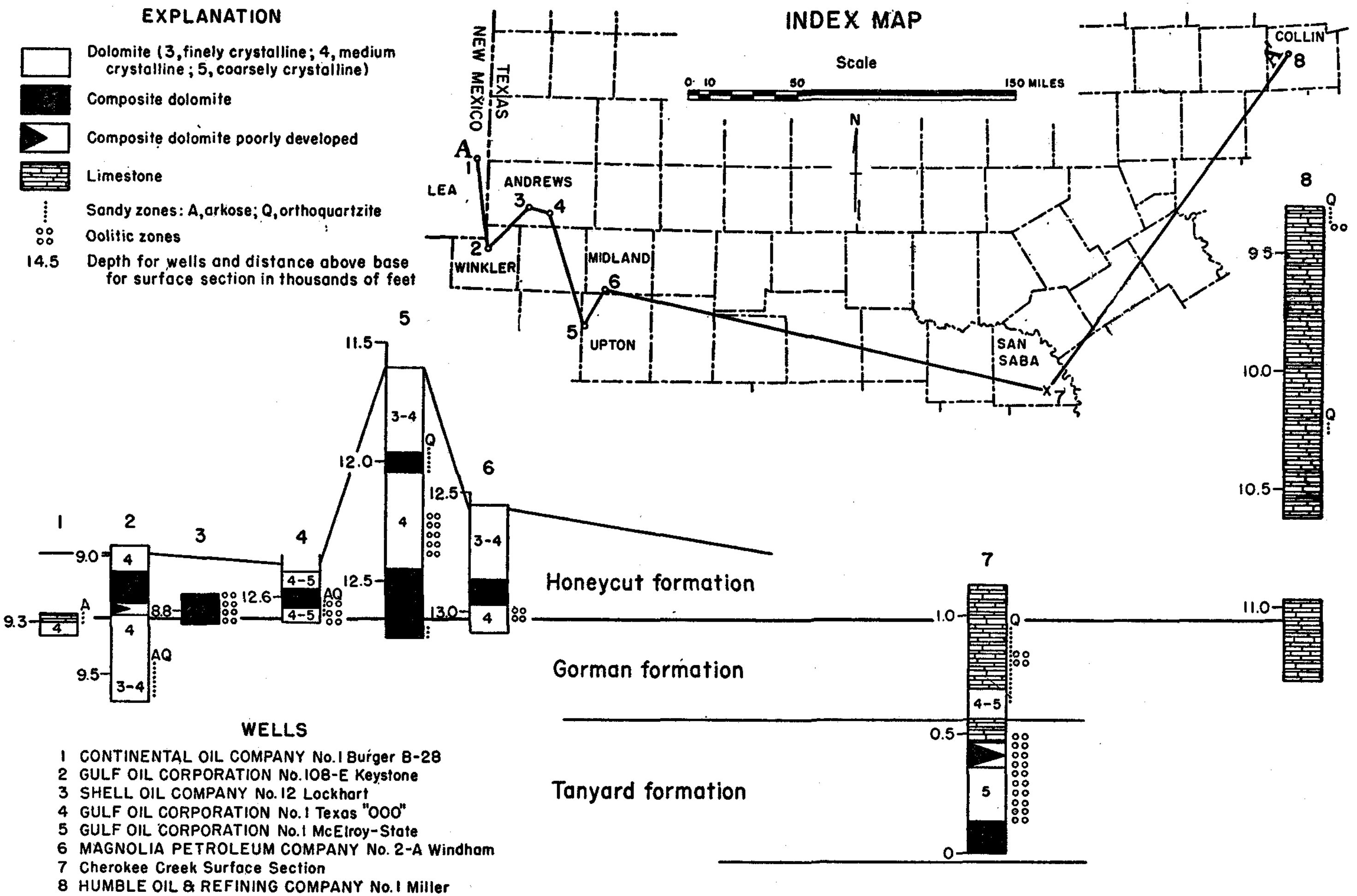

FIG. 16. Diagrammatic representation of rock characteristics of Ellenburger and Arbuckle groups as determined by thin-section examination, Lea County, New Mexico, to Collin County, Texas. Position of formation boundaries is that determined by Barnes, Plates 3, 4, and 6.

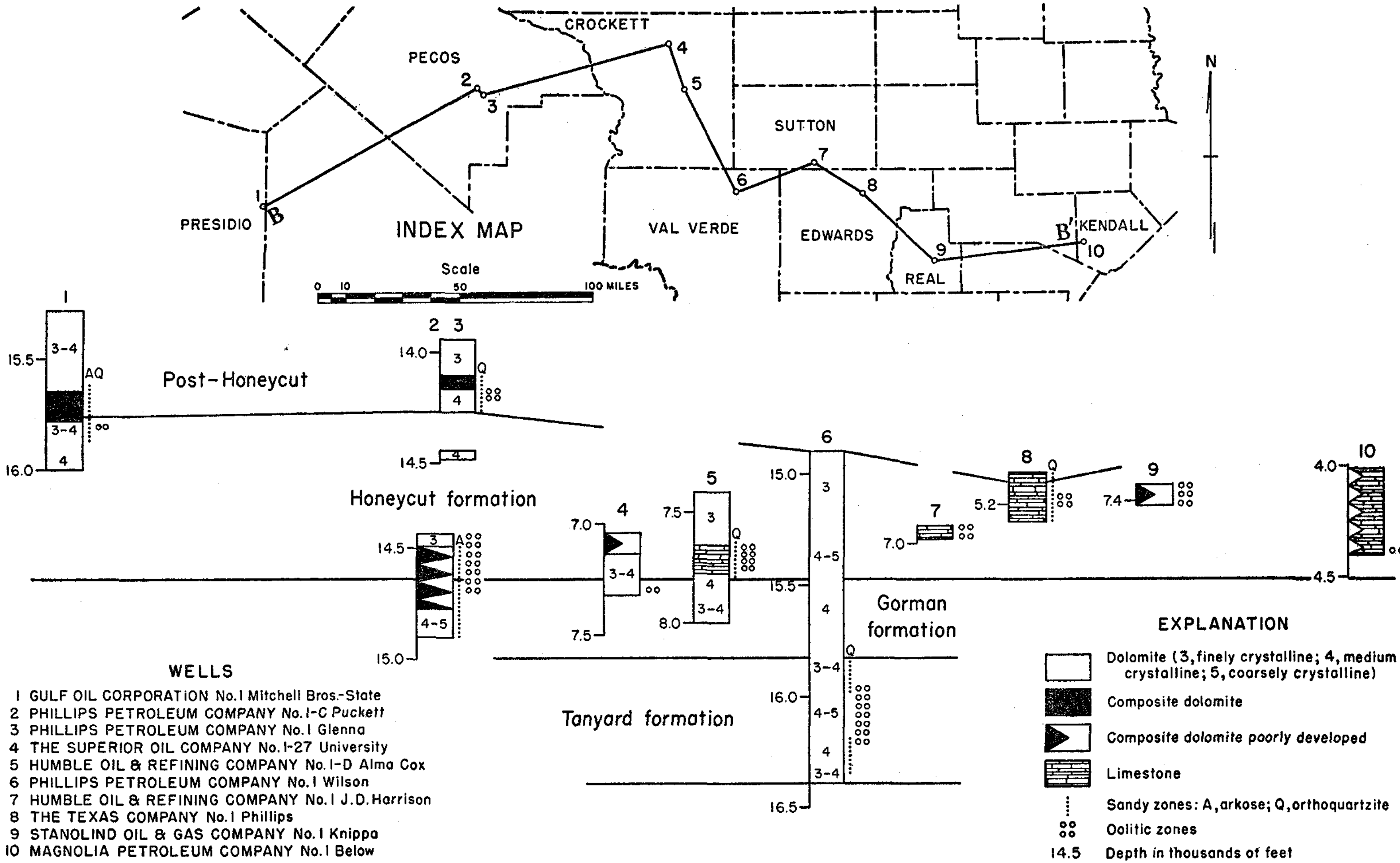

Fig. 17. Diagrammatic representation of rock characteristics of Ellenburger group as determined by thin-section examination, Presidio County to Kendall County, Texas. Position of formation boundaries is that determined by Barnes, Plates 1 and 2.

Ellenburger paleogeography with that of the equivalent-age Beekmantown carbonates of Pennsylvania, which also show subarkosic sandy dolomites to the west, grading into limestones and eventually clayey limestones and shales to the east (Folk, 1952). Here limestones developed because of the freshening of the sea water caused by rainfall on a humid eastern borderland; the same situation may have existed in Texas.

Terrigenous sand.—Arkosic sand is most abundant in a belt from Pecos County, Texas, through Lea County, New Mexico (figs. 15, 16, 17). Outside of that belt, sand occurs only as scattered laminae or isolated grains and consists almost entirely of quartz. The detritus is coarsest and contains the highest amounts of feldspar in Pecos and Lea counties; the writer interprets this as being due to a linear highland or chain of islands with greater relief at the two ends than in the middle.

Sand is generally more abundant in the lower part of the Ellenburger, but there are some conspicuous exceptions.

Chert.—Chert shows little geographic trend in abundance. In the western part of the area it appears to occur consistently in the lower part of the Ellenburger; in the east it tends to occur throughout.

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Clay-Size Minerals in Ellenburger Rocks

EDWARD C. JONAS[11]

ABSTRACT

The clay-size fraction from the insoluble residue of Ellenburger cores was studied by X-ray diffraction. Carbonate was dissolved by batch reaction of the rock with hydrogen resin to minimize the damage generally done to clay minerals by strong acids. The typical suite of clay minerals includes mica, chlorite, and an interlayer mixture of illite and montmorillonite. The rocks are characterized by varying proportions of montmorillonite in the interlayer mixture, the degree of crystallinity of chlorite, and the polymorphic form of mica.

The clay-mineral composition of Ellenburger rocks suggests that the source of this detrital material was an igneous rock subjected to mild chemical weathering and moderately rapid erosion.

INTRODUCTION

The fine-grained character of clay minerals provides them with an exceptional ability to be widely distributed in a sedimentary basin as detrital particles. Clay minerals are, because of this property, potentially important stratigraphic markers in rocks whose gross lithologic character is relatively constant. Interfering with their wide distribution and value as stratigraphic markers is their susceptibility to minor alterations in response to changes in their environment. A change in aggregate particle size (flocculation) is frequently observed to occur in a clay-mineral suite with changing environmental factors such as pH, electrolyte concentration, or electrolyte composition. Minerals of the clay suite can be selectively removed from suspension by flocculation or merely altered by chemical reactions brought about by changes in the character of the electrolyte in which they are suspended. Environmental influences can therefore inhibit the widespread distribution of a single clay-mineral suite. Only in sedimentary basins of relatively uniform chemical environment should one expect to use a clay-mineral suite as a stratigraphic marker.

On the other hand, the general sensitivity of clay minerals to environmental changes can be utilized in making interpretations of the conditions existing at the time and place the clays were deposited in each part of the basin.

The use of clay-mineral data in stratigraphic correlation or depositional environment interpretations presupposes a relatively constant source of detrital material. Variations in the detrital material delivered to a sedimentary basin will surely be reflected in the clay-mineral suite deposited. This complicating factor, like the influence of environment, can be both a disadvantage and a useful tool in developing impressions of the climatic conditions required to produce the observed clay-mineral detritus.

[11] Assistant Professor, Department of Geology, The University of Texas.

SAMPLE PREPARATION

Most of the minerals with which clay minerals are associated in sedimentary rocks are large in particle size compared with clay minerals. They, therefore, are characterized by much stronger X-ray diffraction patterns than those of clay minerals. Quartz and the carbonate minerals are good examples of this relation. It is important in any careful study of the clay-mineral content of sedimentary rocks to eliminate most of the non-clay minerals from the material used to gather diffraction data.

The simplest way of concentrating clay minerals from limestone and dolomitic rock is by chemical solution of the carbonate. Care must be taken to design a chemical treatment that is not harmful to any of the clay minerals. Chlorite even in large crystals is particularly soluble in strong mineral acids and in clay size is much more sensitive to acid. Because chlorite was almost universally present in the Ellenburger samples with which this study was concerned, it seemed wise to establish by direct observation the effect on the clay-mineral fraction of using several acids at several concentration levels.

A dolomite sample was ground and divided into ten parts, each of which was treated either with a different concentration of hydrochloric or acetic acid or with a hydrogen-ion exchange resin. The results of this experiment are given in table 7.

Ideally an evaluation of the damage to the clay wrought by acid treatment of the samples should be made on the basis of an untreated sample. An attempt to gather enough clay that was relatively pure from vein and vug fillings to establish a standard of comparison failed because these samples contained too much carbonate to allow a complete characterization of the clay minerals from the diffraction data. As a result, the best that could be done was to judge the damage to the clay minerals on a relative basis.

The sample treated with a hydrogen-ion exchange resin showed no greater damage than the least damaging acid treatment. For this reason and because the resin treatment is much more manageable than acid treatment, it was chosen for the standard sample preparation procedure.

Each sample of 15 to 20 grams was ground and mixed with 200 ml of water. The hydrogen-ion exchange resin was then added, and the mixture was stirred periodically. Because the exchange reaction with a resin is a contact reaction, solution of the carbonate stopped unless the sample particles were continuously in contact with fresh resin surfaces. In spite of this inconvenience the batch process of resin treatment was used instead of a column process because of the difficulty of suspending the carbonate sample in water to be washed through a column.

When solution of the carbonate was complete the resin was removed by washing through a 100-mesh screen. The insoluble residue was contained in a solution essentially free of dissolved salts. The resin reaction can be represented by the following equation:

$$\mathrm{MgCa(CO_3)_2 + 4H\text{-}resin \rightarrow (Ca,Mg)\text{-}resin + 2CO_2 + 2H_2O}$$

Carbon dioxide is evolved as a gas continuously during the reaction, and calcium and magnesium ions are removed with the resin by simple sieving.

The ease of removal of calcium and magnesium represents another advantage over mineral-acid solution of the carbonate. Following the reaction of hydrochloric acid with dolomite, the water in which the insoluble residue is contained is a highly concentrated solution of calcium and magnesium chloride. These dissolved salts must be removed by elutriation, which in many cases is a lengthy process. It is necessary to remove the dissolved salts in order to disperse the clay fraction of the insoluble residue to the extent that it can be separated from the larger non-clay fraction by sedimentation. If the clay was not readily dispersed in the water remaining after the resin treatment, a small amount of sodium-ion exchange resin was added.

TABLE 7. *Effect of acid and resin treatment on the clay-mineral content of cores from wells shown.*

	DISSOLVING MEDIUM	CONCEN-TRATION (PERCENT)	CLAY MINERALS IN ORDER OF ABUNDANCE	TIME REQUIRED FOR SOLUTION
Gulf Oil Corporation No. 1 McElroy-State, Upton County, depth 12,648 to 12,649 feet	Resin	....	Mica, chlorite, mixed layer	2 days
	Hydrochloric acid	36	Mica, mixed layer, chlorite (damaged)	30 minutes
	Hydrochloric acid	18	Mica, mixed layer, chlorite (damaged)	45 minutes
	Hydrochloric acid	3.6	Mica, chlorite, mixed layer	1 week
	Hydrochloric acid	0.36	Mica, chlorite, mixed layer	3.5 weeks
	Acetic acid	100	Mixed layer, mica (damaged), chlorite	4 days*
	Acetic acid	50	Mixed layer, mica (damaged), chlorite	1 week
	Acetic acid	10	Mixed layer, mica (damaged), chlorite	9 days
	Acetic acid	1	Mica, chlorite, mixed layer	4 weeks
Phillips Petroleum Company No. 1 Wilson, Val Verde County, depth 16,316 feet	Resin	....	Chlorite, mica	2 days
	Hydrochloric acid	10	Mica, chlorite (damaged)	7 days
	Acetic acid	10	Chlorite, mica (damaged)	9 days
Gulf Oil Corporation No. 1 McElroy-State Upton County, depth 11,668 to 11,669 feet	Resin	....	Mica, mixed layer, chlorite	2 days
	Hydrochloric acid	10	Mica, mixed layer, chlorite	7 days
	Acetic acid	10	Mixed layer, mica (damaged), chlorite	9 days

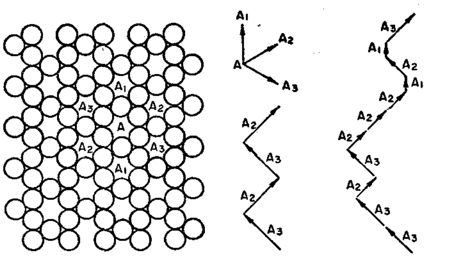
* Solution very slow until concentration is slightly reduced.

The suspension of insoluble residue was then allowed to stand one day and the clay-containing upper layer of suspension was poured off and concentrated by evaporation at a low temperature. The concentrated suspension was then poured on a flat surface and allowed to dry slowly into a flake made up of clay crystals with their *a*- and *b*-crystallographic directions parallel to the surface on which they were allowed to settle. The flakes were suspended in a 5.7-cm radius powder camera with the plane of the flake parallel to the incident X-ray beam. The diffraction pattern under these conditions consisted of lines indicating the *c*-crystallographic dimension of the minerals present. Diffraction patterns were also taken of the same flake after it had soaked in ethylene glycol for several hours and of another flake after heating over night at 150° C.

DESCRIPTION OF THE CLAY-MINERAL SUITE

All the minerals commonly found in the Ellenburger cores studied are related in that they contain the same basic silicate *structural unit, a pair of sheets formed by* the two-dimensional polymerization of silica tetrahedra which are in combination with an octahedral coordination, principally around aluminum, linking them together. The manner in which the atoms are arranged is shown by three stereograms of a model, each photograph having been taken in the direction of a crystallographic axis (Pl. 64). The unit varies slightly from 10 Angstrom units in thickness according to composition, but the major distinctions among the minerals containing this unit are based on variations in the character of the material situated between them.

Mica consists of the basic planar silicate units separated by layers of potassium which firmly bind them together allowing crystal growth in all three crystallographic directions. One silicate unit of mica can be superimposed on another in three different ways and still maintain the same relation between oxygens of the two opposing surfaces. Figure 18 shows schematically the positions of oxygen ions on the silicate-



(a) Oxygen ion arrangement for mica surface — (b) Stacking sequence for muscovite — (c) Stacking sequence for biotite

FIG. 18. Diagram illustrating mica polymorphism.

unit surface. There is perfect hexagonal symmetry about the vacant positions marked A. A similar unit above this one could be rotated about A so that A_1 of the upper unit would lie directly above A_1 of the lower unit. A second positioning with A_1 superimposed on A_2 would still allow the same oxygen-to-oxygen relationship. Likewise, positioning A_1 of the upper unit over A_3 of the lower unit would leave oxygens *of the upper layer in direct apposition* to those in the lower layer.

Because the *c*-crystallographic axis of micas is not perpendicular to the plane containing the *a*- and *b*-axes, it follows that there are three possible orientations of the *c*-axis of one silicate-unit layer with respect to that of the layer superimposed on it. Stacking sequences of these possibilities are almost limitless.

In clay-size micas, X-ray diffraction powder data generally differentiate two groups of these many possible types of crystallization. Micas which grow in pairs of layers, so that A_2 of figure 18(b) would be in the A_3 position one layer up and back in the A_2 position two layers up, form the type of crystallization that can be recognized by diffraction data. Muscovite typifies this kind of crystal growth and is contrasted with those micas in which the layer sequence is not two but one, three, etc. Powder diffraction only distinguishes one muscovite type of crystallization from those that are not the muscovite type. One cannot be sure whether the non-muscovite crystallization is a sequence of three layers or single layers randomly stacked.

Orientation-polymorphism in micas is quite independent of composition with both dioctahedral and trioctahedral micas being found in the two-layer form (Hendricks and Jefferson, 1939).

Illite contains somewhat less potassium between the basic silicate structural units than mica. As the potassium content decreases, sodium, calcium, or magnesium increase and the bond between silicate units decreases in strength. The first manifestation of the decrease in bond strength is a decreasing thickness of the "books" of stacked silicate units and an accompanying decrease in the dimensions of single crystals in both the *a*- and *b*-crystallographic directions. Continued reduction in potassium content results in all of the basic units being detached from other units and complete freedom of the layers to be separated by varying thicknesses of water or other liquids. This final condition represents the structural character of montmorillonite.

Montmorillonite, then, differs from illite principally in the ease with which the interlayer material can be hydrated. Two minerals so arbitrarily distinguished would necessarily combine to form mixtures less obviously classifiable. Stacks of the basic structural units, some of which are separated by interlayer material that easily hydrates and others by material that will not hydrate, can be described as mixed layering of montmorillonite and illite. This type of mixture is fundamentally different and easily distinguished from an ordinary physical mixture of the two minerals as could be developed by collection of sediments from two sources, one supplying montmorillonite and the other illite.

In chlorite the basic silicate units are separated by a layer of magnesium hydroxide which is closely related structurally to brucite. The hydroxide layer binds the silicate units together, preventing expansion similar to that in montmorillonite.

Within a single crystal of chlorite material the space between silicate units can be imperfectly filled with the brucite-like layers, the remaining interlayer spaces being free to adsorb water. An interlayer mixture of chlorite and montmorillonite results and is distinct from an ordinary physical mixture of chlorite and montmorillonite.

Table 8 contains a description of the clay-mineral content of the core samples that were studied. In the column marked "Comments," an attempt has been made to note any changes from one sample to the next that could not be tabulated.

The four samples listed below did not lend themselves to the tabulated description and are therefore treated separately.

1. Phillips Petroleum Company No. 1-C Puckett, Pecos County, depth 14,853 feet, shows essentially nothing in the clay fraction except mica. No chemical weathering in the source area is suggested. This sample was taken near the contact between the carbonate unit and underlying granite. Fragments of the granite are incorporated in the carbonate rock in this position. The granite is in larger angular fragments that would again suggest no chemical weathering. The unweathered mica certainly came directly from the granite fragments.
2. Gulf Oil Corporation No. 1 McElroy-State, Upton County, depth 12,398 feet, contains well-crystallized chlorite and mica. There is a third component which appears to be of the attapulgite type of clay mineral.
3. Gulf Oil Corporation No. 1 McElroy-State, Upton County, depth 12,702 feet, contains almost no mineral other than mica. A very small amount of poorly crystallized chlorite is also present.
4. Phillips Petroleum Company No. 1 Wilson, Val Verde County, depth 15,593 feet, in addition to containing very little mica and exceptionally good chlorite, contains a small amount of amphibole. No other sample studied has a comparable suite.

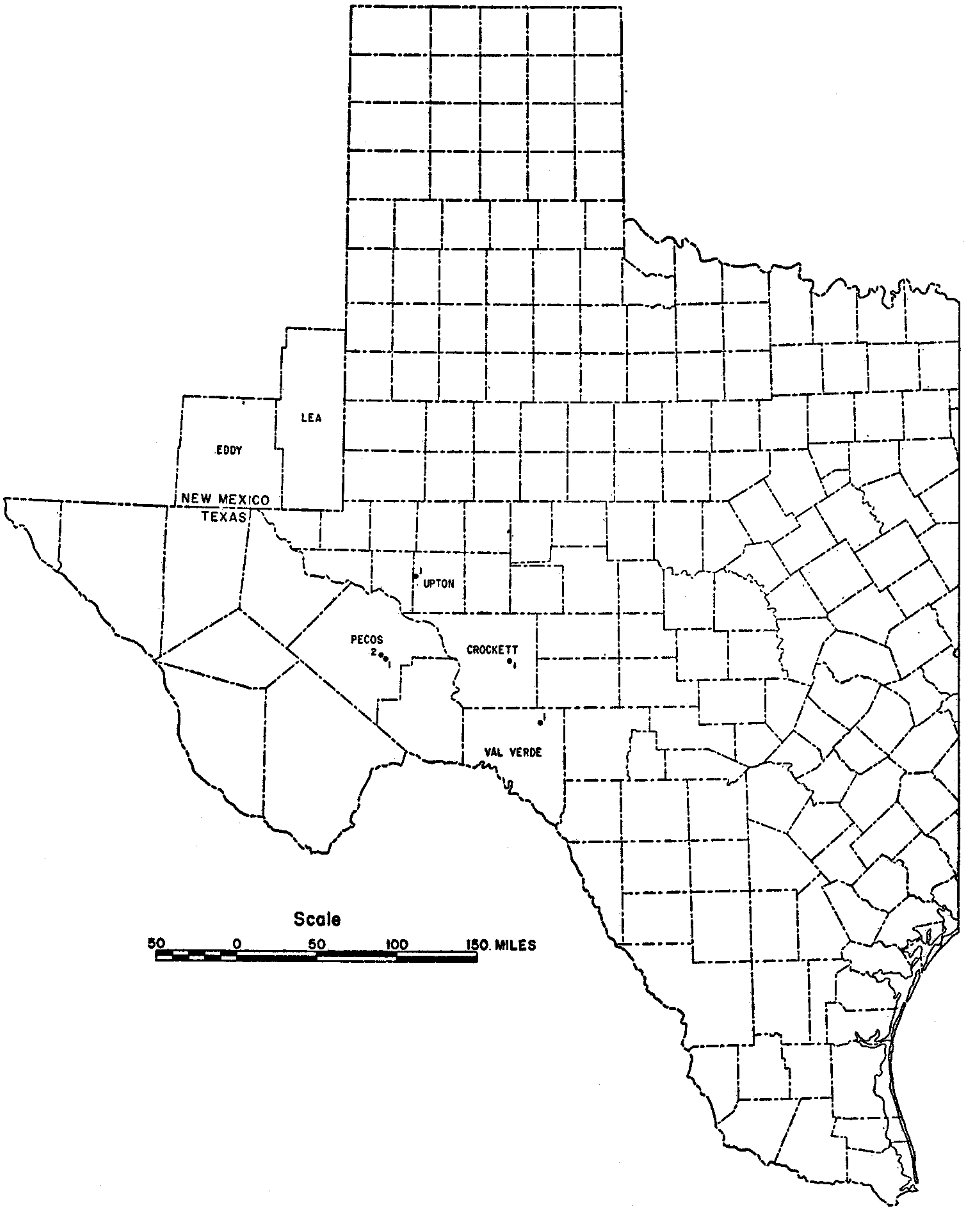


FIG. 19. Map showing wells from which clay-size minerals were examined.

TEXAS

CROCKETT COUNTY
1. Humble Oil & Rfg. Co. #1-D Alma Cox

PECOS COUNTY
1. Phillips Petroleum Co. #1 Glenna
2. Phillips Petroleum Co. #1-C Puckett

UPTON COUNTY
1. Gulf Oil Corp. #1 McElroy-State

VAL VERDE COUNTY
1. Phillips Petroleum Co. #1 Wilson

TABLE 8. *Clay-mineral content of dolomite and limestone cores from wells shown in figure 19.* (Limestone cores indicated by asterisk.)

WELL	DEPTH (FEET)	MICA	CHLORITE	MIXED LAYER (ILLITE-MONT-MORILLONITE)	COMMENTS
Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County	7,543	3+	2+	1+	Mixed layer, rich in montmorillonite
	7,635*	3	2	1	Decreasing montmorillonite in mixed layer
	7,654*	3	2	1	
	7,672*	3	2	1	Very little montmorillonite in mixed layer
	7,690*	2	1	..	
	7,730*	2	2	3	Well-crystallized chlorite, mixed layer low in montmorillonite
	7,750*	1	2	3	Poorly crystallized chlorite, mixed layer low in montmorillonite
	7,770*	3	1	2	Well-crystallized chlorite, mixed layer high in montmorillonite
	7,830	3	1	2	Well-crystallized chlorite, montmorillonite decreased in mixed layer
	7,910	1	3	2	Poorly crystallized chlorite
	7,984	1	2	3	Poorly crystallized chlorite
Phillips Petroleum Company No. 1 Glenna, Pecos County	13,944	2	2	2	
	14,008	1	2	2	
	14,090	1	2	3	Montmorillonite in mixed layer is increasing
	14,198	1	2	3	Much montmorillonite in mixed layer
	14,300	2	1	3	Decreasing montmorillonite in mixed layer
	14,400	1	2	3	Very little montmorillonite in mixed layer
	14,500	1	2	3	

+3 = least abundant; 2 = medium abundance; 1 = most abundant.

TABLE 8. (Continued)

WELL	DEPTH (FEET)	MICA	CHLORITE	MIXED LAYER (ILLITE-MONT-MORILLONITE)	COMMENTS
Phillips Petroleum Company No. 1-C Puckett, Pecos County	13,236	1	2	3	
	13,300	2	1	3	
	13,400	2	1	3	Well-crystallized chlorite
	13,500	2	2	2	Very little montmorillonite in mixed layer, poorly crystallized chlorite
	14,200	2	2	2	Very little montmorillonite in mixed layer
	14,215	2	2	2	
	14,300	2	1	3	
	14,341	2	2	2	
	14,400	2	2	2	
	14,610	2	1	2	
	14,647	2	1	2	
	14,700	2	2	2	
	14,854	1	..	..	
Gulf Oil Corporation No. 1 McElroy-State, Upton County	11,895	2	1	3	Well-crystallized chlorite, mixed layer low in montmorillonite
	11,999	2	2	3	Poorly crystallized chlorite
	12,099	2	3	..	Chlorite mixed-layered with montmorillonite
	12,197	1	2	3	Very little mixed layer, poorly crystallized chlorite
	12,301	1	2	3	Very little mixed layer, well-crystallized chlorite
	12,398	1	2	..	Small amount of fibrous clay mineral
	12,497		No data		
	12,598	1	2	3	Very little mixed layer
	12,702	1	3	3	Very little chlorite and mixed layer

TABLE 8. (Continued)

WELL	DEPTH (FEET)	MICA	CHLORITE	MIXED LAYER (ILLITE-MONT-MORILLONITE)	COMMENTS
Phillips Petroleum Company No. 1	14,981	1	..	2	
Wilson, Val Verde County	15,112	1	2	..	
	15,440	1	2	..	Chlorite mixed-layered with montmorillonite
	15,593	2	1	..	Well-crystallized chlorite
	15,702	1	2	..	Very little chlorite
	15,918	1	2	3	Poorly crystallized chlorite
	16,071	1	2	3	Well-crystallized chlorite
	16,166	1	2	3	Poorly crystallized chlorite
	16,316	1	2	..	Well-crystallized chlorite, little feldspar
	16,340	1	2	3	Well-crystallized chlorite, little feldspar

ORIGIN OF CLAY MINERALS

Much information concerning the weathering of well-crystallized minerals and development of clay minerals can be gleaned from soils literature (Jenny, 1941). The character of the actual processes by which minerals weather is still a controversial issue with very little observational data that can be directly applied to the question. One can draw some conclusions on a purely structural basis which help complete the understanding of clay-mineral genesis.

The origin of clay-size micas in sediments must be considered from two points of view. Large grains of mica can be decreased to clay size during mechanical weathering in the source area and subsequent transportation to a sedimentary basin. In this case of simple decrease in particle size, the mica retains the polymorphic form of the mica in the source rock. If the original mica was of the muscovite type of crystallization, then the clay derived from it would also be of the muscovite type of crystallization.

On the other hand, some montmorillonite which is placed in a potassium-rich environment increases its potassium content by a base-exchange reaction. Provided the potassium content is increased sufficiently, the end product of such a reaction would be mica. Mica formed by this process would have very limited polymorphism. Because the silicate units of which this mica would be built were originally individual (in the montmorillonite form) and bound together by first weak and then gradually increasing forces as the potassium content increased, it is not likely that the units should be stacked in any but a completely random manner with respect to one another. One would not expect to find the two-layer muscovite type crystallization formed in this way but rather the single-layer one. It is not valid to assume, however, that all single-layer polymorphs of mica originated from montmorillonite.

The two processes described above, either degradation or potassium exchange, could under slightly different conditions produce an illite-montmorillonite interlayer mixture instead of mica. Chemical weathering of micaceous source rock that is more severe than that yielding clay-size mica would produce material deficient in potassium. A potassium deficiency is accompanied by a partial expansibility of the mica (an interlayer mixture of illite and montmorillonite). Residual soils formed from micaceous parent rocks are known to have lost enough potassium to become interlayer mixtures rich in montmorillonite (Wood, 1941).

Montmorillonite deposited in a potassium-rich environment more frequently acquires only enough potassium to develop into an interlayer mixture of illite and montmorillonite rather than a well-crystallized mica (Grim and Johns, 1954). Montmorillonite that forms in volcanic ash deposits as a devitrification product of the ash would be less likely to take up potassium from its environment than would that formed from mica. In mica every fourth tetrahedral unit is an aluminum tetrahedron instead of silicon. The clay developed from simple degradation of mica would therefore have a maximum of one-fourth tetrahedral aluminum but possibly somewhat less. For each tetrahedral aluminum there is a possible site for potassium to be taken up from the environment. Bentonitic montmorillonite has low tetrahedral aluminum and would be expected to take up very little potassium. On the other hand, montmorillonite that is a degradation product of mica could, as an upper limit, take up enough potassium to reform the mica because of its generally higher tetrahedral aluminum.

Chlorite, likewise, has two possible origins. Metamorphic chlorite which is subjected to mechanical weathering and transportation is degraded to clay size. Montmorillonitic sediments being deposited in a magnesium-rich environment of greater than pH7 are known to develop chlorite at the expense of montmorillonite (Grim and Johns, 1954). Chlorite formed from montmorillonite produces a distinctly less perfect diffraction than the clay-size metamorphic chlorite, even though no recognizable montmorillonite layers are observed to remain.

Post-depositional recrystallization of all of the clay minerals is possible. Chlorite seems to be the most susceptible to recrystallization. Unfortunately metamorphic and authigenic chlorite cannot be differentiated by X-ray diffraction methods. The mica minerals undoubtedly are somewhat affected by recrystallization, but the extent and result are not known.

GEOLOGIC IMPLICATIONS OF THE ELLENBURGER CLAY-MINERAL SUITE

The typical suite of clay minerals found in the Ellenburger cores included mica, chlorite, and an interlayer mixture of illite and montmorillonite. The mica is dioctahedral and of the muscovite type of crystallization. It can be reasonably concluded that this phase is detrital because diagenetic mica from montmorillonite is not likely to occur as the two-layer muscovite polymorph. Muscovite source rocks could be either igneous or sedimentary, the sedimentary source being derived from an earlier igneous rock.

The one well in which cores were studied to the base of the carbonate rock showed increasing quantities of muscovite in the clay fraction. This and an accompanying decrease in the interlayer mixture of montmorillonite and illite, which is suspected of being a weathering product of the mica, strongly suggest that the clay-size muscovite in the Ellenburger had its source in earlier igneous rock.

The interlayer mixture of montmorillonite and illite varies somewhat in its proportion of expansible or montmorillonitic layers. It is reasonable to conclude that the interlayer mixture is the weathering product of the rock which also yielded muscovite to Ellenburger carbonates. The intensity of chemical weathering in the source area would control the proportion of the montmorillonite in the interlayer mixture. Sharp variations in climate and/or topography over a limited geographic region are not to be expected. Therefore, variations in the proportion of montmorillonite in an interlayer mixture developed in this way should provide a basis for correlation. However, from the potentially correlatable sections that were studied, no definite correlation was observed.

It should be pointed out that a lack of intense variations in the proportion of montmorillonite in the mixture hampered a decisive test of this possible correlation tool. There were very few samples that had no detectable montmorillonite, and at the best, montmorillonite was only a minor part of the interlayer mixture. Another possible interference lies in the susceptibility of interlayer mixtures of this kind to acquire potassium from their deposition medium in order to increase the proportion of illite at the expense of montmorillonite. It can be concluded that weathering in the source area was sufficiently intense to produce at least as much montmorillonite as was observed in the sample but possibly more.

Chlorite in the clay fraction varies from a very poorly organized phase that necessarily formed diagenetically to a well-crystallized phase comparable to metamorphic chlorite. Diagenetic chlorite, being extremely fine grained and imperfectly crystallized, would be the most soluble of the clay-mineral suite. Recrystallization of this material long after burial would develop a chlorite of larger particle size more comparable to the metamorphic mineral. A microscopic examination of the samples containing well-crystallized chlorite should provide evidence for a decision between the two possible origins. If metamorphic rock fragments or other metamorphic minerals are found in the rock, the chlorite would almost certainly be of metamorphic origin. On the other hand, recrystallization of diagenetic chlorite should produce crystals large enough to be observed under a petrographic microscope as being authigenically formed.

These data suggest that the igneous source rock was exposed in a region of rather mild weathering conditions. Chemical weathering would not have been so intense as to have completely destroyed muscovite but would have been sufficiently intense to form some potassium-deficient detritus that was deposited as an interlayer mixture. The topographic relief would have been sufficient to preclude the development of a deep residual soil and to provide adequate drainage for the removal of potassium liberated during weathering but not great enough to eliminate chemical weathering. These conditions could be met by a mature topography in a temperate humid climate.

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Chemical Examination of Pre-Simpson Paleozoic Rocks

VIRGIL E. BARNES

ABSTRACT

Spectrochemical and ordinary chemical analytical methods were applied to the problem of subdividing pre-Simpson rocks. The erratic distribution of various elements in the dolomite sequences shows that chemical methods do not provide a sound basis for subdivision where pre-Simpson rocks are dolomite; the results for limestone are more promising, but it is only in the eastern part of the area that limestone makes up a substantial part of the sequence.

The possibility of using variations in the abundance of stable isotopes for identifying rock units is discussed, and it is concluded that many more data about the present distribution of stable isotopes in recent sediments are needed before trying to apply the results to ancient rocks.

The active-isotope methods of absolute-age determination (strontium-rubidium and potassium-argon methods) depend upon the presence of glauconite or authigenic feldspar. Since these minerals are absent in the Ellenburger the active-isotope methods could not be used even if the methods were sufficiently refined.

In the area to the southeast where most of the spectrochemical work on limestone was done the various constituents are mostly erratically distributed in the upper two-thirds of the Honeycut formation. The lower third of the Honeycut formation, all the Gorman formation, and the upper half of the Tanyard formation are poor in most constituents except lime and are of rather uniform composition. Below the middle of the Tanyard most constituents, except magnesia, cupric oxide, and strontium oxide, are more abundant and somewhat erratically distributed. The lower part of the San Saba member, Morgan Creek limestone, and the limestone in the Lion Mountain sandstone are especially rich in iron and soda. The Cap Mountain limestone, except for a high manganous monoxide and strontium oxide content, resembles more nearly the Ellenburger than it does the rest of the pre-Ellenburger rocks. Phosphorous pentoxide determined by ordinary chemical methods is distinctly more abundant in most Cambrian rocks than in Ordovician rocks.

In Collin County rocks equivalent to the Honeycut formation and post-Honeycut beds were analyzed and nothing was found for subdividing them except possibly the presence of chromic sesquioxide in the upper part of the West Spring Creek formation.

INTRODUCTION

The major chemical constituents of the pre-Simpson sequence of rocks are lime, magnesia, and silica. Lime and magnesia cannot be used for correlation because of lateral intergradation between limestone and dolomite; analysis for these constituents is chiefly of value in determining the suitability of the rock for industrial purposes. In this project analyses of lime and magnesia were of value in providing a basis for comparing chemical composition and variations in the property of thermoluminescence (pp. 180–181). The amount of silica in the rock can be estimated quickly and easily by examining residues using optical methods; chemical analysis to determine this constituent is not justified for purposes of correlation studies.

Other constituents, mostly minor and trace constituents, cannot be satisfactorily

TABLE 9. *Comparison of analyses made by spectrochemical and by conventional chemical methods, using cores from Phillips Petroleum Company No. 1 Wilson, Val Verde County.*

Depth	SiO_2				Al_2O_3				Fe_2O_3				TiO_2			
(*feet*)	BEG	ASL	Dif.	%V	BEG	ASL	Dif.	%V	BEG	ASL	Dif.	%V	BEG	ASL	Dif.	%V
14,981	4.21	5.0	+0.79	19	0.74	0.65	−0.09	12	0.31	0.33	+0.02	6	0.031	0.02	−0.011	35
15,011	7.33	6.5	−0.83	11	1.46	1.8	+0.34	23	0.71	0.46	−0.25	35	0.039	0.048	+0.009	23
15,045	5.29	6.5	+1.21	23	1.21	0.88	−0.33	27	0.41	0.52	+0.11	27	0.030	0.031	+0.001	3
15,081	8.14	11.2	+3.06	38	1.66	0.72	−0.94	57	0.62	0.69	+0.07	11	0.046	0.025	−0.021	46
15,112	5.76	5.9	+0.14	2	0.77	0.78	+0.01	1	0.66	0.56	−0.10	15	0.030	0.029	−0.001	3
15,145	3.01	3.4	+0.39	13	0.29	0.16	−0.13	45	0.42	0.28	−0.14	33	0.010	0.01	0	0
15,183	3.25	3.6	+0.35	11	0.30	0.40	+0.10	33	0.48	0.33	−0.15	31	0.019	0.016	−0.003	16
15,209	2.60	2.7	+0.10	4	0.45	0.25	−0.20	44	0.29	0.35	+0.06	21	0.015	0.014	−0.001	7
15,237	5.70	5.7	0	0	0.82	0.41	−0.41	50	0.22	0.31	+0.09	41	0.02	0.011	−0.009	45
15,268	8.05	6.1	−1.95	24	2.08	1.2	−0.88	42	0.61	0.43	−0.18	29	0.027	0.034	+0.007	26
15,308	3.40	3.2	−0.2	6	0.40	0.16	−0.24	60	0.16	0.23	+0.07	44	0.02	0.01	−0.01	50
15,343	4.67	5.2	+0.53	11	0.93	0.50	−0.43	46	0.35	0.41	+0.06	17	0.03	0.024	−0.006	20
15,371	3.67	3.5	−0.17	5	0.57	0.41	−0.16	28	0.40	0.42	+0.02	5	0.020	0.017	−0.003	15
15,402	3.04	3.1	+0.06	2	0.63	0.27	−0.36	57	0.26	0.35	+0.09	3	0.03	0.015	−0.015	50
15,440	3.06	3.3	+0.24	8	0.81	0.52	−0.29	36	0.26	0.38	+0.12	46	0.04	0.026	−0.014	35
15,462	2.38	2.3	−0.08	3	0.17	0.20	+0.03	18	0.12	0.26	+0.14	117	0.01	0.011	+0.001	10
15,485	3.66	2.9	−0.76	21	1.45	0.78	−0.67	46	0.70	0.61	−0.09	13	0.040	0.039	−0.001	2
15,522	6.37	7.1	+0.73	11	0.07	0.24	+0.17	243	0.11	0.23	+0.12	109	0.02	0.012	−0.008	40
15,555	4.18	4.8	+0.62	15	0.14	0.26	+0.12	86	0.33	0.24	−0.09	27	0.008	0.0095	+0.0015	19
15,593	2.41	2.6	+0.19	8	0.48	0.25	−0.23	48	0.12	0.32	+0.20	167	0.004	0.011	+0.007	175
15,639	0.71	2.9	+2.19	308	0.00	0.20	+0.20	∞	0.17	0.31	+0.14	82	0.02	0.015	−0.005	25
15,679	4.34	3.7	−0.64	15	0.68	0.65	−0.03	4	0.68	0.43	−0.25	37	0.027	0.026	−0.001	4
15,702	2.45	0.95	−1.50	61	0.44	0.08	−0.36	82	0.19	0.25	+0.06	32	0.01	0.008	−0.002	20
15,729	11.59	10.5	−1.09	9	0.30	0.40	+0.10	33	0.35	0.37	+0.02	6	0.036	0.022	−0.014	39
15,756	3.19	3.1	−0.09	3	0.55	0.52	−0.03	5	0.62	0.47	−0.15	24	0.024	0.024	0	0
15,791	5.32	4.6	−0.72	14	0.21	0.28	+0.07	33	0.28	0.38	+0.10	36	0.024	0.014	+0.01	4
15,819	2.28	2.9	+0.62	27	0.57	0.23	−0.34	60	0.21	0.28	+0.07	33	0.019	0.015	−0.004	21
15,851	2.91	2.9	−0.01	0	0.48	0.32	−0.16	33	0.24	0.28	+0.04	17	0.018	0.018	0	0
15,885	3.49	3.5	+0.01	0	0.62	0.28	−0.34	55	0.27	0.40	+0.13	48	0.028	0.016	−0.012	43
15,918	21.67	21.0	−0.67	3	0.48	0.83	+0.35	73	0.68	0.70	+0.02	3	0.072	0.034	−0.038	53
15,955	4.88	4.5	−0.38	8	1.36	0.52	−0.84	62	0.17	0.45	+0.28	165	0.030	0.027	−0.003	10
15,983	7.57	9.3	+1.73	23	0.73	0.38	−0.35	48	0.35	0.80	+0.45	129	0.035	0.022	−0.013	37
16,016	8.37	8.9	+0.53	6	0.60	0.20	−0.40	67	0.20	0.41	+0.21	105	0.023	0.015	−0.008	35
16,048	1.88	2.4	+0.52	28	0.04	0.23	+0.19	475	0.44	0.23	−0.21	48	0.010	0.013	+0.003	30
16,071	8.37	8.9	+0.53	6	0.38	0.33	−0.05	13	0.28	0.40	+0.12	43	0.036	0.019	−0.017	47
16,098	19.71	21.0	+1.29	6	1.78	0.62	−1.16	65	0.81	1.15	+0.34	42	0.073	0.014	−0.059	81
16,129	0.92	1.5	+0.58	63	0.11	0.12	+0.01	9	0.12	0.20	+0.08	67	0.010	0.007	−0.003	30
16,166	4.16	6.0	+1.84	44	0.70	0.40	−0.30	43	0.47	0.53	+0.06	13	0.037	0.023	−0.014	38
16,197	3.00	2.9	−0.1	3	0.16	0.43	+0.27	169	0.35	0.40	+0.05	14	0.032	0.023	−0.009	28
16,235	1.67	3.0	+1.33	80	0.61	0.45	−0.16	26	0.39	0.47	+0.08	21	0.032	0.025	−0.007	22
16,263	1.78	2.4	+0.62	35	0.08	0.40	+0.32	400	0.27	0.45	+0.18	67	0.019	0.018	−0.001	5
16,292	1.41	1.9	+0.49	35	0.09	0.19	+0.10	111	0.43	0.26	−0.17	39	0.034	0.014	−0.020	59
16,316	2.97	2.7	−0.27	9	0.99	0.48	−0.51	51	0.65	0.48	−0.17	26	0.052	0.025	−0.027	52
16,340	4.64	5.7	+1.06	23	1.36	0.90	−0.46	34	0.62	0.49	−0.13	21	0.020	0.036	+0.016	80

BEG, analyses by Bureau of Economic Geology.
ASL, analyses by American Spectrochemical Laboratory.
Dif, difference between analyses from the two sources.
%V, percentage variation between analyses.

estimated, or even detected, without chemical or spectrochemical analysis, and prior to this study little was known about their amount and distribution in pre-Simpson Paleozoic rocks. It seemed likely that the composition of the body of water in which pre-Simpson sediments were deposited might have varied, that the composition of the terrigenous materials might also have varied from time to time, and that these variations might be recorded in the present composition of the rocks. It was soon found, so far as dolomite is concerned, that if any original difference existed it was obliterated by the dolomitization process. Quantitatively dolomite is the most important pre-Simpson rock and in many areas the only one present; consequently, if the minor and trace-element content has been changed in amount and redistributed during dolomitization, analysis for these elements will not furnish data usable for correlation. Limestone showed early promise that various units might have different minor and trace-element characteristics, and this line of investigation was continued, even though the applications of the findings might be limited because limestone is mostly far removed from the area where the Ellenburger contains the most oil.

Analytical data for minor and trace elements are best obtained for many elements by spectrochemical analysis. Phosphorous, an important element, below the limit of detectability by spectrochemical methods for the amounts present in pre-Simpson rocks, is best determined colorimetrically. Sulfur also, in the amount present in pre-Simpson rocks, does not seem amenable to detection spectrochemically. Although pyrite (iron sulfide) in small quantities is ubiquitous, it would be desirable to know how much is present when interpreting sea-floor conditions during pre-Simpson time.

The state of oxidation of the iron was not determined; all of it was reported as Fe_2O_3, and where iron oxide is mentioned it means the value of iron calculated to ferric oxide.

One group of samples analyzed spectrochemically was also analyzed by conventional chemical methods (gravimetric, volumetric, and colorimetric methods) duplicating the analyses of four constituents—silica, alumina, iron oxide, and titania. The results of these two sets of analyses are compared in table 9. Spectrochemical analyses, supposedly accurate within 5 or 10 percent of the amount present, did not reach this accuracy for more than half of the samples for silica and for very few samples for the other three constituents, when compared with conventional chemical analyses. Part of the reason for the low accuracy of spectrochemical analyses lies in the small sample used for analysis. With spectrochemical analyses the weight-percent error is large for the major constituents, whereas the weight-percent error is small in determining minor elements and trace elements.

The spectrochemical analyses were made by the American Spectrochemical Laboratory, Inc., 557 Minna Street, San Francisco, California, under the direction of C. E. Harvey. The limit of detectability for some constituents as stated by Harvey is given in table 10. The conventional chemical analyses were made by R. M. Wheeler and D. A. Schofield, Bureau of Economic Geology, The University of Texas.

TABLE 10. *Limit of detectability by spectrochemical analyses for some constituents* (in percent).

	Nov. 7, 1952*	Dec. 18, 1952	Feb. 20, 1953†
K_2O	0.1		0.2
ZnO	0.05		
ZrO_2	0.03		
B_2O_3	0.03		0.005
TiO_2	0.01		
Na_2O	0.01		0.05
Co_2O_3, Ga_2O_3, Sc_2O_3	0.003		
PbO	0.003		0.0005
BeO	0.002		
NiO	0.002		0.0002
MnO, V_2O_5, Cr_2O_3	0.001		
SrO, BaO	0.0005		
F		0.01	0.05

* Applies to first 36 spot samples, analyzed from Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County. Of these constituents, those not reported in the analyses are presumed to be below the limit of detectability.

† Applies to next 44 spot samples, analyzed from Phillips Petroleum Company No. 1 Wilson, Val Verde County. Fluorine not detected in any sample. Limit of detectability for rest of analyses not given; statement made "Other elements not detected."

Location of wells and surface sections from which chemical data were obtained is shown in figure 20.

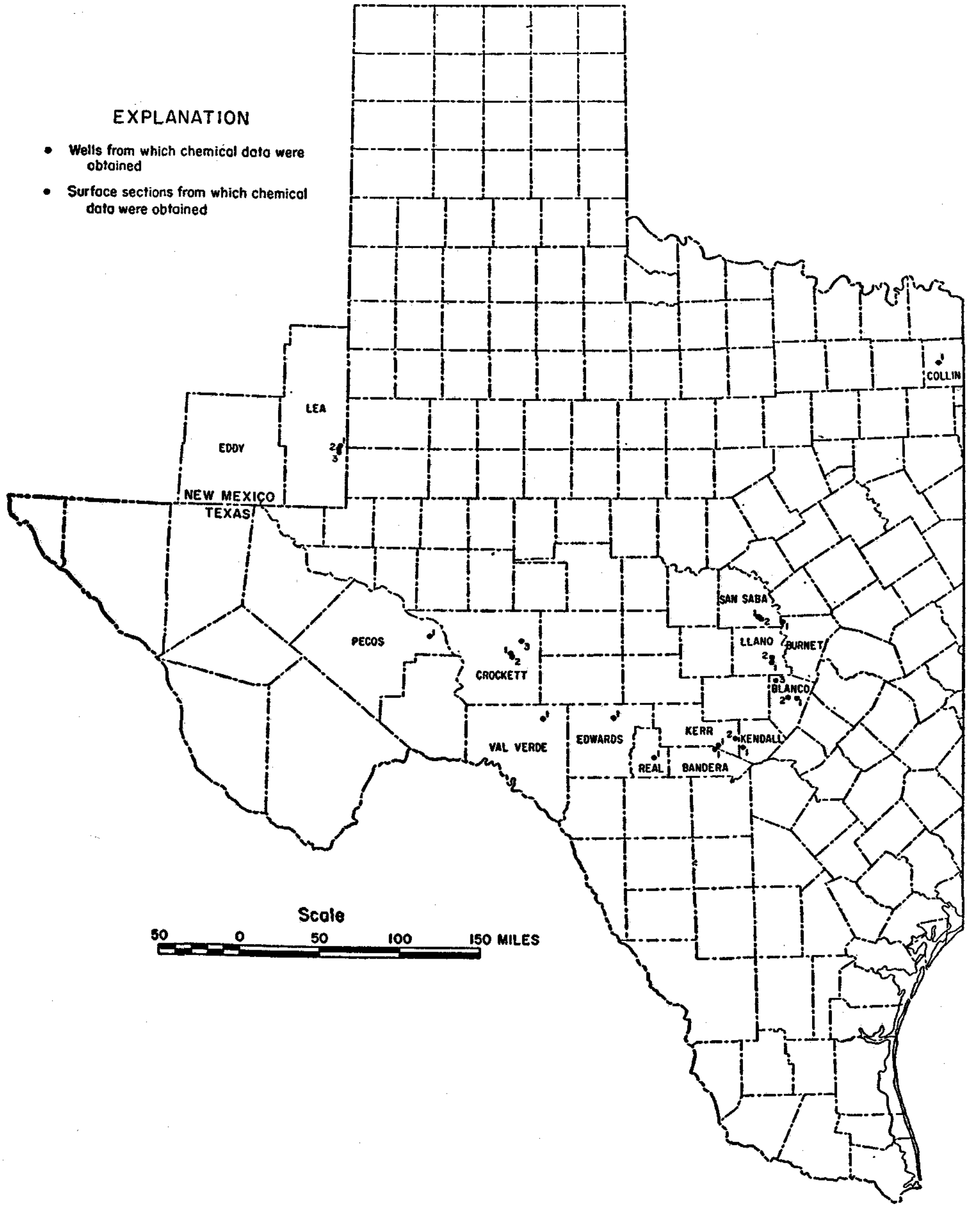

Fig. 20. Map showing wells and surface sections from which chemical data were utilized

Fig. 20, explanation (continued)—

NEW MEXICO

LEA COUNTY
1. Continental Oil Co. #1 Burger B-28
2. Humble Oil & Rfg. Co. #3 "V" N. M. State
3. Humble Oil & Rfg. Co. #6 "V" N. M. State

TEXAS

BANDERA COUNTY
1. G. L. Rowsey #2 Fee

BLANCO COUNTY
1. Honeycut Bend section
2. Pedernales River section
3. White Creek section

BURNET COUNTY
1. Tanyard section

COLLIN COUNTY
1. Humble Oil & Rfg. Co. #1 Miller

CROCKETT COUNTY
1. Humble Oil & Rfg. Co. #1-C Alma Cox
2. Humble Oil & Rfg. Co. #1-D Alma Cox
3. Humble Oil & Rfg. Co. #2 Harvick

EDWARDS COUNTY
1. The Texas Co. #1 Phillips

KENDALL COUNTY
1. Magnolia Petroleum Co. #1 Below

KERR COUNTY
1. G. L. Rowsey #2 Nowlin
2. Tucker Drilling Co. #1 Dr. Roy E. Perkins

LLANO COUNTY
1. Moore Hollow section
2. Warren Springs section

PECOS COUNTY
1. Standard Oil Co. of Texas #2-1 Claude Owens

REAL COUNTY
1. Stanolind Oil & Gas Co. #1 Knippa

SAN SABA COUNTY
1. Cherokee Creek section
2. Kirk Ranch section

VAL VERDE COUNTY
1. Phillips Petroleum Co. #1 Wilson

SPECTROCHEMICAL ANALYSIS

A total of 197 analyses (Appendix G) on 195 samples from 15 wells were obtained by spectrochemical methods. Of these, 44 samples (43 dolomite and 1 limestone) were analyzed from Phillips Petroleum Company No. 1 Wilson, Val Verde County (Pl. 7); 40 samples (21 dolomite, 14 limestone, 4 chert, and 1 shale) from Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County (Pl. 8); 61 samples (all limestone) from Magnolia Petroleum Company No. 1 Below, Kendall County (Pl. 9); 29 samples (all limestone) from Humble Oil & Refining Company No. 1 Miller, Collin County (Pl. 10); and 23 samples (all limestone), not over 6 samples from any one well (Pl. 8).

All samples from Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County, except two duplicate samples, were washed in distilled water until a negative chloride test was obtained. Little difference in composition was found except that chromic sesquioxide is less abundant in both unwashed samples, cupric oxide is more abundant in one, potash in both, and titania in one unwashed sample. These differences appear to have no significance so far as brine content is concerned but help point out the limitations of spectrochemical work. Samples from other wells were not washed.

Carbonate Rock Chemical Data Analyzed by Wells

For Phillips Petroleum Company No. 1 Wilson, Val Verde County (Pl. 7), it was found that silica and iron oxide are richer in the upper part of the Tanyard and that alumina is slightly richer in the Honeycut formation; otherwise, nothing was found that could be used for correlation. The erratic distribution of most constituents in this well suggests that they were mostly redistributed during dolomitization. The least likely constituent to be redistributed is probably alumina.

The abundance and distribution of the rare and trace elements in Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County (Pl. 8), depend on whether the rock is limestone or dolomite. The elements vary less erratically in the limestone than in the dolomite, lending support to the idea that the elements are indiscriminately redistributed during dolomitization. Silica, alumina, and iron oxide are slightly less abundant; soda, potash, titania, manganous monoxide, and barium oxide are distinctly less abundant; and strontium oxide is distinctly more abundant in the lower limestone part of the Honeycut formation than in dolomite of the overlying part of the Honeycut and the underlying Gorman formation. Cupric oxide declines downward and thus holds an intermediate position.

At two levels, one limestone and the other dolomite, unveined and veined materials were analyzed separately. The veined limestone contains less lime; somewhat more magnesia, silica, cupric oxide, manganous monoxide, barium oxide, chromic sesquioxide, soda, and potash; and much more alumina and iron oxide. The veined dolomite contains somewhat more lime and iron oxide and somewhat less magnesia, silica, alumina, titania, and barium oxide.

A pebble from a limestone intraformational conglomerate was analyzed separately from the bulk of the rock. The pebble is somewhat richer in silica, iron oxide, cupric oxide, and soda and somewhat poorer in barium oxide. The rest of the constituents compare very closely.

Limestone only was analyzed from Magnolia Petroleum No. 1 Below, Kendall County (Pl. 9); therefore lime is predominant; however, magnesia is invariably present, ranges from 1 to nearly 8 percent, and averages perhaps 2 percent. In the upper two-thirds of the Honeycut formation most of the other constituents are erratically distributed. The lower third of the Honeycut formation, all the Gorman formation, and the upper half of the Tanyard formation are poor in most constituents except lime and are of rather uniform composition. Below the middle of the Tanyard most constituents, except magnesia, cupric oxide, and strontium oxide, are more abundant and somewhat erratically distributed. The lower part of the San Saba member, Morgan Creek limestone, and the limestone of the Lion Mountain sandstone are especially rich in iron oxide, titania, manganous monoxide, and soda. The Cap Mountain limestone, except for a high manganous monoxide and strontium oxide content, resembles more nearly the Ellenburger than it does the rest of the pre-Ellenburger rocks.

Spectrochemical analyses, except possibly for the presence of chromium sesquioxide in the upper part of the West Spring Creek formation, do not appear to be usable for subdividing the portion of the Arbuckle group drilled in Humble Oil & Refining Company No. 1 Miller, Collin County (Pl. 10).

For the remaining group of wells (Pl. 8), the most diagnostic feature distinguishing pre-Ellenburger rocks is the abundance of soda and silica. The high barium oxide and nickel monoxide content of the Wilberns and Riley formations may also be significant.

Carbonate Rock Spectrochemical Data Analyzed Regionally

The distribution of the chemical constituents in each well is visible at a glance in Plates 7 to 10; however, it is not as easy to compare the constituents from well to well. For this purpose table 11 was prepared so that the regional distribution of each constituent can be seen readily. Data discussed later from surface sections in the Llano region are included for comparison.

As shown in table 11, silica is fairly uniformly distributed from well to well at any one level but is much more abundant in the lower units. The Gorman formation contains the least. Alumina, iron oxide, titania, manganous monoxide, soda, and nickel monoxide have about the same distribution as silica.

Cupric oxide and barium oxide are slightly more abundant in Magnolia Petroleum Company No. 1 Below, Kendall County, with cupric oxide about equally distributed in the various geologic units, and barium oxide most abundant in the San Saba member.

Strontium oxide and chromic sesquioxide are least abundant in Phillips Petroleum Company No. 1 Wilson, Val Verde County; they are about equally distributed in the geologic units in each well except that strontium oxide is about three times as abundant in the Cap Mountain limestone of the Below well.

Of the constituents not shown in table 11, potash is reported only for Ellenburger rocks from the Wilson and Cox wells and is about equally distributed. Zirconia is mostly in the Morgan Creek limestone from the Below well, and boron oxide, confined to the Wilson well, is about equally distributed throughout the Ellenburger group. Vanadium pentoxide and lead monoxide are rare except in the Wilson well in which they are present in about one-quarter of the samples. Vanadium pentoxide is slightly more common in the Honeycut formation and lead monoxide is more common in the Tanyard formation.

Chert and Shale Spectrochemical Data

Four cherts were analyzed from Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County, three from the Gorman formation and one from the Honeycut formation. Lime ranges from 2.2 to 4.1 percent and magnesia from 0.43 to 1.4 percent. Silica ranges from 88 to 95 percent and alumina from 0.28 to 0.80 percent. The alumina is well within the range of that contained in the adjacent carbonate rocks, lending support to the idea that this chert is formed by the replacement of the enclosing slightly argillaceous sediment. It seems likely that chert precipitated directly on the sea floor might contain less impurities. Iron oxide, titania, cupric oxide,

TABLE 11. *Regional comparison, by geologic units and wells, of chemical constituents (range and average amount) in pre-Simpson carbonate rocks.*

UNIT	PHILLIPS NO. 1 WILSON	HUMBLE NO. 1-D COX	MAGNOLIA NO. 1 BELOW	HUMBLE NO. 1 MILLER	ALL OTHER WELLS	LLANO REGION SECTIONS
			SILICA (SiO_2)			
Post-Honeycut	....	....	....	1.6–8.8(4.3)	....	....
Honeycut	2.3–11.2(4.8)	1.2–18(3.5)	1.2–19(7.2)	1.0–6.7(3.9)	0.5–11.5(4.0)	1.96–4.80(3.1)
Gorman	0.95–10.5(4.2)	2–7.5(1.0)	2.3–6.3(3.6)	2.0–6.7(4.5)	....	1.48–12.82(5.3)
Tanyard	1.5–21.0(6.4)	....	4.4–11.4(8.0)	....	....	0.20–33.80(5.2)
San Saba	....	....	3.2–28(8.9)	....	....	0.42–14.40(3.0)
Morgan Creek	....	....	12.5–20(15.3)	....	6.8–21(13.9)	....
Lion Mountain	....	....	(20.5)	....	....	....
Cap Mountain	....	....	1.9–11.5(6.8)	....	19.0–21.5(20.2)	....
			ALUMINA (Al_2O_3)			
Post-Honeycut	....	....	....	0.24–1.65(.60)	....	....
Honeycut	0.16–1.8(.58)	0.09–2.6(.50)	0.31–1.42(.58)	0.18–1.05(.37)	0.18–1.80(.57)	0.39–.79(.59)
Gorman	0.08–.78(.35)	0.10–1.4(.44)	0.31–.48(.39)	0.28–.70(.43)	....	0.28–1.34(.46)
Tanyard	0.12–.90(.42)	....	0.45–2.10(1.35)	....	....	0–.42(.25)
San Saba	....	....	0.67–1.80(1.20)	....	....	0.05–.46(.17)
Morgan Creek	....	....	0.24–2.45(1.53)	....	0.91–2.10(1.50)	....
Lion Mountain	....	....	(1.30)	....	....	....
Cap Mountain	....	....	0.24–1.40(.78)	....	1.40–1.85(1.62)	....
			IRON (Fe_2O_3)			
Post-Honeycut	....	....	....	0.12–.55(.23)	....	....
Honeycut	0.23–.69(.39)	0.06–.93(.23)	0.05–3.85(.54)	0.07–.67(.19)	0.004–.78(.19)	0.25–.83(.41)
Gorman	0.23–.61(.39)	0.17–.52(.26)	0.04–.17(.11)	0.14–.42(.24)	....	0.13–2.25(.43)
Tanyard	0.20–1.15(.48)	....	0.20–.77(.52)	....	....	0.10–1.17(.21)
San Saba	....	....	0.42–2.10(.82)	....	....	0.10–1.04(.27)
Morgan Creek	....	....	1.75–2.95(2.37)	....	1.25–2.25(1.75)	....
Lion Mountain	....	....	(2.20)	....	....	....
Cap Mountain	....	....	.73–1.30(.89)	....	1.15–1.40(1.27)	....
			TITANIA (TiO_2)			
Post-Honeycut	....	....	....	0.009–.06(.018)	....	
Honeycut	0.01–.048(.021)	0–.087(.019)	0.011–.09(.032)	0.004–.031(.011)	0.004–.045(.015)	
Gorman	0.008–.039(.018)	0–.09(.022)	0.011–.027(.017)	0.007–.014(.010)	....	
Tanyard	0.007–.036(.021)	....	0.022–.13(.067)	....	....	
San Saba	....	....	0.03–.25(.097)	....	....	
Morgan Creek	....	....	0.032–.21(.157)	....	0.086–.32(.20)	
Lion Mountain	....	....	(.250)	....	....	
Cap Mountain	....	....	.012–.13(.081)	....	0.13–.24(.18)	

CUPRIC OXIDE (CuO)

Post-Honeycut	....	....	....	0.005–.012(.008)	....
Honeycut	0.0025–.007(.004)	0.0035–.009(.006)	0.006–.017(.011)	0.004–.014(.007)	0.004–.012(.007)
Gorman	0.0025–.005(.003)	0.0022–.0041(.003)	0.006–.009(.008)	0.005–.007(.007)	....
Tanyard	0.002–.0065(.004)	....	0.006–.009(.007)	....	....
San Saba	....	....	0.005–.013(.008)	....	....
Morgan Creek	....	....	0.004–.012(.007)	....	0.005–.007(.006)
Lion Mountain	....	....	(.011)	....	....
Cap Mountain	....	....	0.004–.012(.007)	....	0.005–.006(.005)

MANGANOUS MONOXIDE (MnO)

Post-Honeycut	....	....	....	0.005–.015(.008)	....
Honeycut	0.0003–.0019(.001)	0.0008–.0085(0.002)	0.001–.045(.006)	0.005–.13(.025)	0.006–.032(.017)
Gorman	0.005–.015(.010)	0.008–.048(.015)	0–.009(.004)	0.006–.010(.008)	....
Tanyard	0.0065–.019(.013)	....	0.006–.022(.014)	....	....
San Saba	....	....	0.013–.29(.045)	....	....
Morgan Creek	....	....	0.078–.22(.123)	....	0.037–.045(.041)
Lion Mountain	....	....	(.350)	....	....
Cap Mountain	....	....	0.035–.76(.281)	....	0.21–.045(.13)

BARIUM OXIDE (BaO)

Post-Honeycut	....	....	....	0.002–.008(.003)	....
Honeycut	0.0003–.0019(.001)	0.0008–.0085(0.002)	0.001–.045(.006)	0.001–.005(.003)	0.001–.021(.003)
Gorman	0.0003–.009(.003)	0.0007–.0095(.001)	0.002–.005(.003)	0.002–.021(.008)	....
Tanyard	0.0004–.0055(.002)	....	0.004–.013(.010)	....	....
San Saba	....	....	0.006–.14(.018)	....	....
Morgan Creek	....	....	0.01–.023(.014)	....	0.008–.010(.009)
Lion Mountain	....	....	(.011)	....	....
Cap Mountain	....	....	0.006–.016(.011)	....	0.014–.011(.012)

STRONTIUM OXIDE (SrO)

Post-Honeycut	....	....	....	0.016–.025(.019)	....
Honeycut	0.0025–.02(.066)	0.0034–.025(.012)	0.006–.02(.013)	0.076–.024(.020)	0.006–.031(.016)
Gorman	0.002–.007(.005)	0.0015–.0085(.005)	0.012–.02(.015)	0.013–.025(.017)	....
Tanyard	0.001–.011(.005)	....	0.013–.019(.016)	....	....
San Saba	....	....	0.009–.02(.015)	....	....
Morgan Creek	....	....	0.010–.016(.014)	....	0.006–.014(.010)
Lion Mountain	....	....	(.010)	....	....
Cap Mountain	....	....	0.012–.045(.034)	....	0.008–.011(.009)

TABLE 11.—(continued). *Regional comparison, by geologic units and wells, of chemical constituents (range and average amount) in pre-Simpson carbonate rocks.*

UNIT	PHILLIPS NO. 1 WILSON	HUMBLE NO. 1-D COX	MAGNOLIA NO. 1 BELOW	HUMBLE NO. 1 MILLER	ALL OTHER WELLS	LLANO REGION SECTIONS
			CHROMIC SESQUIOXIDE (Cr_2O_3)			
Post-Honeycut	....	....	....	0–.002(.001)	....	
Honeycut	0.0002–.0012(.0005)	0–.005(.0016)	0–.015(.0019)	0–.002(nil)	0–.003(.0005)	
Gorman	0.0003–.0007(.0004)	0–.004(.0011)	None	None	....	
Tanyard	0.0003–.0012(.0005)	....	0.0007–.002(.0014)	....	....	
San Saba	....	....	0.0007–.002(.0014)	....	....	
Morgan Creek	....	....	0.001–.004(.0015)	....	0.001–.003(.0020)	
Lion Mountain	....	....	(.0020)	....	....	
Cap Mountain	....	....	0–.002(.0010)	....	0.001–.002(.0015)	
			NICKEL MONOXIDE (NiO)			
Post-Honeycut	....	....	....	None	....	
Honeycut	0–.001(.0003)	None	0–.016(.0022)	None	None	
Gorman	0–.0006(.0002)	None	0–.002(.0003)	None	....	
Tanyard	0–.0013(.0003)	....	0–.003(.0002)	....	....	
San Saba	....	....	0.002–.005(.0028)	....	....	
Morgan Creek	....	....	0.002–.007(.0040)	....	0.001–.003(.002)	
Lion Mountain	....	....	(.0050)	....	....	
Cap Muontain	....	....	0–.003(.0016)	....	(.002)	
			SODA (Na_2O)			
Post-Honeycut	....	....	....	0–.10(.04)	....	
Honeycut	0.05–.16(.09)	0–.09(.03)	0–.12(.02)	0–.06(.01)	0–.06(.01)	
Gorman	0–.07(.05)	0.05–.15(.08)	0–.04(.01)	None	....	
Tanyard	0–.17(.09)	....	0–.09(.05)	....	....	
San Saba	....	....	0.04–.35(.11)	....	....	
Morgan Creek	....	....	0–.32(.25)	....	0.19–.55(.37)	
Lion Mountain	....	....	(.23)	....	....	
Cap Mountain	....	....	0–.19(.11)	....	0.43–.55(.49)	

chromic sesquioxide, and soda, except in one sample, are similar in amount to that found in the adjacent rocks, indicating that these constituents, as well as alumina, are stable during silica replacement. Barium oxide, too, mostly shows little change, except for a marked increase to 0.13 percent in the sample from the Honeycut formation.

In the Cox well a slightly calcareous shale analyzed from the Honeycut formation contains 1.7 percent lime and 0.90 percent magnesia. The aluminum-bearing minerals of carbonate rocks are among the most stable minerals present. If this shale is representative of that contained in the carbonate rocks, then a guess can be made whether or not the rare and trace elements are associated with the carbonate minerals or with the clay minerals. Alumina is 21 times as abundant in this shale as in the average carbonate rock analyzed from this well. When this factor was applied to the rest of the rare and trace elements, it was found that 66 percent as much titania; about 20 percent as much barium oxide, chromic sesquioxide, and iron oxide; 13 percent as much soda; 5 percent as much cupric oxide; and ⅔ of 1 percent as much manganous monoxide and strontium oxide were present as would be called for if these constituents were concentrated with the clay. Potash was in excess, and vanadium pentoxide detected in the shale was not found in the carbonate rocks. This method of examining the data suggests that the potash, vanadium pentoxide, and titania are mostly with the clay; and that most of the barium oxide, chromic sesquioxide, iron, and soda and almost all of the manganous monoxide, strontium oxide, and cupric oxide are with the carbonate fraction.

Spectrochemical Data for Rocks Above the Ellenburger

Samples analyzed from above the Ellenburger include a rather impure carbonate rock from the Simpson group; the distribution of elements is similar to that found in the Honeycut formation. Samples from each of the Marble Falls limestone, Chappel limestone, and an unidentified limestone in the Pennsylvanian are similar in composition to the Honeycut formation except for a higher barium oxide content and the presence of nickel monoxide in the unidentified limestone.

Phillips Petroleum Company No. 1 Wilson, Val Verde County

Samples from the Wilson well analyzed spectrochemically were also analyzed by conventional chemical methods (Appendix H); the values obtained are shown graphically on Plate 7, where the results for silica, alumina, iron oxide, and titania can be directly compared with those obtained by spectrochemical analysis. These constituents as determined by the two methods are also compared in table 9 and discussed on page 146. Lime, magnesia, and phosphorous pentoxide were not estimated spectrochemically.

The curves for silica obtained by spectrochemical and conventional chemical methods compare closely, with only about four samples as much as 2 percent apart. The curve for alumina obtained by conventional chemical methods has greater amplitude but otherwise mostly reflects the curve obtained by spectrochemical methods. The amount of alumina determined spectrographically averages somewhat less; for one sample the difference is 1.3 percent. The values determined by conventional chemical methods are somewhat erratic, except for the lower part of the Gorman formation, where they average slightly less than elsewhere.

The curves for iron oxide obtained by spectrochemical and conventional chemical methods have about the same amplitude, with iron oxide determined spectrochemically averaging slightly higher. The values determined by conventional chemical methods are erratic throughout, with little variation among the three formations.

The curve for titania obtained by conventional chemical methods has greater amplitude and only in part reflects the curve obtained by spectrochemical means. The amount of titania determined spectrochemically is somewhat less; for one sample the difference is about 0.06 percent. The distribution of titania determined by conventional chemical methods is erratic; it is perhaps slightly more abundant in the Tanyard formation.

All the samples, excluding one limestone, are dolomite with a range from 23.50 to 32.12 percent lime, from 14.24 to 21.40 percent magnesia, from 0.003 to 0.033 percent phosphorous pentoxide, and from 34.50 to 47.10 percent ignition loss including water (not shown on Pl. 7). Each formation contains about the same amount of phosphorous pentoxide with about the same amount of variation in each formation.

Surface Sections

While the writer was measuring and describing sections and mapping Cambrian and Ordovician rocks in the Llano region, it was found that phosphatic brachiopods are common in many of the Cambrian rocks and essentially absent in Ordovician ones. Five-foot composite samples of carbonate rocks collected at about 30-foot intervals from the Tanyard and White Creek sections were analyzed for phosphorous pentoxide to determine whether any one portion of the section is richer than another (Appendix I; fig. 21). It was found that phosphorous pentoxide is distinctly more abundant downward from a point 200 feet below the top of the San Saba member.

Cloud and Barnes (1948, pp. 377–381) tabulated analyses of Ellenburger rocks from the Cherokee area and both Ellenburger and Wilberns rocks from the Johnson City area. These analyses (fig. 22) were made primarily to determine whether the rock is pure enough for commercial use, and only the more likely parts of the stratigraphic column were analyzed. Also included in figure 22 are parts of five analyses by Goldich and Parmelee (1947) from the Riley Mountain section, Llano County. The other constituents determined by Goldich and Parmelee were not plotted; they found that phosphorous pentoxide ranges from 0.003 to 0.008 percent, titania from 0.003 to 0.021 percent, and manganous monoxide from 0.003 to 0.014 percent.

From the analysis of the Llano region rocks alone, it appears that quartz mainly must constitute the insoluble material, that clay is insignificant, and that iron is probably higher than average because of glauconite. In table 11, analyses of Llano region carbonate rocks are compared with analyses of the same units in wells. The Honeycut and Gorman rocks compare closely in composition, whereas the Tanyard and San Saba surface rocks are much more pure than they are in the subsurface.

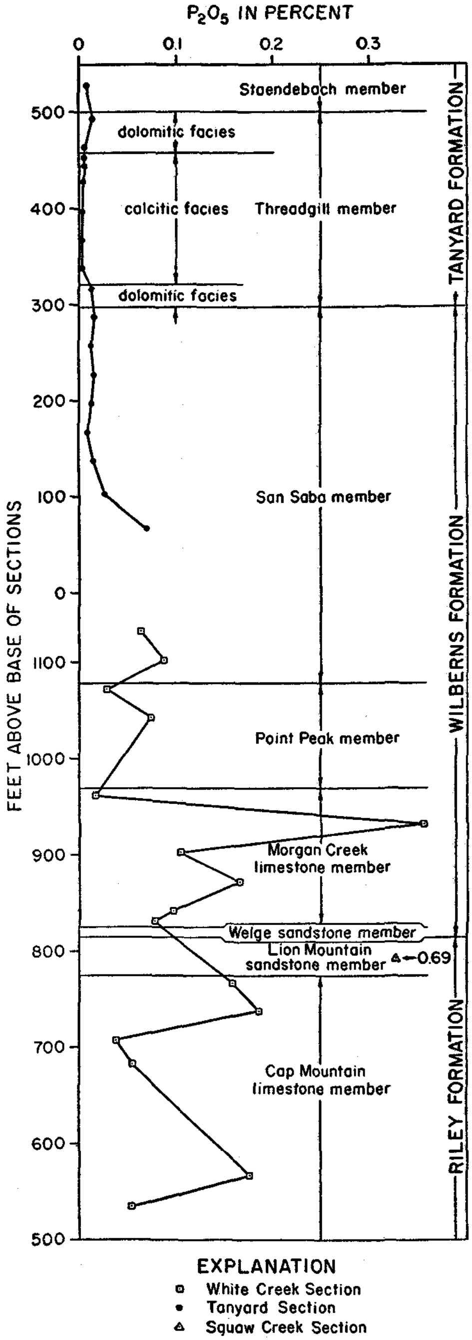

FIG. 21. Diagram showing amount of phosphorous pentoxide (P_2O_5) in White Creek and Tanyard sections, Llano region.

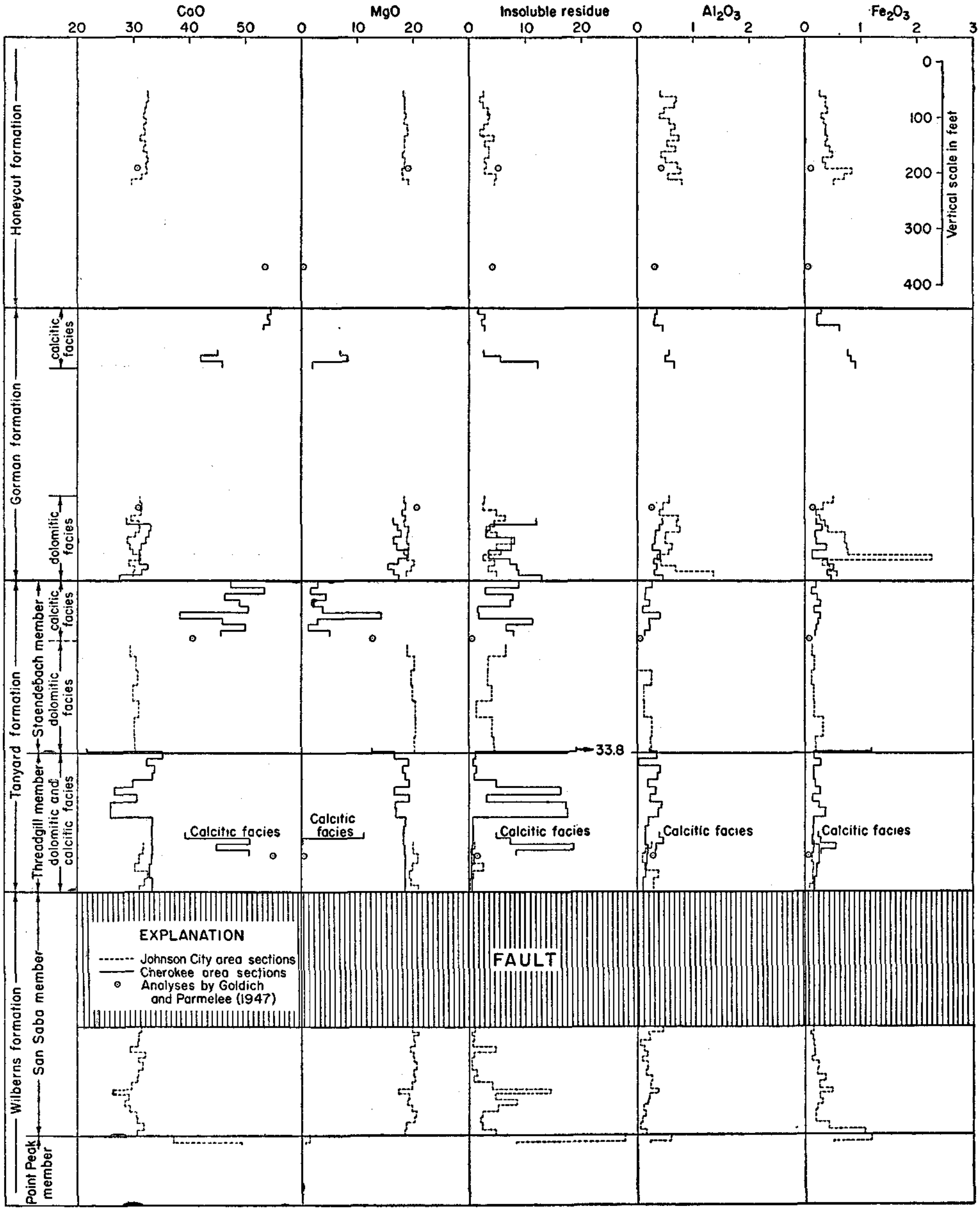

Fig. 22. Diagram showing chemical composition of pre-Simpson rocks, surface sections, Llano region.

ISOTOPE ANALYSIS

While no actual analyses for active or stable isotopes were made during the pre-Simpson project, the literature was examined and the various possible applications of isotope analysis for correlation of carbonate rocks considered. Those methods using active isotopes for absolute-age determinations are outlined briefly, followed by a section on the stable isotopes.

Absolute Age Determination

Strontium-rubidium method.—Rubidium consists of about 28 percent of the active isotope Rb^{87} and 72 percent of the inactive isotope Rb^{85}. The beta decay of Rb^{87} yields strontium^{87} (Sr^{87}). The decay constant for Rb^{87} is about 1.15×10^{-11} per year, and the halflife is about 6.0×10^{10} years. So far the Rb^{87}—Sr^{87} method of age determination has been chiefly limited to determinations on the mineral lepidolite, with a recent suggestion (Herzog et al., 1956) that it is also applicable for "Several K-minerals, many kinds of rocks and meteorites, and in general, high potassium, low calcium materials."

Rankama and Sahama (1950, pp. 441–442) stated that rubidium follows potassium during the weathering-sedimentation cycle and becomes absorbed in argillaceous sediments. The carbonate rocks of southern Lapland contain no rubidium. These facts indicate that the Rb^{87}—Sr^{87} method could not be used for absolute-age determination of carbonate rock. However, glauconite (555 grams per ton), even richer in rubidium than shale (300 grams per ton), might be of value for absolute-age determination.

Following the meeting of the Ad Hoc Committee on Nuclear Geology in Washington, D.C., April 28, 1956, an informal group was formed for collecting accurately dated glauconite samples. Patrick M. Hurley, of the Massachusetts Institute of Technology, where glauconite is being investigated, offered to receive, process, and distribute samples to individuals working with glauconite, thus insuring the use of standard material.

The writer and others have furnished 11 glauconite samples from throughout the Upper Cambrian of the Llano region, including one from Magnolia Petroleum Company No. 1 Below, Kendall County. In addition, samples have been furnished from about 30 feet above the base of the Lower Ordovician near the top of the San Saba member; the basal glauconitic member of the Stribling formation, Lower or Middle Devonian; the basal few inches of the Barnett formation, Mississippian; and the basal foot of the Marble Falls limestone, Lower Pennsylvanian.

When the results from these samples and many others from throughout the stratigraphic column are evaluated, it will be known if the strontium-rubidium method holds promise for absolute-age determination and if it is sensitive enough to give the relative position of samples within a portion of a geologic system. The results given in table 12 suggest that this method may never be refined enough for this purpose.

The data in table 12 (P. M. Hurley, letter dated October 25, 1956) include two of the 11 Upper Cambrian samples mentioned above. That sample Gl-15 from Magnolia Petroleum Company No. 1 Below, Kendall County, is from the Lion Mountain instead of the Welge might be argued since it is from 2 feet below Franconia fossils and 13 feet above Dresbach fossils (p. 82). The samples are arranged in order of decreasing age. Although some of the age determinations appear to be contradictory, if the large limit of error is considered it is seen that none are.

Authigenic feldspar (adularia) should also be usable for age determination by the Rb^{87}—Sr^{87} method providing it formed early during diagenesis. In the Llano uplift, authigenic feldspar is common in all the Cambrian units and the lower part of the Tanyard formation and ranges from crystals that appear to be entirely authi-

TABLE 12. *Rubidium-strontium (Rb-Sr) age determinations on glauconite* (data by R. F. Cormier, Massachusetts Institute of Technology).

SAMPLE	FORMATION	LOCATION	GEOLOGIC AGE	TOTAL Rb (ppm)	Rb^{87} (ppm)	NORMAL SR (ppm)	RADIOGENIC SR		Rb/Sr AGES	
							I.D.* (ppm)	I.R.* (ppm)	I.D.	I.R.
Gl–2(A)	Mount Whyte formation	Brazeau River, Alberta, Canada	Upper Lower Cambrian	215	60.8	30.6	0.33	......	390±(50)	....
Gl–2(B)	Same	Same	Same	186	52.7	116	0.29	0.34	400±(100)	465±(65)
Gl–16	Lion Mountain member, Riley formation	San Saba County, Texas	Late early Late Cambrian	204	57.8	43.0	0.32	0.33	397±(200)	410±(30)
Gl–15	Lion Mountain member (?), Riley formation (?)	Kendall County, Texas	Late early Late Cambrian	230	65.1	40.8	0.35	0.35	386±(95)	392±(30)
Gl–12	Franconia formation	Readstown, Wisconsin	Middle Upper Cambrian	196	55.4	10.8	......	0.34	....	436±(20)
Gl–1	Lodi shale of Trempealeau formation	Western Wisconsin	Upper Upper Cambrian	193	54.7	10.6	0.31	......	412±(60)	....
Gl–3	....	Stenbrottet, Sweden	Lowest Ordovician	308	87.8	12.9	0.46	......	380±(40)	....
Gl–11	....	Stenbrottet, Sweden	Lowest Ordovician	307	86.9	16.7	0.51	0.45	420±(80)	375±(20)

* I.D., value calculated from strontium isotope dilution data alone. I.R., value calculated using isotopic analysis of pure strontium extracted from the glauconite in conjunction with the isotope dilution data.
Gl-1 (R-3210) Loc. 146—section 26, T. 12 N., R. 7 W. Collected by R. R. Shrock.
Gl-2 (R-3211) Glauconitic sandstone, Rocky Mountains. Collected by M. D. Rostoker.
Gl-3, Gl-11 (R-3212) Glauconitic limestone, 10 Km. southeast of Falkoping, Vastergotland. Donated by H. B. Whittington.
Gl-12 (R-3219) Glauconitic sandstone. Collected by C. S. Bays.
Gl-15 (R-3222) USGS Loc. 1988. Glauconitic sandstone core from depth 6,350 feet, Magnolia Petroleum Company No. 1 Below. Donated by A. R. Palmer.
Gl-16 (R-3223) Glauconitic sandstone from 41 feet beneath the top of the 61-foot thick Lion Mountain sandstone member of the Riley formation and 557 feet above the base of the Little Llano River section (LL-557). Collected and donated by A. R. Palmer.

genic to thin overgrowths on previously existing microcline grains.

Walker (1952) determined the relative percent of feldspar (much of it authigenic) in the fine sand and silt fraction of several samples from the Llano region (table 13). Some samples in the Point Peak member of the Wilberns formation are especially rich in authigenic feldspar, but none so far examined are free of older feldspar and thus none are suitable for age determination unless some method of separation can be devised.

Potassium-argon method.—Potassium consists of three isotopes of which only one, K^{40}, constituting about 0.0119 percent, is active. It decays by K-electron capture to $argon^{40}$ with the emission of a gamma ray and by beta emission to $calcium^{40}$. The decay constant for K^{40} is about 0.55×10^{-9}, and the halflife about 1.3×10^9 years.

Earlier work suggested that argon is lost by diffusion in some minerals and that analyses of such minerals, especially feldspar, would give erroneous age determinations. Wasserburg and Hayden (1955) found no evidence for diffusion and stated: "It was found that with a branching ratio $\lambda e/\lambda\beta = 0.085 \pm 0.005$ and a decay constant $\lambda = 0.55 \times 10^{-9}$/yr, the A^{40}/K^{40} ages could be brought into agreement with the Pb-U ages for samples ranging from 260 to 1860 m. y. No evidence was found for the loss of argon by diffusion from potassium feldspars." Gentner and Kley (1955) calculated a branching

TABLE 13. *Relative percent of quartz and feldspar in fine sand and silt fraction, Cambrian rocks, Llano region* (Walker, 1952).

ROCK UNIT AND SECTION	FEET ABOVE BASE	QUARTZ	FELDSPAR
San Saba member—			
Bluff Creek	120–125	61	39
James River	630–635	85	15
James River	590–595	96	4
James River	565–570	72	28
James River	445–450	48	52
Point Peak member—			
White Creek	980–985	23	77
James River	250–260	34	66
Welge sandstone member—			
James River	85–90	100	0
White Creek	820–825	100	0
Morgan Creek	595–600	100	0
Pontotoc	695–700	97	3
Lion Mountain sandstone member—			
James River	20–25	82	18
James River	5–10	88	12
White Creek	800–805	99	1
Little Llano River	540–545	64	36
Cap Mountain limestone member—			
Threadgill Creek	640–645	43	57
Threadgill Creek	500–505	81	19
White Creek	620–625	60	40
White Creek	520–525	88	12
White Creek	435–440	60	40
White Creek	345–350	80	20
Morgan Creek	395–400	61	39
Morgan Creek	350–355	97	3
Hickory sandstone member—			
White Creek	250–255	65	35
White Creek	140–145	72	28
White Creek	5–10	85	15
Little Llano River	350–355	96	4
Pontotoc	395–400	98	2

ratio λ K: $\lambda\beta$ of 0.104 which they believe to be more nearly correct.

Wasserburg (1956) suggests that glauconite may be usable for absolute-age determination and that an absolute sedimentary time scale may eventually be established. This, however, would be of no help in subdividing the nonglauconitic Ellenburger part of the pre-Simpson Paleozoic sequence.

Authigenic feldspar, as mentioned above, is common in some of the pre-Simpson rocks but is unsuited for age determination because of an admixture of previously existing microcline. If pure authigenic feldspar could be separated, then a mineral of wider distribution in pre-Simpson rocks than glauconite would be available for absolute-age determination.

Isotope Abundance

Carbon isotopes.—The stable carbon isotopes C^{12} and C^{13} compositions of limestone and coal were investigated by Jeffery et al. (1955). Previous work had been on the distribution of these isotopes in nature (Craig, 1953), with a review of the field up to 1953 by Ingerson (1953). Landergren (1954) did important work on marine sediments.

Jeffery et al. (1955) discussed the various depositional, diagenetic, and post-depositional processes which may have produced the carbon-isotope composition of the specimens they examined. They stated:

> It has been shown that the observed variations in isotopic composition are not due entirely to varying depositional environment in the case of the limestones, and possibly not due entirely to differing original plant biotopes in the case of the coals. Such anomalous variations can be attributed only to changes in the isotopic composition of the hydrosphere and atmosphere from one time to another. It is suggested that the fundamental causes for these variations are the periodic diastrophisms which change the balance of the carbon cycle in the lithosphere.

Landergren (1954) also noticed a "tendency to periodicity" in the C^{13} abundance of specimens of Upper Ordovician limestone from a deep boring. If periodicity exists and the span of each cycle is of the order of the length between orogenies, then analysis for carbon isotopes might be useful for subdividing the limestone of the pre-Simpson Paleozoic. Dolomite probably is not suitable because of the manner in which it has formed, making it likely that the final rock will not have the same isotope composition as the original sediment.

Oxygen isotopes.—Oxygen represented by isotopes O^{16}, O^{17}, and O^{18} and being an integral part of water is readily fractionated in nature by atmospheric processes. Webster, Wahl, and Urey (1935) studied the reaction $2H_2O^{18} + CO_2{}^{16} \rightleftarrows 2H_2O^{16} + CO_2{}^{18}$ and suggested that fractionation takes place with some concentration of O^{18} in the CO_2. That this is true is suggested by above-normal concentration of heavy oxygen in carbonate rocks (Dole and Slobod, 1940; Teis, 1950).

Urey (1947) first suggested using the O^{18} content of $CaCO_3$ as a geologic thermometer and later (1948) suggested that it is possible to determine the temperature at which organisms grew within 1° C., providing the isotopic content of the ocean in which they grew is the same as today, that the organism did not fractionate the isotopes, and that no significant isotopic change has taken place since. Epstein and Mayeda (1953) pointed out the magnitude of the variation in the isotopic composition of the present ocean and suggested that the temperature of growth may not be determinable closer than 10° C.

Silverman (1951), in examining the isotopic composition of oxygen in silicates, found the sedimentary siliceous deposits to be richer in the O^{18} isotope than the oxygen in igneous rocks. He believed this difference to be largely due to an exchange reaction between silica and water during the processes of sedimentation.

If the isotopic composition of the ocean as a whole has varied considerably from time to time or if there has been drastic climatic changes, it is possible that oxygen isotope studies might yield usable results for subdividing pre-Simpson Paleozoic rocks.

Silicon isotopes.—Natural variations in the isotopic composition of silicon, Si^{28} and Si^{30}, have been investigated by Reynolds and Verhoogen (1953). They found that silica deposited from sea water (Franciscan chert, Miocene chert, and marine diatomite) is richer in Si^{30} than igneous rocks and suggested that this enrichment is due to organic processes. Chert from the Dover chalk, however, was found to be enriched in Si^{28}, and no explanation for this was offered.

Allenby (1954) submitted a similar paper for publication about the time the one by Reynolds and Verhoogen appeared. He found tripolite and radiolaria earth to be enriched in Si^{30}.

The value of a study of the isotopic composition of silicon in chert of pre-Simpson rocks is still a moot question as too few analyses have been made and too little is known about the distribution of silicon isotopes in time. The difficulty of making silicon isotope analyses is another deterrent to their use.

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Thermoluminescence of Pre-Simpson Paleozoic Rocks

VIRGIL E. BARNES

ABSTRACT

Because the thermoluminescence properties of dolomite and limestone are not directly comparable, each rock type must be examined separately to determine whether any thermoluminescence characteristic exists which is usable for subdividing and correlating pre-Simpson rocks.

The glow curves for irradiated limestone show some variation, the low-temperature peak being more intense for most of the Ordovician limestone than for most of the Cambrian limestone. The Cambrian limestone is mostly granular and the Ordovician limestone is mostly aphanitic, except for the El Paso limestone in the Franklin Mountains. This exception suggests that grain size is not the controlling factor in the difference in the amount of thermoluminescence between Cambrian and Ordovician rock. This difference, so far as the Cambrian is concerned, may be caused, at least in some samples, by the presence of dolomite or in general by higher insoluble-residue content, by darker color, or possibly by increased pressure.

The peak-height ratios for limestone generally do not show consistent variations. The ratio of the medium- to low-temperature peaks increases slightly downward except in Humble Oil & Refining Company No. 1 Miller, Collin County, which shows little variation. The other ratios are erratic and none appear to be of value for subdividing the pre-Simpson.

The glow curves for dolomite have no apparent consistency in intensity either for age or grain size of the dolomite, except that the low-temperature peak is generally more intense that the high-temperature peak for the younger and finer-grained dolomite. The reverse is true for the older and coarser-grained dolomite; however, there are many exceptions.

The peak-height ratios for dolomite are even more erratic than for limestone, but discernible variations are detectable for all ratios. The ratio of the high- to low-temperature peaks increases downward, and the same is true for the ratios of the medium-to-low temperature peaks except in one well in which there is no change. The ratio of the medium to high-temperature peaks decreases downward. Grain size does not appear to be related to peak-height ratios.

Thermoluminescence is of little value for subdividing Ellenburger rocks, and little is gained by being able to distinguish (and even this not too consistently) between Ellenburger and older rocks by thermoluminescence because there are easier ways of making distinctions.

INTRODUCTION

The property exhibited by some materials of emitting visible light when heated to a point below which they would naturally start to glow is known as thermoluminescenec. This property is readily demonstrated by placing limestone, or any other equally thermoluminescent material, either crushed to millimeter size or cut as a thin wafer, on a hot plate in a darkened room and then observing while heating. A specimen once heated will not exhibit this property a second time unless exposed meanwhile to some kind of high-energy radiation.

Until recently the currently accepted theory of thermoluminescence, as traced by Saunders (1953, p. 118), who quoted Mayer and Przibram (1914), was as follows: "Certain groups of electrons are displaced by radiation from their normal positions and take up new metastable positions among the atoms." Heating causes the electrons to return to their stable positions with the emission of light, and it is this light produced during heating which is called thermoluminescence.

Zeller, Wray, and Daniels (1957, p. 123) found that:

> Freshly precipitated calcium carbonate with no radiation, and very young limestone deposits with little exposure to radiation, exhibited some thermoluminescence. It is apparent then, that the thermoluminescence of geological samples does

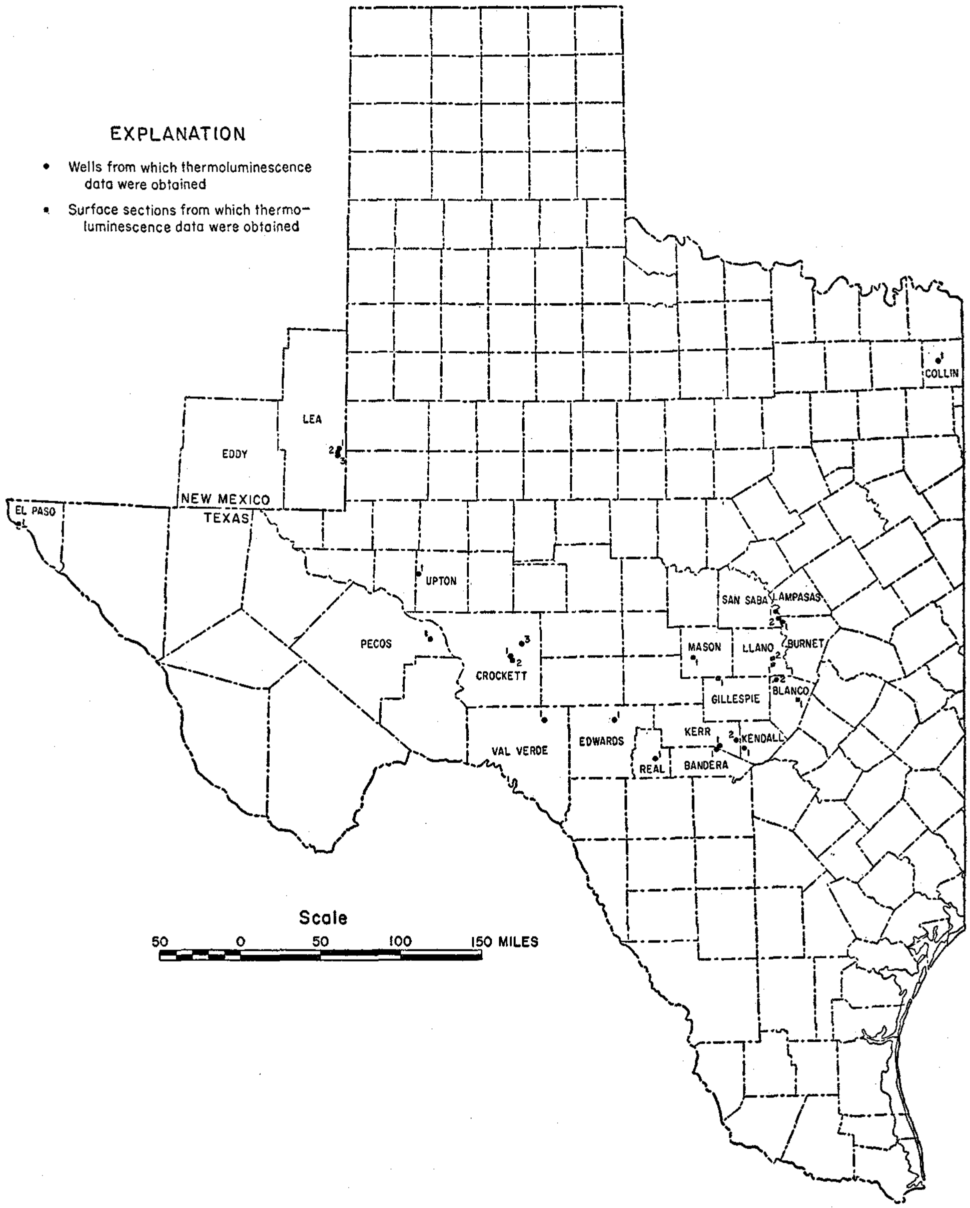

FIG. 23. Map showing wells and surface sections from which thermoluminescence data were obtained.

not start from zero at the time of deposition as had been previously assumed. It is clear also from these studies that there are at least two genetic types of thermoluminescence shown by calcium carbonate. One type is developed at the time the crystals of the calcium carbonate precipitate are formed, and the other is produced by radiation damage with gamma rays or other high energy radiation.

In recent years much of the research on thermoluminescence has been carried on by a group of workers at the University of Wisconsin. Progress reports, including review of previous work, were prepared by Daniels (1951?), Daniels, Boyd, and Saunders (1951?), Morehead and Daniels (1951?), Parks (1951?), and Zeller (1951?). Additional reports of progress were made by Daniels (1953?, 1954?), Pitrat (1953?, 1954?), Zeller (1953?, 1954?), and Zeller and Wray (1954?), and Bergstrom (1953) made a report on correlation of some Pennsylvanian limestones. Modified versions of some of the short progress reports cited have since been published (Daniels, Boyd, and Saunders, 1953; Parks, 1953; Pitrat, 1956; Saunders, 1953; Saunders, Morehead, and Daniels, 1953; Zeller, 1954a, 1954b; Zeller, Wray, and Daniels, 1955, 1957; Zeller and Wray, 1956).

It was hoped that Dr. Zeller would write the present discussion, but since that was not feasible, the writer undertook to do so. Therefore, procedure and instrumentation are slighted, and the main emphasis is placed on interpretation and evaluation of data furnished by members of the Wisconsin group.

Wells and surface sections from which thermoluminescence data were obtained during the pre-Simpson project are shown in figure 23.

Fig. 23, explanation (continued)—

NEW MEXICO

LEA COUNTY
1. Continental Oil Co. #1 Burger B-28
2. Humble Oil & Rfg. Co. #3 "V" N. M. State
3. Humble Oil & Rfg. Co. #6 "V" N. M. State

TEXAS

BANDERA COUNTY
1. G. L. Rowsey #2 Fee

BLANCO COUNTY
1. Honeycut Bend section
2. White Creek section

BURNET COUNTY
1. Tanyard section

COLLIN COUNTY
1. Humble Oil & Rfg. Co. #1 Miller

CROCKETT COUNTY
1. Humble Oil & Rfg. Co. #1-C Alma Cox
2. Humble Oil & Rfg. Co. #1-D Alma Cox
3. Humble Oil & Rfg. Co. #2 Harvick

EDWARDS COUNTY
1. The Texas Co. #1 Phillips

EL PASO COUNTY
1. Franklin Mountains section

GILLESPIE COUNTY
1. Threadgill Creek section

KENDALL COUNTY
1. Magnolia Petroleum Co. #1 Below

KERR COUNTY
1. G. L. Rowsey #2 Nowlin
2. Tucker Drilling Co. #1 Dr. Roy E. Perkins

LLANO COUNTY
1. Moore Hollow section
2. Warren Springs section

MASON COUNTY
1. Pete Hollow section

PECOS COUNTY
1. Standard Oil Co. of Texas #2-1 Claude Owens

REAL COUNTY
1. Stanolind Oil & Gas Co. #1 Knippa

SAN SABA COUNTY
1. Gorman Falls section
2. Spicewood Creek section

UPTON COUNTY
1. Gulf Oil Corp. #1 McElroy-State

VAL VERDE COUNTY
1. Phillips Petroleum Co. #1 Wilson

All thermoluminescence tests for the pre-Simpson project were made at the University of Wisconsin by John A. S. Adams, Donald F. Saunders, and Edward J. Zeller; this group operated for a while as the "TL Associates." For thermoluminescence tests they used the portion of powdered samples which passed through a 100-mesh screen and remained on a 200-mesh screen. This sampling practice was questioned by the writer, and at his suggestion the effects of the fineness of grinding and the length of time of grinding were investigated.

In figure 24, three seive fractions of the same sample are compared for their thermoluminescence properties and found to be similar. Particle size, therefore, unless this sample is unique, makes little difference in the property of thermoluminescence. The sampling technique used is at least a waste of time and where impurities are present may even introduce a bias if there is a differential rate of grinding for the various constituents.

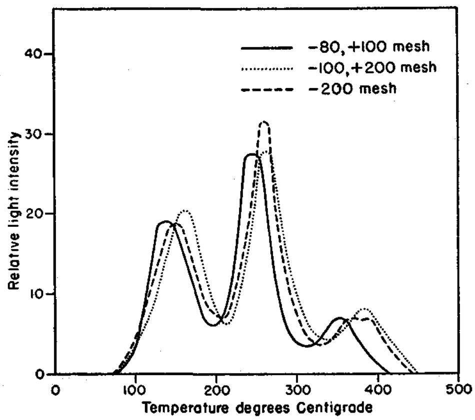

FIG. 24. Diagram showing the lack of effect of fineness of grinding on thermoluminescence properties of pre-Simpson rocks.

Zeller, Wray, and Daniels (1957) stated: "Experiments with solid and powdered samples of limestones older than Eocene have shown that the effects of grinding are sufficiently small as to be undetectable with our present apparatus; however, there is little doubt that small errors are introduced in this way." No data are presented to substantiate this statement, and the observations are at complete variance with the data obtained for dolomite.

The effect of the length of time of grinding on thermoluminescence using dolomite is compared in figure 25. This shows distinctly that the longer a sample is ground, the less thermoluminescent it is. Two factors may be involved in this decrease in thermoluminescence, since the sample tested contained 11.6 percent insoluble residue including clay, feldspar, quartz, and pyrite. A differential rate of grinding, if the grinding were protracted, might produce a sample high in non-thermoluminescent insoluble material, but this is unlikely to happen with a sample ground only a minute or so. That thermoluminescence is

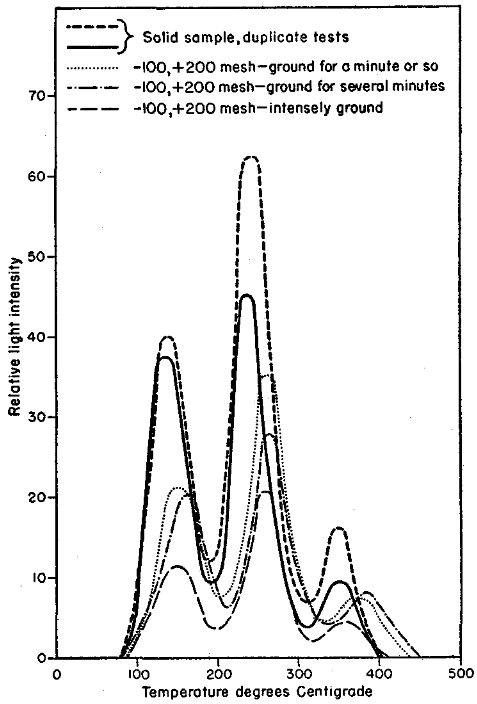

FIG. 25. Diagram showing effect of the length of time of grinding on thermoluminescence properties of pre-Simpson rocks.

progressively destroyed as grinding proceeds seems to be the more likely explanation.

Comparison of the total amount of thermoluminescence for *ground* samples, if this is true, will therefore be useless, since some samples will be affected more than others by grinding. The thermoluminescence peak-height ratios remain rather constant, however, no matter how long the sample is ground, and these can be used, or at least an attempt can be made to use them, for purposes of correlation.

The first 65 samples tested were spot samples carefully collected to avoid veins and chert and clay as beds and along stylolites. The rest were *composite* samples mostly chip-sampled from 5- to 10-foot intervals, with special attention given to making the samples representative. Duplicate thermoluminescence tests were made on each sample.

ANALYSIS OF DATA

Analysis of the thermoluminescence data was chiefly the work of the writer with the "TL Associates" being consulted only during the early part of the project. They furnished, for all samples tested, tracings of the glow curves and a table of calculated peak-height ratios (Appendix J).

The first testing was on 15 samples from Phillips Petroleum Company No. 1 Wilson, Val Verde County, with about a hundred-foot sample spacing, to see if thermoluminescence held any promise for subdividing dolomite in the pre-Simpson group of rocks. The preliminary data obtained appeared promising. The peak-height ratios for these samples are plotted in figure 26A, and the glow curves are incorporated in figure 27. The medium- to low-temperature peak ratios (M/L) fall into three distinct groups, as shown by the vertical and horizontal dashed lines. The medium- to high-temperature peak ratios (M/H) fall mostly in two groups, and the high- to low-temperature peak ratios (H/L) distinctly fall into two groups.

Sixteen additional samples from this well

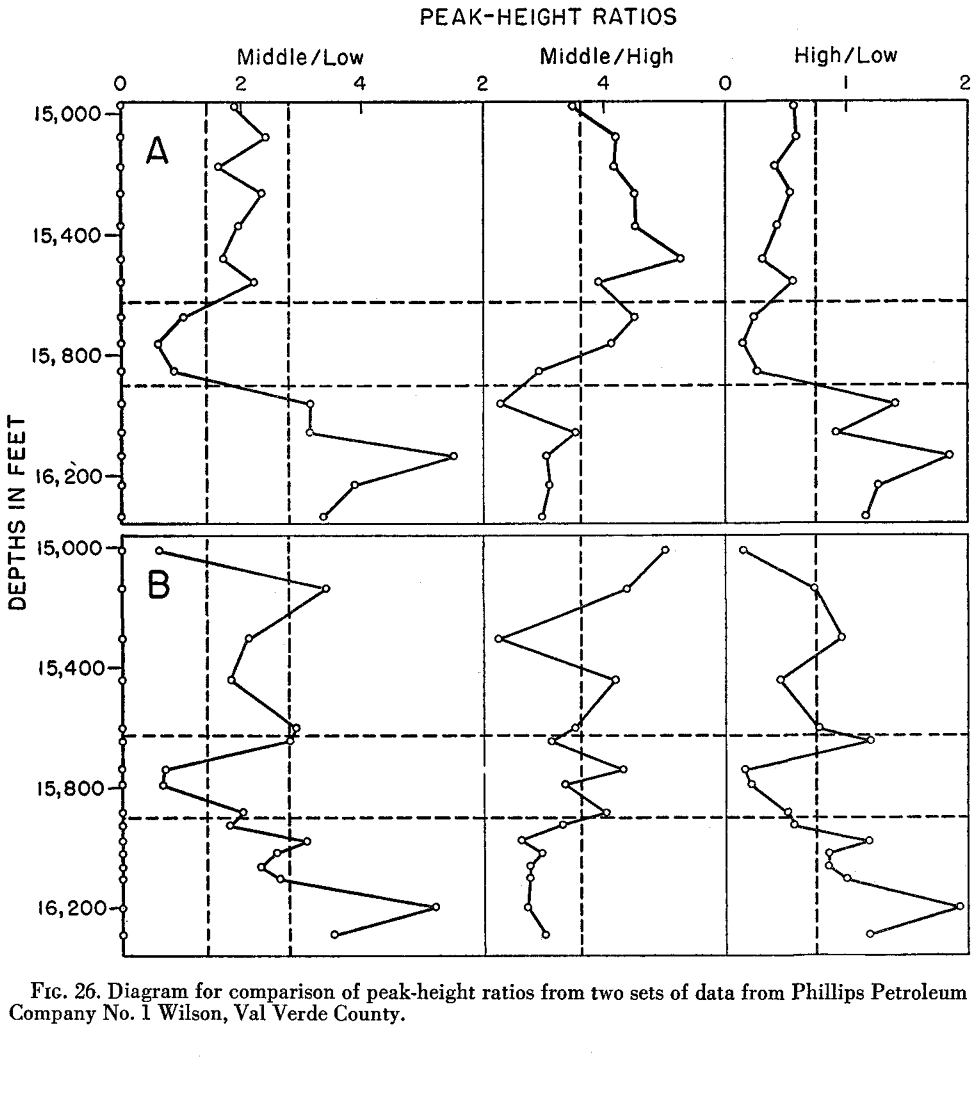

FIG. 26. Diagram for comparison of peak-height ratios from two sets of data from Phillips Petroleum Company No. 1 Wilson, Val Verde County.

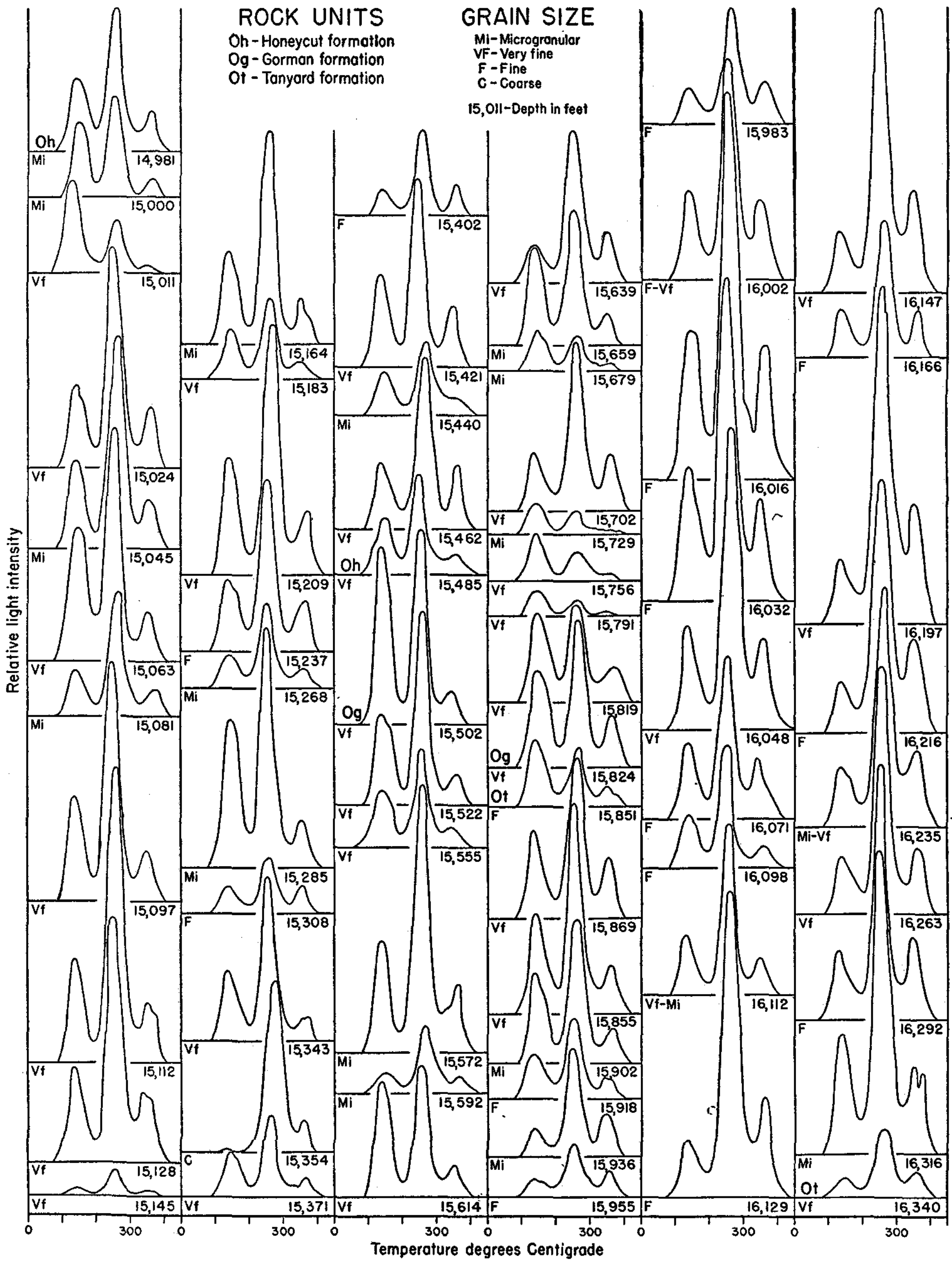

Fig. 27. Thermoluminescence glow curves of dolomite, Phillips Petroleum Company No. 1 Wilson, Val Verde County.

were tested and the peak-height ratios are plotted in figure 26B. The M/L curve approximates the curve obtained with the first group of samples; however, the middle zone is considerably narrowed. The two divisions shown by the M/H curve are less distinct, and although the general shape of the H/L curve is similar to that in figure 26A, it is almost impossible to point to any particular grouping.

The results from these few samples, because of their wide spacing, are inconclusive. The "TL Associates" suggested a spacing of only a few feet as likely to yield more usable results. The writer in trying to arrive at a more realistic sample interval decided that if usable results could not be obtained with a spacing of about 20 feet, the method would not be practicable. With this figure in mind, an additional 31 samples were tested and the peak-height ratios, as well as those from the previous 31 samples, are plotted on Plate 11; their glow curves are shown in figure 27. While there is a general break in the peak-height ratios at a depth of about 15,930 feet, there is no clear-cut division between values below and above this point. Values are erratic for all curves, but the general trend is an increase downward for the peak-height ratios for the M/L and H/L curves and a decrease downward for the peak-height ratios for the M/H curve. These results are of little value for dividing the thick dolomite sequence in this well into recognizable units and suggest that a decrease in the spacing of samples is not warranted.

The glow curves (fig. 27) show very little that might be of value for correlation except that the low-temperature peak is usually more intense than the high-temperature peak above 16,112 feet and the high-temperature peak is usually more intense than the low-temperature peak below this depth. There seems to be no correlation between amount of thermoluminescence and grain size or age.

Forty-five samples from Gulf Oil Corporation No. 1 McElroy-State, Upton County, were tested for thermoluminescence. The peak-height ratios are plotted on Plate 12, and the glow curves are shown in figure 28. The values for the peak-height ratios are erratic with no trend discernible for the M/L curve, the M/H curve decreases downward, and the H/L curve increases slightly downward. When equivalent portions of this well and the Wilson well are compared, it is seen that the ratios for M/L and H/L are much higher for the No. 1 McElroy-State and for the M/H curve slightly lower.

The glow curves (fig. 28) show nothing of value for correlation. The intensity of the low- and high-temperature peaks is reversed from that found for the Wilson well where the two wells correspond in age.

The erratic values found for the thermoluminescence of pre-Simpson dolomite for the first two wells tested discouraged additional work with this rock in the subsurface. The reason for the erratic values for thermoluminescence in dolomite may be redistribution of elements during dolomitization, as suggested by spectrochemical work discussed on page 146. Limestone was found to be of a more consistent composition spectrochemically, and for this reason it was thought that it might also yield more consistent thermoluminescence results. The rest of the testing on subsurface samples was confined to limestone, even though it is not the most important pre-Simpson rock. Results if favorable might be used locally in the subsurface around the Llano region and be of value for regional correlation.

Sixty-one limestone samples from Magnolia Petroleum Company No. 1 Below, Kendall County, were tested for thermoluminescence; the peak-height ratios are plotted on Plate 13, and the glow curves are shown in figure 29. The two Carboniferous limestones have thermoluminescence properties which are distinct from those of the pre-Simpson rocks. The peak-height ratios for the M/L curve increase slightly downward, for the M/H curve increase noticeably downward, and little change can be seen for them in the H/L curve. Thermoluminescence of samples from the middle of the Tanyard downward is mostly fairly distinct from that of the samples above this level; however, there are a few anomalous values in each group.

The glow curves (fig. 29) show little of value for correlation except that the intensity of thermoluminescence for the Wilberns with a few exceptions is mostly less

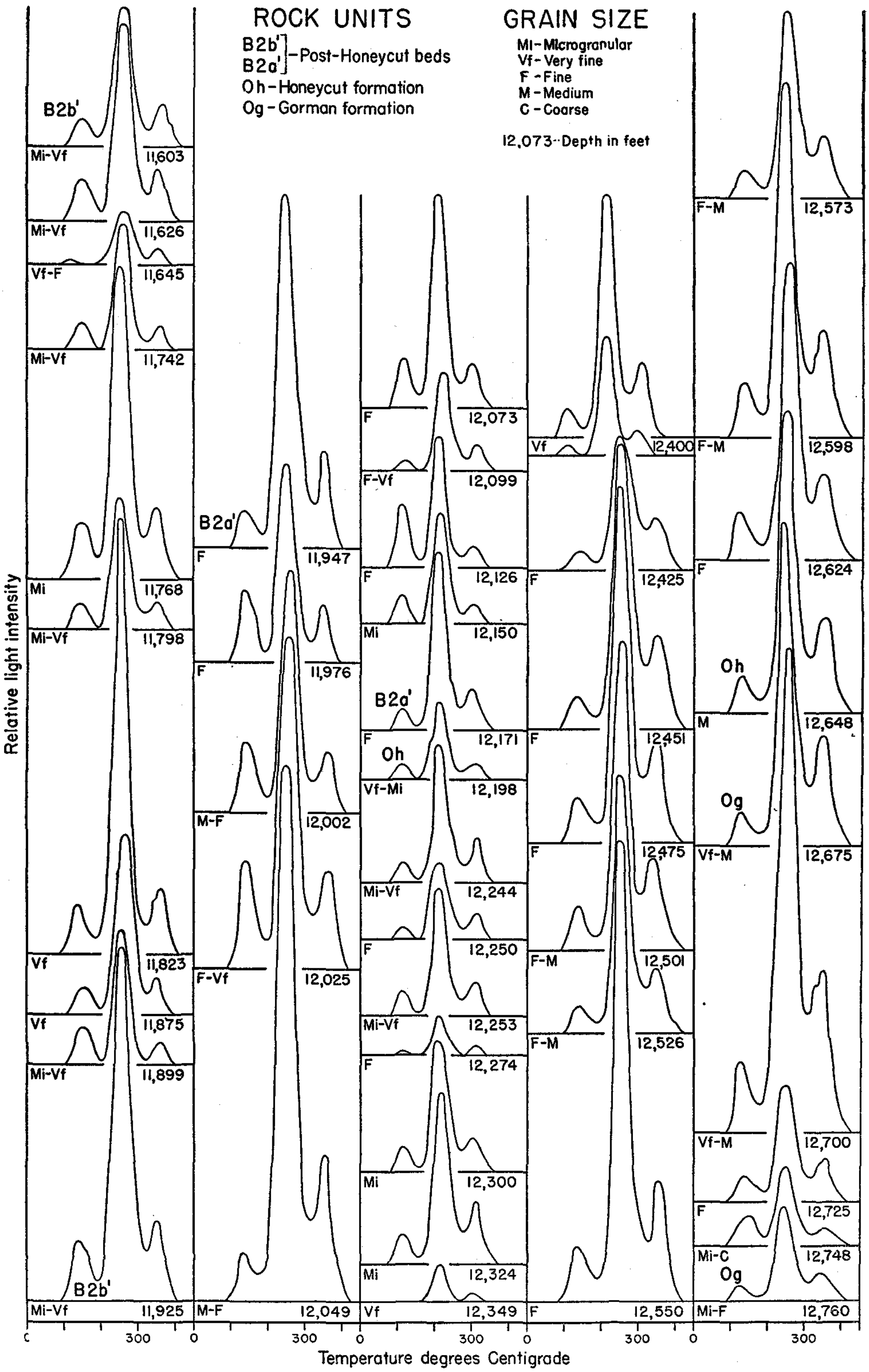

FIG. 28. Thermoluminescence glow curves of dolomite, Gulf Oil Corporation No. 1 McElroy-State, Upton County, Texas.

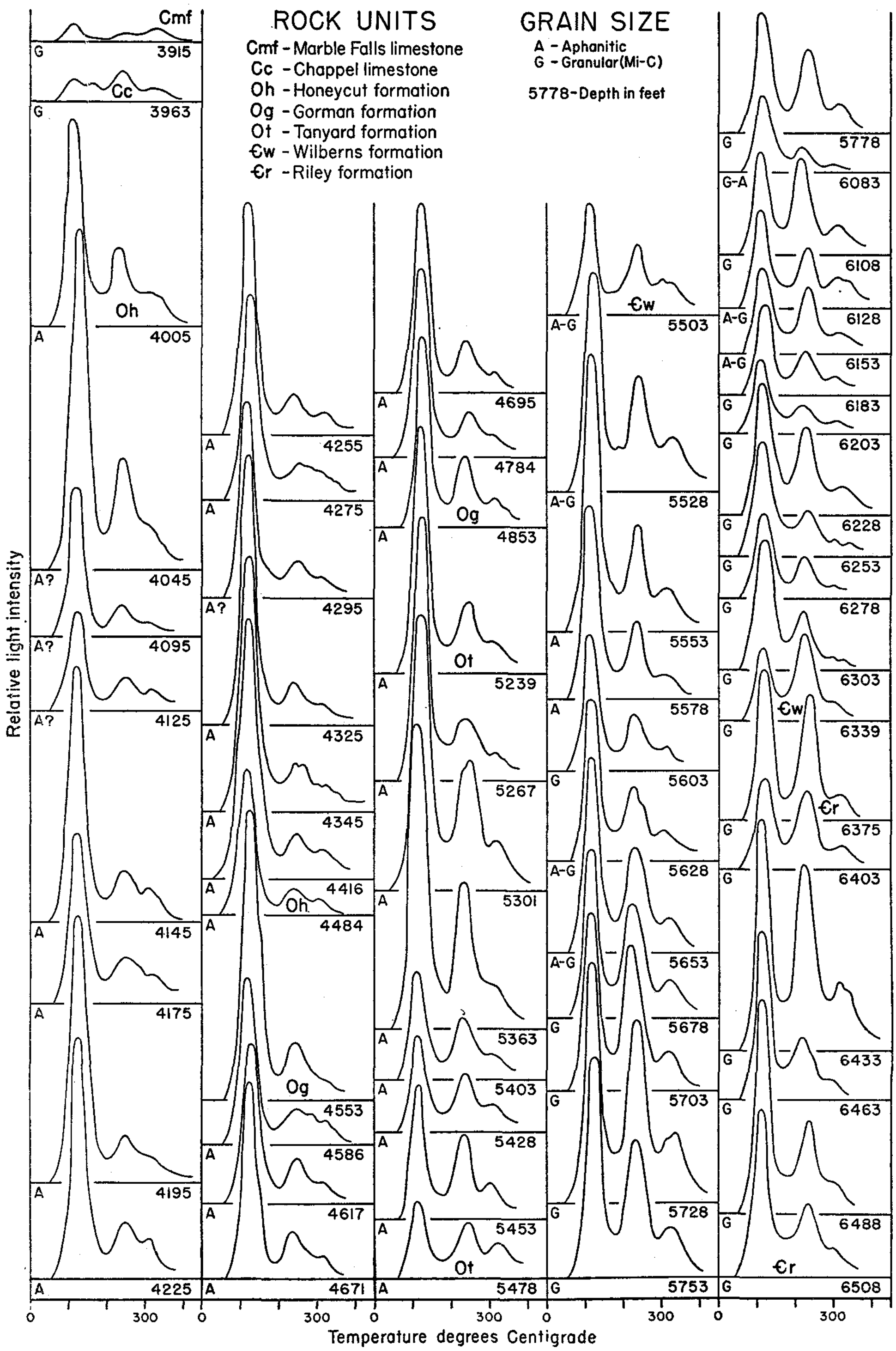

FIG. 29. Thermoluminescence glow curves of limestone, Magnolia Petroleum Company No. 1 Below, Kendall County, Texas.

than that for either the Ellenburger or the Cap Mountain limestone.

The rest of the wells in which limestone was cored were next tested, including 29 samples from Humble Oil & Refining Company No. 1 Miller, Collin County. This well is in the Arbuckle facies and many of the samples tested are from strata younger than those sampled in the Below well. The peak-height ratios are plotted on Plate 14, and the glow curves are shown in figure 30. Seven out of the 29 samples, scattered throughout the well, were without a high-temperature peak. Disregarding these samples, the peak-height ratios for the M/L and H/L curves are similar to those from the upper part of the Below well, but the M/H peak-height ratios for correlative portions are much higher in the Miller well. The glow curves (fig. 30) show nothing of value for correlation.

The peak-height ratios for limestone samples from the rest of the wells in this group, 27 in number with no more than 6 samples from any one well, are plotted on Plate 15, and their glow curves shown in figure 30. Many of the samples are from the Honeycut formation, two are from the Simpson group, and four are from the Wilberns and Riley formations. The peak-height ratios for the M/L and H/L curves are about the same as found for limestone in other wells. The peak-height ratios for the M/H curve range from about the same as found for the Below well to about the same as found for the Miller well. The glow curves (fig. 30) are much less intense for the Cambrian samples than for the Ellenburger samples.

Lack of wells penetrating long sections of limestone hampered the thermoluminescence work and made the results inconclusive. In order to add to the data, surface sections were utilized and a total of 140 samples, both limestone and dolomite, was tested. The peak-height ratios are shown on Plate 16 and the glow curves for dolomite in figure 31 and for limestone in figure 32.

The peak-height ratios for the M/L and H/L curves fall mostly in two distinct groups, depending upon whether the samples are limestone or dolomite, and values falling near the dividing line are mostly mixtures of the two. The peak-height ratios for the M/H curve are erratic for both limestone and dolomite. The peak-height ratios for the M/L and H/L curves become somewhat greater downward for dolomite, but the values are too erratic to be of value for correlation. These ratios are also slightly higher downward for limestone.

The glow curves for limestone (fig. 32) are arranged in general with the aphanitic and younger limestone to the left and the older and granular limestone to the right, except that the Franklin Mountains granular limestone is the youngest. The aphanitic limestone characteristically has a very strong low-temperature peak, and the other two peaks are much weaker with the medium-temperature one the higher of the two. A few glow curves with about equally intense low- and medium-temperature peaks are mostly mixtures of limestone and dolomite; these samples are from 285 to 290 (287) feet in the Pete Hollow section, 450 to 455 (452) feet in the Tanyard section, and 365 to 370 (367) feet in the Spicewood Creek section. Because of lack of space, the median figure (in parentheses) is shown on the diagram. The samples of granular limestone from 765 to 770 (767) feet and 830 to 835 (832) feet in the White Creek section also have about equal low- and medium-temperature peaks; however, these samples are not appreciably dolomitic. The glow curves for the Franklin Mountains granular limestone are similar to those for the aphanitic limestone. The rest of the granular limestone is not as thermoluminescent; the peak strengths are in the same order as for the aphanitic limestone, but the low-temperature peak is much nearer the middle-temperature peak in strength. Some tendency is noticed for the amount of thermoluminescence to increase upward stratigraphically in the sections composed of granular limestone.

Five samples of stromatolitic reef rock —0 to 5 (2), 40 to 45 (42), and 70 to 75

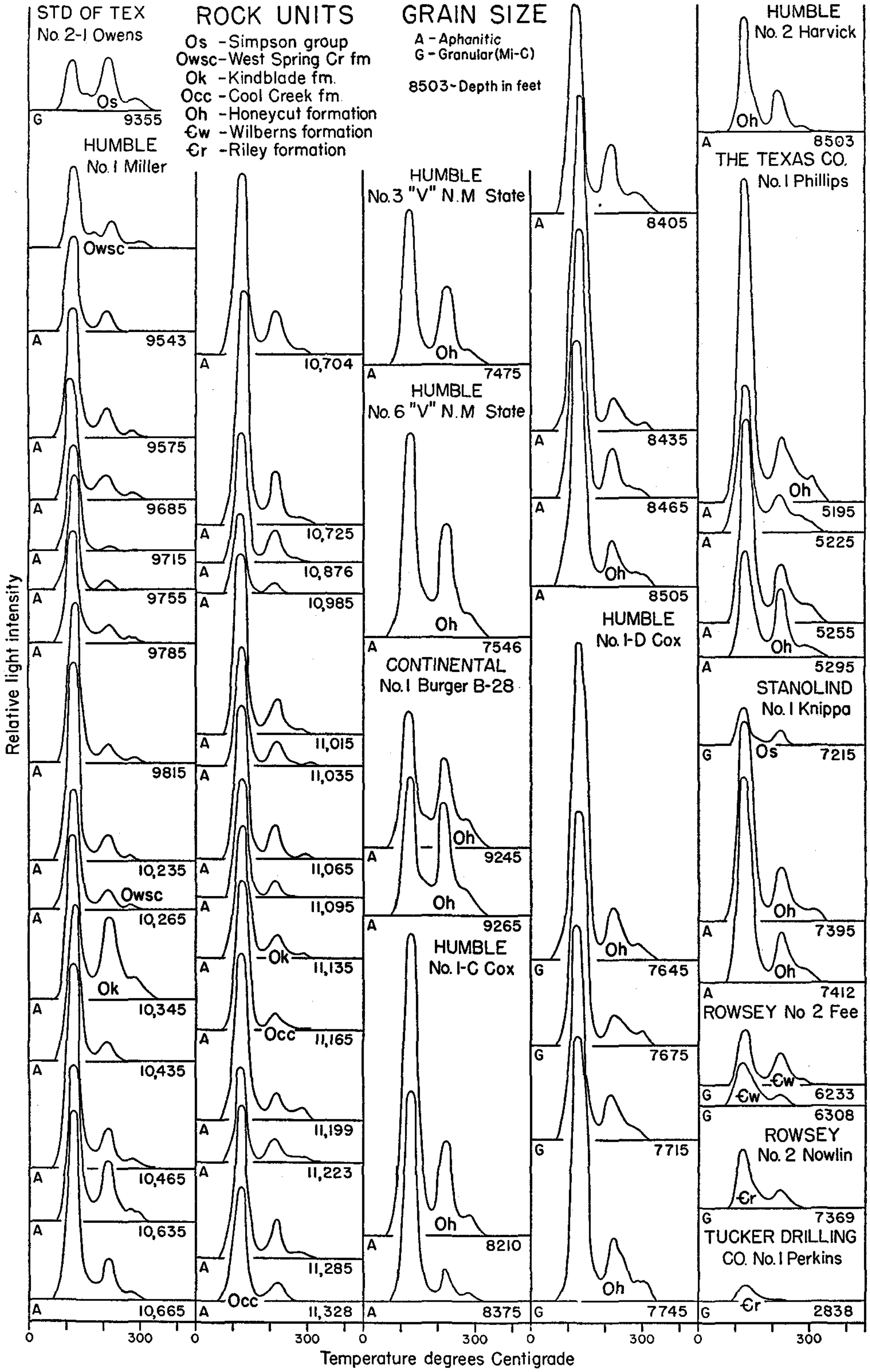

FIG. 30. Thermoluminescence glow curves of limestone, Humble Oil & Refining Company No. 1 Miller, Collin County, and various other wells as shown.

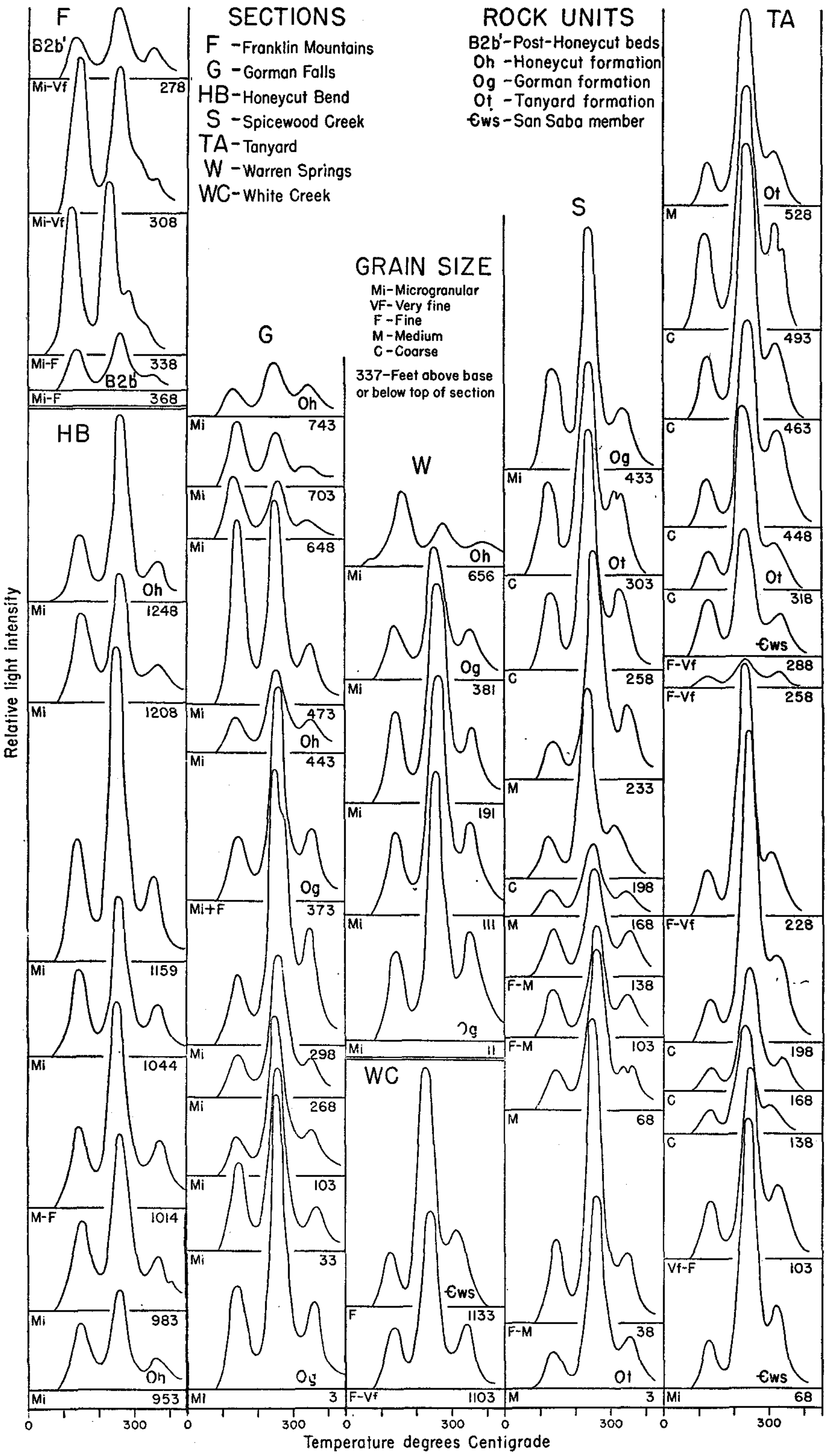

FIG. 31. Thermoluminescence glow curves of dolomite from surface sections.

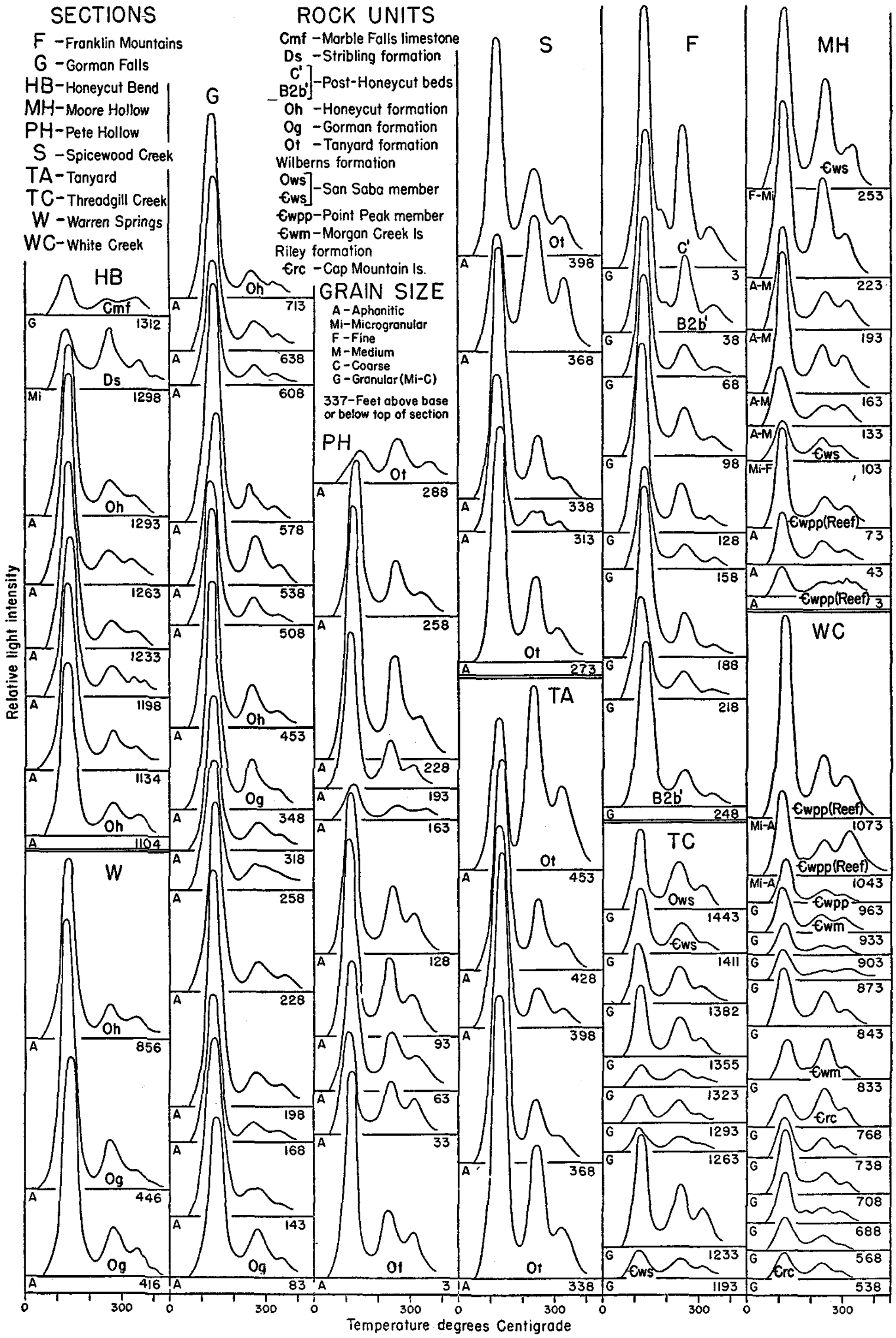

FIG. 32. Thermoluminescence glow curves of limestone from surface sections.

(72) feet in the Moore Hollow section and 1,040 to 1,045 (1,042) and 1,070 to 1,075 (1,072) feet in the White Creek section—also become progressively more thermoluminescent upward. In general, for pre-Simpson rocks the finer grained the rock, the more thermoluminescent it is.

The glow curves for dolomite (fig. 31) are arranged in general with the younger and finer grained ones to the left and the older and coarser-grained ones to the right. The medium-temperature peak for dolomite is mostly considerably more intense than for the other two peaks. The low-temperature peak in general is more intense than the high-temperature peak for the younger and finer-grained dolomite. The reverse is mostly true for the older and coarser-grained dolomite; however, there are many exceptions. Where medium- and low-temperature peaks are about equal, calcite is present in appreciable amounts. The Franklin Mountains samples mostly contain both dolomite and limestone. The Gorman Falls samples 470 to 475 (472), 645 to 650 (647), and 700 to 705 (702) feet and the Warren Springs sample 653 to 658 (655) feet are very calcitic.

RELATION OF COMPOSITION AND THERMOLUMINESCENCE

Early during the present project it became obvious that limestone and dolomite have distinctive thermoluminescence characteristics. The dolomite is characterized by a strong medium-temperature thermoluminescence peak, whereas limestone is characterized by a strong low-temperature thermoluminescence peak.

The shape of the glow curve and the amount of thermoluminescence are related to the carbonate mineral composition—chiefly calcite and dolomite. The end member molecules, calcium carbonate and calcium-magnesium carbonate, show little tendency to be miscible; however, calcium-magnesium carbonate (common dolomite) is miscible in all proportions with calcium-iron carbonate (ferrodolomite) and with calcium-manganese carbonate (mangandolomite). The effect of the ferrodolomite and mangandolomite molecules on thermoluminescence is unknown. Also the effect of the presence of other molecules or elements that might be included in the carbonate minerals is unknown.

In an attempt to gain some information on the effect caused by other elements, many of the samples tested for thermoluminescence were analyzed spectrochemically. It is almost impossible, of course, to state exactly how much of any of the elements detected is actually in the carbonate minerals and how much is interstitial to or included in the carbonate minerals in some non-thermoluminescent form.

The results for spectrochemical tests are plotted on Plates 7–10 and the thermoluminescence tests for the same wells are plotted on Plates 11, 13–15. Except for the relationship already stated, namely, that dolomite has a strong medium-temperature peak and limestone a strong low-temperature peak, little if any correlation can be seen between thermoluminescence and composition. Even when the medium- and low-temperature peak-height ratios are compared with magnesia for either dolomite or limestone individually, the over-all correspondence is poor except for part of Magnolia Petroleum Company No. 1 Below, Kendall County. In this well the correspondence is fair for the Tanyard and Wilberns formations where high peak-height ratios for M/L correspond to high magnesia content. Above this level the peak-height ratios for M/L are very low and show little correspondence with the magnesia content. The few samples analyzed from the Riley formation show a reversed relationship to that found in the Wilberns and Tanyard formations. Here the higher the peak-height ratio for M/L, the lower the magnesia. In this same well, high iron corresponds with high peak-height ratios for M/H; however, there are many exceptions. For the rest of the limestone and all the dolomite tested, no correspondence was seen between the peak-height ratios and composition.

Lewis (1956) determined the thermoluminescence of 18 samples of a vertical limestone-dolomite transition in the Honeycut formation in interval 84 of the Honeycut Bend section (Cloud and Barnes, 1948, p. 326). Mineral composition determined by differential thermal analysis showed that the samples in the 5-foot bed range from 6.3 to 100 percent calcite, 0.0 to 93.7 percent dolomite, and 81.1 to 100 percent total carbonate. He concluded that:

> The principal conclusions which can be based on experimental results reported in this paper are the following.
>
> (1) The ratio of the glow-curve peaks at approximately 120° and at 240° of the Honeycut Bend limestone after irradiation with cobalt-60 γ-rays can be simply related to the mineralogical composition.
>
> (2) The glow curves of unirradiated dolomite from the Honeycut Bend produce only a single peak at approximately 310° while those samples with 15% or more calcite produce recognizable peaks at 240° and 310°.
>
> (3) The contribution to the glow curve of any free magnesite which might be present in these limestones is negligible.

The third comment is hardly relevant since it is very seldom, if ever, in nature that calcite is found in the presence of magnesite or magnesite in the presence of calcite. Lewis' experimental data showed that magnesite has very feeble thermoluminescence; therefore if present it could not contribute much to the glow curve of any limestone.

USE OF THERMOLUMINESCENCE FOR CORRELATION

Thermoluminescence is practically useless for subdividing Ellenburger rocks and of little use for separating the Ellenburger from the rocks beneath. The few samples of overlying rock tested, however, are distinct from Ellenburger rocks. Ordinarily the overlying rocks are easily distinguished from the Ellenburger and only in a few isolated cases would it be likely that thermoluminescence would be needed to differentiate the two, providing, of course, sufficient testing of overlying rocks has been done and their thermoluminescence found to be distinctive.

CONCLUSIONS

Thermoluminescence is of no practical value for identifying units within the pre-Simpson sequence of Paleozoic rocks, even though some rather poorly defined differences exist where the sequence is limestone. The values for dolomite are erratic throughout the sequence. The glow curve of dolomite is characterized by an intense medium-temperature peak and that of limestone by an intense low-temperature peak; therefore, thermoluminescence can be used to distinguish limestone and dolomite in the pre-Simpson sequence. Simpler ways are known of distinguishing the two rocks.

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Use of Color for Correlating Pre-Simpson Paleozoic Rocks

VIRGIL E. BARNES

ABSTRACT

The pre-Simpson sequence of Paleozoic rocks has a sufficient color range so that recording color furnishes contributory evidence for the identification of various units. These rocks as a whole darken toward the Val Verde, Delaware, and Anadarko basins and also somewhat toward the Collin County area of northeast Texas.

COLLECTION OF DATA

When the first samples were described, close comparison was made with a copy of the Rock Color Chart (1948) and the appropriate color stated. As the project progressed, less and less reference was made to the chart and more reliance placed on memory, but even at the last, occasional comparisons were made. It was discovered after the project was completed that the chart used had darkened; the grays, for example, were found to be darker by almost one shade, that is, light gray on the used chart was about medium light gray on a new copy of the chart which was used for purpose of comparison. The reason for the darkening of the chart is probably twofold: (1) accumulation of grime over the years and (2) the presence of hydrochloric acid fumes. Pages of the chart which had not been referred to very often were less changed but also showed some darkening.

Color was found to appear different on sawed and on crushed surfaces; therefore, it should be recorded only from uniformly prepared material if it is to be used for correlation.

As description of cores and samples progressed, it became apparent that if color was to be used for correlation, the large number of color terms used should be reduced to fewer categories; the following were finally chosen: (1) various shades of pink and red, (2) various shades of green and greenish gray, excluding the very light tones, (3) all other colors of medium intensity or darker, and (4) all other colors of an intensity less than medium.

EVALUATION OF DATA

Many of the cores examined during this pre-Simpson project were chip-sampled, crushed to simulate cuttings, and mounted on log strips as described on pages 21–22. Cuttings from a few wells were also mounted in the same manner. With these sample-mounted logs, a direct color comparison is possible between cores and cuttings. All the mounted logs were arranged approximately in order as shown in the various well-correlation sections. The wells as a whole range widely in color intensity; in table 14 they are arranged approximately in order of decreasing intensity.

TABLE 14. *Wells arranged in approximate order of decrease in color intensity.*

(1) (Darkest) Phillips Petroleum Company No. 1 Glenna, Pecos County
Phillips Petroleum Company No. 1-C Puckett, Pecos County
(2) Phillips Petroleum Company No. 1 Wilson, Val Verde County
(3) Richardson & Bass No. 1 Federal-Cobb, Eddy County, New Mexico
(4) G. L. Rowsey No. 2 Fee, Bandera County
(5) Sinclair Oil & Gas Company No. 9, McElroy, Upton County
(6) Stanolind Oil & Gas Company No. 1 Knippa, Real County
Lea County, New Mexico—
Continental Oil Company No. 1 Burger B-28
Humble Oil & Refining Company No. 6 "V" N. M. State
Shell Oil Company No. 5 State
Andrews County, Texas—
Humble Oil & Refining Company No. 2 Evelyn Lineberry

Humble Oil & Refining Company No. 37 Parker
Shell Oil Company No. 12 Lockhart
Ralph Lowe No. 1 Southland Royalty
The Superior Oil Company No. 1-36-A University
Gulf Oil Corporation No. 1-E State "AM"
Gulf Oil Corporation No. 1 Texas "000"
Gulf Oil Corporation No. 108-E Keystone, Winkler County
Magnolia Petroleum Company No. 2-A Windham, Midland County
Gulf Oil Corporation No. 1 McElroy-State, Upton County
Wilshire Oil Company No. 23-118 Windham, Upton County
Gulf Oil Corporation No. 1 Mitchell Bros. —State, Presidio County
The Superior Oil Company No. 1-27 University, Crockett County
American Trading & Production Corporation No. 1 Sauer, Schleicher County
Standard Oil Company of Texas No. 2-1 Claude Owens, Pecos County

(7) Humble Oil & Refining Company No. 1 Miller, Collin County
(8) Humble Oil & Refining Company No. 1-M University, Reagan County
Humble Oil & Refining Company No. 1-D Alma Cox, Crockett County
Humble Oil & Refining Company No. 1-C Alma Cox, Crockett County
The Atlantic Refining Company No. 1 Noelke, Irion County
Humble Oil & Refining Company No. 1 J. D. Harrison, Sutton County
Deep Rock Oil Corporation No. 1 Moore Estate, Clay County
(9) Magnolia Petroleum Company No. 1 Shannon Hospital, Crockett County
(10) The Texas Company No. 1 Phillips, Edwards County
Magnolia Petroleum Company No. 1 Below, Kendall County
(11) Roland K. Blumberg No. 1 Wagner, Blanco County
(12) Gilcrease Oil Company No. 1 Feril, Comanche County
(13) (Lightest) L. U. Rowntree No. 1 Richard Kott, Gillespie County

Such an over-all comparison is not strictly accurate as different parts of the geologic column are compared in different wells, some being entirely Ordovician, others entirely Cambrian, and a few both Ordovician and Cambrian. The results of this color comparison are shown in figure 33. The data, even though sparse, show that the lightest-colored rocks are in and around the Llano region and that the darkest are in the Val Verde—Pecos County area. This suggests either that central Texas is far removed from a source of terrigenous material or that the rocks there were deposited under oxidizing conditions, and that the Val Verde—Pecos County area is nearer to a source of dark-colored terrigenous material or that the rocks were deposited under reducing conditions. The rocks are also dark in the Delaware and Anadarko basins.

In discussing the color of the various units, reference is made both to the color descriptions and to the mounted sample logs (Pl. 65). Unit C′ is somewhat lighter colored than the underlying B2b′ unit. The B2b′ unit in the Phillips Petroleum Company No. 1 Glenna and No. 1-C Puckett, Pecos County, is perhaps the darkest rock seen in any of the wells. In Standard Oil Company of Texas No. 2-1 Claude Owens, Pecos County, and Gulf Oil Corporation No. 1 McElroy-State, Upton County, the B2b′ unit is much lighter colored. Unit B2a′ is lighter colored than the overlying B2b′ unit and eastward becomes darker, approaching the color of the B2b′ unit.

The upper part of the Honeycut formation is darker than the B2a′ unit, and downward the Honeycut is lighter colored. Regionally the Honeycut is lightest colored in L. U. Rowntree No. 1 Richard Kott, Gillespie County, and darkens in all directions from here except possibly northward. The Gorman formation to the west is somewhat darker colored than the immediately overlying part of the Honeycut formation; to the east the two are of about the same color. In the west the Gorman is about the same color as the underlying Tanyard. Eastward the upper part of the Tanyard is lighter colored than the Gorman formation, the middle about the same color as the Gorman formation, and the lower part, Threadgill member, much lighter than the Gorman formation.

The upper part of the San Saba member to the west is similar in color to the overlying Tanyard and the lower part is lighter colored. In the Llano region, the San Saba is mostly darker than the Tanyard except in the extreme eastern part of the region where it is very light gray, similar to the overlying Threadgill member. The same is true to the east and southeast in the subsurface in Shell Oil Company No. 1 Purcell, Williamson County, and Roland K. Blumberg No. 1 Wagner, Blanco County.

The Point Peak shale in part is greenish gray to medium olive gray and in general is darker than the overlying San Saba member. The Morgan Creek, mostly greenish gray except for a pinkish zone at its base and locally a much thinner pinkish zone at its top, is possibly darker colored than the overlying Point Peak shale. The pinkish zones are not recognized west of Menard and Kimble counties.

The Welge sandstone is mostly a light-colored unit but in some wells west of the Llano region is reddish or brownish. To the southeast it is dark green owing to the presence of glauconite. The Lion Mountain sandstone is mostly dark green greensand, and in the subsurface to the west of the Llano region a dark brown limonitic zone at its top is suggestive of an ancient soil.

The Cap Mountain limestone is mostly a light-colored unit with some pinks and reds in its lower part in the Llano region, and in the subsurface to the southeast where it is thickest the lower part is very dark greenish gray. This dark color persists in this area into the upper part of the Hickory sandstone, followed downward by very gray sandstone. The red zone in the Cap Mountain limestone when traced northwestward becomes the top part of the Hickory sandstone. This red zone, 100 to 200 feet thick, continues westward and northward and rises toward the top of the Riley formation; this can be explained by erosion at the top of the Riley since an unconformity is present, by less Riley beds being deposited, or by a combination of these factors. The sand grains in this zone are well rounded, polished, and coated by thin layers of red iron oxide, and in a few wells the iron oxide is brown. Beneath the red zone is about 150 feet of light-colored sandstone, followed by about 100 to 150 feet of pinkish sandstone, and again light-colored sandstone to the Precambrian.

Discussions with geologists working with pre-Simpson rocks brought out the fact that some rely on so-called "weathering zones" for correlation. The zones are recognized by colors such as red, pink, and various browns. Except for the fossil "soil" zone at the top of the Lion Mountain sandstone, no undoubted correlatable "weathering zones" have been recognized during the present work. Colors that could be attributed to weathering are present in some wells, absent in others, and when logged have a very erratic distribution except for the red zones at the bottom and top of the Morgan Creek limestone and in the Hickory, which may be caused in some manner other than by weathering.

A few wells, like L. U. Rowntree No. 1 Richard Kott in Gillespie County, have hundreds of feet of pastel pinks and purples which actually may be caused by weathering. In the Kott well the weathering would have taken place while these rocks were exposed prior to Cretaceous sedimentation. Phillips Petroleum Company No. 1 Spiller, Kimble County, and Taylor Oil and Gas Company No. 1 Judkins, Schleicher County, also have an abnormal amount of pink rock in them. Perhaps the change in color took place following the Pennsylvanian period of faulting.

Samples from Gilcrease Oil Company No. 1 Feril, Comanche County, have not been examined in detail. Only 5 feet of samples appear to be Cap Mountain, about a normal amount of Lion Mountain is present, and both the Welge, which is thicker than normal, and the Hickory sandstone are dark red.

If color alone is used (Pl. 65), Richardson & Bass No. 1 Federal-Cobb, Eddy County, New Mexico, appears to be miscorrelated. The color of the rock more nearly matches the upper part of the Honeycut formation or the B2b′ unit. Other evidence, possibly outweighing the color evidence, indicates that the correlation shown is preferable. The same is true about the color of Magnolia Petroleum Company No. 2-A Windham, Midland County, but many other factors suggest that the correlation shown is correct.

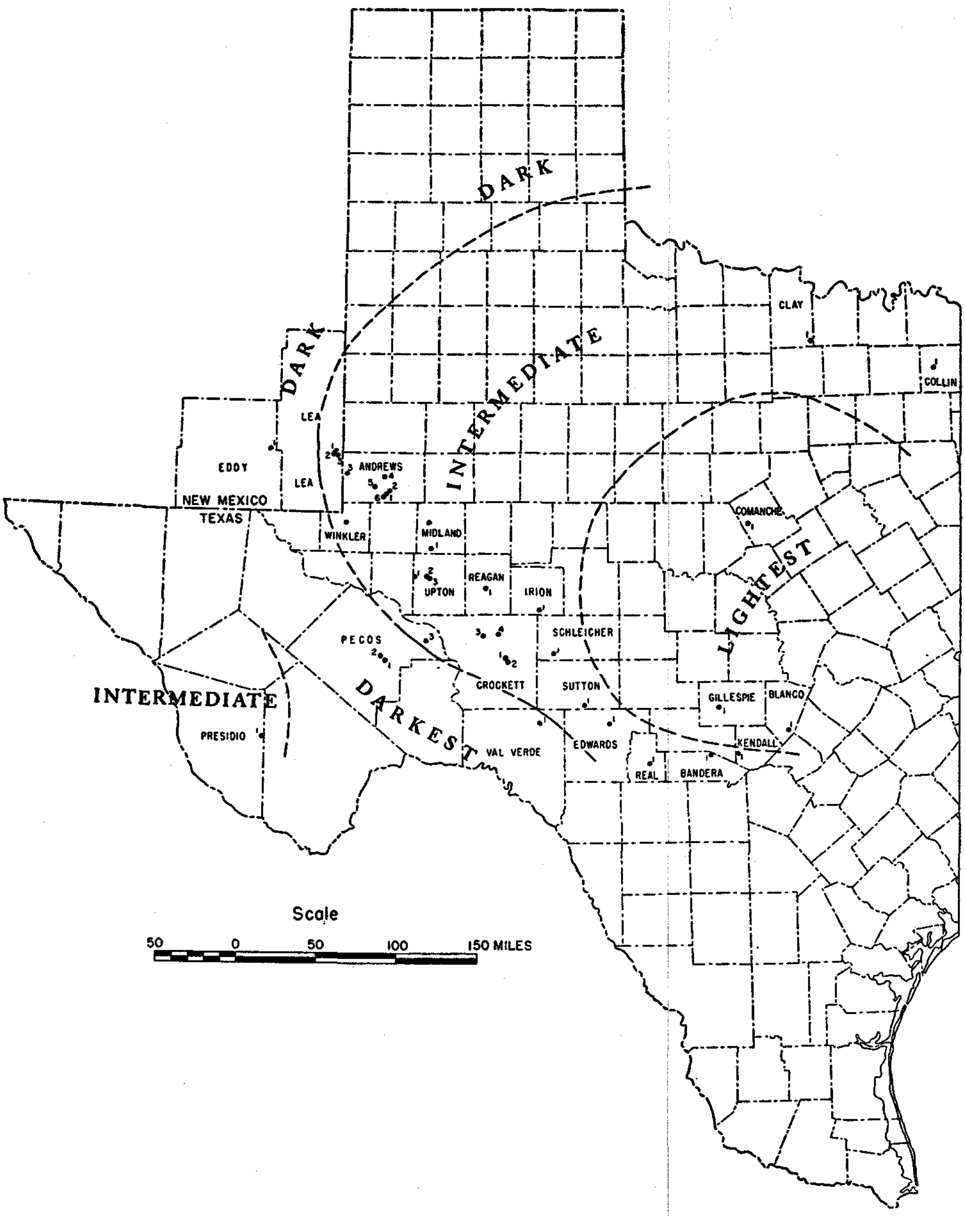

FIG. 33. Map showing distribution of intensity of color in pre-Simpson Paleozoic rocks and wells for which sample-mounted logs were prepared.

NEW MEXICO

EDDY COUNTY

1. Richardson & Bass #1 Federal-Cobb

LEA COUNTY

1. Continental Oil Co. #1 Burger B-28
2. Humble Oil & Rfg. Co. #6 "V" N. M. State
3. Shell Oil Co. #5 State

TEXAS

ANDREWS COUNTY

1. Gulf Oil Corp. #1-E State "AM"
2. Gulf Oil Corp. #1 Texas "000"
3. Humble Oil & Rfg. Co. # 2 Evelyn Lineberry
4. Ralph Lowe #1 Southland Royalty
5. Shell Oil Co. #12 Lockhart
6. The Superior Oil Co. #1-36-A University

CONCLUSIONS

Color variations are present in pre-Simpson Paleozoic rocks and are useful contributory evidence for correlation. Units of the Ellenburger which are relatively lighter colored are C′, B2a′, lower part of the Honeycut formation, and in part of the area the upper and lower thirds of the Tanyard formation. The relatively darker-colored units include B2b′, the upper part of the Honeycut formation, and in part of the area the Gorman formation and the middle third of the Tanyard formation.

Greenish gray of various shades is common in the Wilberns and Riley formations. A red zone in the Riley transgresses laterally northwestward from the Cap Mountain to the Hickory sandstone, a prominent pink zone is at the base of the Morgan Creek limestone in the Wilberns, and another is very locally at its top.

In using color for correlation it should be kept in mind that these rocks as a whole darken toward the Val Verde, Delaware, and Anadarko basins and to a lesser extent toward the Collin County area of northeast Texas.

REFERENCE

ROCK-COLOR CHART COMMITTEE (1948) Rock color chart, National Research Council, Washington, D. C.

Fig. 33, explanation (continued)—

BANDERA COUNTY
1. G. L. Rowsey #2 Fee

BLANCO COUNTY
1. Roland K. Blumberg #1 Wagner

CLAY COUNTY
1. Deep Rock Oil Corp. #1 Moore Estate

COLLIN COUNTY
1. Humble Oil & Rfg. Co. #1 Miller

COMANCHE COUNTY
1. Gilcrease Oil Co. #1 Feril

CROCKETT COUNTY
1. Humble Oil & Rfg. Co. #1-C Alma Cox
2. Humble Oil & Rfg. Co. #1-D Alma Cox
3. Magnolia Petroleum Co. #1 Shannon Hospital
4. The Superior Oil Co. #1-27 University

EDWARDS COUNTY
1. The Texas Co. #1 Phillips

GILLESPIE COUNTY
1. L. U. Rowntree #1 Richard Kott

IRION COUNTY
1. The Atlantic Rfg. Co. #1 Noelke

KENDALL COUNTY
1. Magnolia Petroleum Co. #1 Below

MIDLAND COUNTY
1. Magnolia Petroleum Co. #2-A Windham

PECOS COUNTY
1. Phillips Petroleum Co. #1 Glenna
2. Phillips Petroleum Co. #1-C Puckett
3. Standard Oil Co. of Texas #2-1 Claude Owens

PRESIDIO COUNTY
1. Gulf Oil Corp. #1 Mitchell Bros.—State

REAGAN COUNTY
1. Humble Oil & Rfg. Co. #1-M University

REAL COUNTY
1. Stanolind Oil & Gas Co. #1 Knippa

SCHLEICHER COUNTY
1. American Trading & Prod. Corp. #1 Sauer

SUTTON COUNTY
1. Humble Oil & Rfg. Co. #1 J. D. Harrison

UPTON COUNTY
1. Gulf Oil Corp. #1 McElroy-State
2. Sinclair Oil & Gas Co. #9 McElroy
3. Wilshire Oil Co. #23-118 Windham

VAL VERDE COUNTY
1. Phillips Petroleum Co. #1 Wilson

WINKLER COUNTY
1. Gulf Oil Corp. #108-E Keystone

Insoluble Residues of Ellenburger Subsurface Rocks

VIRGIL E. BARNES AND LANE P. DIXON

ABSTRACT

Insoluble residues were examined from rocks of the Ellenburger group in Texas and southeast New Mexico and the results compared with correlations made from all available criteria. It was found that correlations made with acid-insoluble residues alone, while of some value, are not nearly as reliable as correlations made by using all available evidence, which of course includes observation of the insoluble materials as they are found in the rock.

INTRODUCTION

Except possibly for binocular-microscope examination of untreated cuttings, the insoluble-residue technique is used more than any other method in efforts to subdivide the Ellenburger group of rocks. Because this technique is widely known (McQueen, 1931; Ireland, 1936; Hendricks, 1952; McCracken, 1955), not as much undivided attention was given to it during the present project as to other less well-known techniques. Insoluble materials are important for correlation, as shown in other parts of the publication (pp. 44–47).

For this paper, Dixon supervised the sampling and preparation of residues, described the residues, and supervised the preparation of Plate 17. The insoluble residue correlation shown on Plate 17 is Dixon's, made before the final correlations were made on Plates 1 to 6. The text is entirely the responsibility of Barnes. Wells from which insoluble residues were examined are shown in figure 34.

PREPARATION OF RESIDUES

Residues were prepared from cores which were carefully scrubbed to remove drilling mud and other adhering foreign material. The cores were chip-sampled every few inches and composite samples made for each 10-foot interval. The composite samples were passed through a jaw crusher, reducing them to about the size of cuttings. Ten-gram samples were dissolved in a 200-ml beaker using 1 part of chemically pure hydrochloric acid to 3 parts of water. Commercial-grade acid if low in sulfate could be used instead, but the commercial-grade acid available to the project was so sulfate-ladened that gypsum precipitated on the insoluble material. The residue was filtered under vacuum, washed several times with distilled water, dried in an oven at 105° C., and weighed. The weight was multiplied by 10 to obtain the percent residue. Before examining the residue with the binocular microscope, the minus 100-mesh material was removed by sieving.

GLOSSARY OF SELECTED TECHNICAL TERMS

Most of the technical terms used herein are those listed by Cloud and Barnes (1948, pp. 15–19); a few are from Hendricks (1952). Definitions not listed by Cloud and Barnes follow.

Chert

Botryoidal (beekite)—translucent, probably originally mostly formed through fossil replacement; when unbroken it is commonly in very small, knobby, button-shaped bodies.

Brecciated—fragmental chert, in part possibly intraclastic (conglomeratic), cemented by other chert.

Embedded sand grains—see chert matrix sand (Cloud and Barnes).

Granular—composed of grains of closely packed crystals. All chert falls in the smaller grain size when measured in terms of the usual grain-size scales such as those of DeFord (1946), Udden (1898), Wentworth (1922), and Lane et al. (1947). The following grain-size scale was used to determine whether grain size might be of value for correlation:

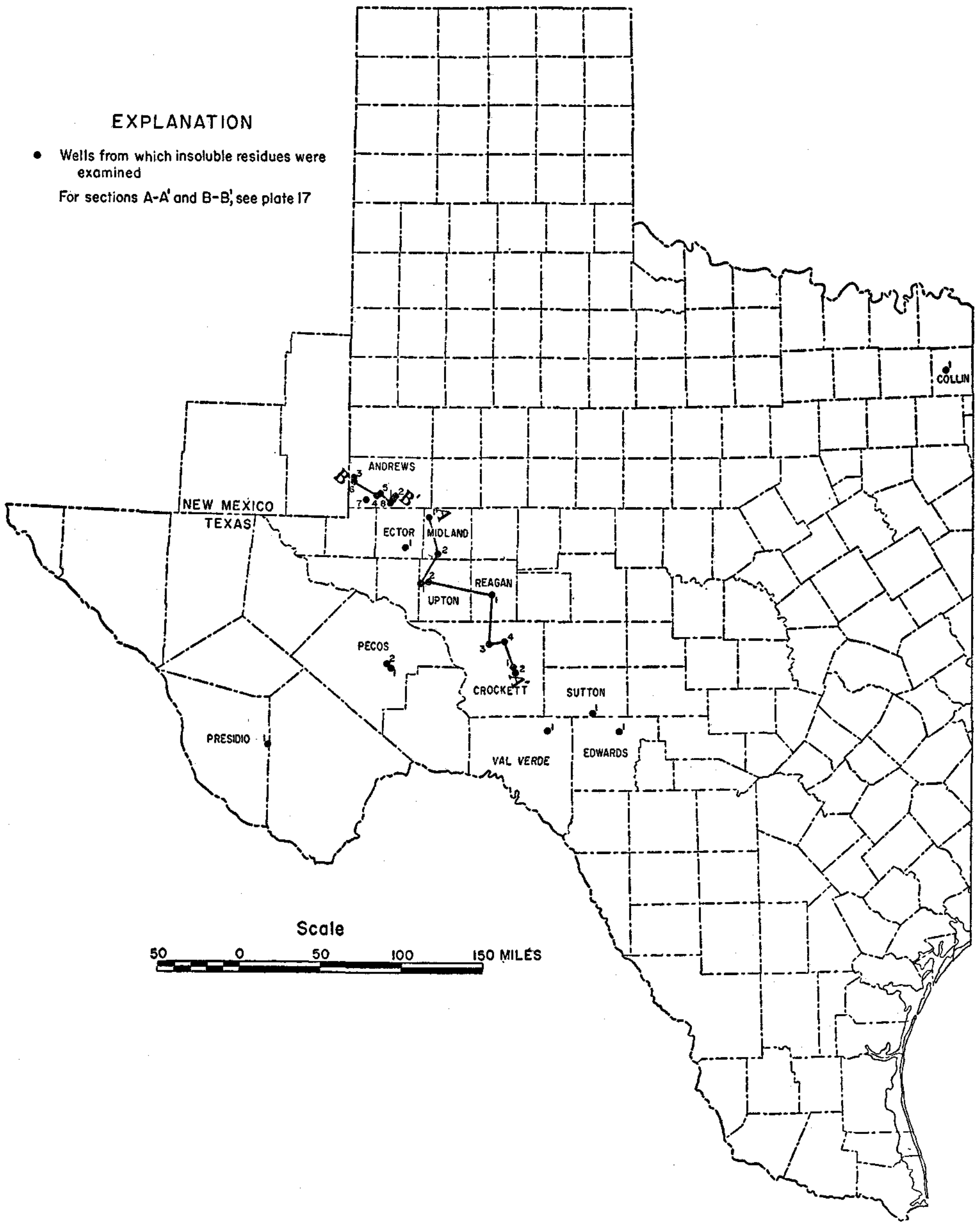

FIG. 34. Map showing wells from which insoluble residues were examined.

Chert (continued)

Granular (continued)

Smooth (aphanitic)—Less than 0.025 mm
Microgranular—0.025 to 0.05 mm
Very fine grained—0.05 to 0.1 mm
Fine grained—0.1 to 0.2 mm
Medium grained—0.2 to 0.4 mm
Coarse grained—Greater than 0.4 mm

On the graphic sections (Pl. 17) the number of grain sizes has been reduced from six to four—less than 0.025 mm, 0.025 to 0.1 mm, 0.1 to 0.4 mm, and more than 0.4 mm.

Granulated—tiny grains or granules tightly to loosely held together in small irregular masses or fragments (Hendricks, 1952). (Granules in this sense does not mean granule in the sense of the next grain size above sand, because the upper limit given for granulated material is about 0.5 mm.)

Pseudo-oolitic—having the appearance of an oolite, but the spheres are without concentric banding.

Opaque—equals porcelaneous, subporcelaneous, and semiporcelaneous of Cloud and Barnes.

Translucent—equals chalcedonic, subchalcedonic, and semichalcedonic of Cloud and Barnes.

Chalky—resembles chalk or tripoli (Hendricks, 1952).

Color—for describing color, comparison was made with the Rock Color Chart (1948).

Shale—waxy to granular, hard to soft, thin partings and interstitial fillings (Hendricks, 1952).

Silt and clay—because of the method of preparation of the residue it was impracticable to distinguish between silt and clay. For this study silt and clay are lumped, and the amount of each is not estimated separately.

Fig. 34, explanation (continued)—

TEXAS

ANDREWS COUNTY
1. Gulf Oil Corp. #1-E State "AM"
2. Gulf Oil Corp. #1 Texas "000"
3. Humble Oil & Rfg. Co. #2 Evelyn Lineberry
4. Humble Oil & Rfg. Co. #37 Parker
5. Shell Oil Co. #12 Lockhart
6. Shell Oil Co. #1 Pinson
7. Shell Oil Co. #7 Ratliff & Bedford
8. The Superior Oil Co. #1-36-A University

COLLIN COUNTY
1. Humble Oil & Rfg. Co. #1 Miller

CROCKETT COUNTY
1. Humble Oil & Rfg. Co. #1-C Alma Cox
2. Humble Oil & Rfg. Co. #1-D Alma Cox
3. Magnolia Petroleum Co. #1 Shannon Hospital
4. The Superior Oil Co. #1-27 University

ECTOR COUNTY
1. Cities Service Oil Co. #1-E Foster

EDWARDS COUNTY
1. The Texas Co. #1 Phillips

MIDLAND COUNTY
1. Magnolia Petroleum Co. #1 Nobles
2. Magnolia Petroleum Co. #2-A Windham

PECOS COUNTY
1. Phillips Petroleum Co. #1 Glenna
2. Phillips Petroleum Co. #1-C Puckett

PRESIDIO COUNTY
1. Gulf Oil Corp. #1 Mitchell Bros.—State

REAGAN COUNTY
1. Humble Oil & Rfg. Co. #1-M University

SUTTON COUNTY
1. Humble Oil & Rfg. Co. #1 J. D. Harrison

UPTON COUNTY
1. Gulf Oil Corp. #1 McElroy-State
2. Sinclair Oil & Gas Co. #9 McElroy

VAL VERDE COUNTY
1. Phillips Petroleum Co. #1 Wilson

ANALYSIS OF DATA

Even though data are sparse, those recorded are analyzed and some generalizations made. The logs are too complicated to be comprehended at a glance, and as data continue to be collected, it will be found that many things recorded are either too ubiquitous or too rare to be of value for correlation. It is also possible that the present manner of presentation has concealed diagnostic features.

The top of a chalky chert zone (Pl. 17) was used by Dixon for correlation. In the following discussion each item recorded was examined separately and its distribution in reference to the top of the chalky chert zone noted. Smooth, translucent chert is fairly scarce above the top of the chalky chert zone and fairly common and uniformly distributed below the top of the chalky chert zone, with Gulf Oil Corporation No. 1 McElroy-State, Upton County, being an important exception. Granular, translucent chert is more abundant below the top of the chalky chert than it is above. Opaque chert, both smooth and granular, is sporadically distributed and less abundant above the top of the chalky chert zone. Granulated chert is too rare and irregularly distributed to be of any value for correlation.

Dolomoldic chert is less common above the top of the chalky chert zone, but in some wells it is fairly uniformly distributed throughout. Dolocasts are rare and mostly below the top of the chalky chert zone. Ooids and pseudo-ooids are slightly more abundant below the top of the chalky chert zone. Oomolds are very rare and banded chert is rare. Embedded sand grains are mostly below the top of the chalky chert zone. Botryoidal chert is rare and mostly in and adjacent to the chalky chert zone. Conglomeratic or brecciated chert is rare and appears to occupy about the same position. Quartz druse is more abundant below the top of the chalky chert zone and is rare in the highest beds.

Sand is somewhat sporadic in occurrence, and in some wells its abundance reflects the nearness laterally of basement rocks. The occurrence of aggregated sand is even more sporadic. Most of the sand displays various degrees of frosting and rounding, and therefore these properties are of no value for correlation. Angularity where present seems to be indicative of the nearness of basement rocks laterally. The size and sorting of the sand are about the same throughout.

Non-aggregated silt and clay are in general more abundant above the top of the chalky chert zone. The total aggregated shale and clay particles vary in amount from well to well, and their occurrence in each well is usually sporadic. The portion of the aggregated shale and clay particles which is black to medium light gray appears to be proportionally somewhat more abundant upward. The light gray to white aggregated shale and clay particles are sparse and sporadically distributed. Green shale may be more abundant upward but some wells, such as Phillips Petroleum Company No. 1-C Puckett and No. 1 Glenna, Pecos County, and No. 1 Wilson, Val Verde County, are almost devoid of green shale. This reflects a change in depositional environment southward. Red shale is too rare to be of any use in correlation. Dolomolds in shale vary widely in amount from well to well, and in any one well have mostly sporadic distribution.

Comparison of color intensity of chert is usually of little value for purposes of correlation. The chert in general becomes darker southward, indicating an approach toward an environment of less pure carbonate deposition or possibly a less well-oxygenated environment. The chert in Phillips Petroleum Company No. 1-C Puckett and No. 1 Glenna, Pecos County, and No. 1 Wilson, Val Verde County, is darker than average but similar in color, with a general color correlation between the two areas, indicating that these two wells are in about the same depositional environment. The distribution of cherts of various shades of olive-gray appears to be sporadic.

Of the accessory minerals pyrite is present throughout and is nondiagnostic. Quartz is sporadically distributed throughout except that none is present in Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, and in the upper few hundred feet of Humble Oil & Refining Company No. 1 Miller, Collin County. Anhydrite is less common than quartz and is sporadically distributed in wells from Crockett County westward.

The presence of feldspar usually indicates the nearness of basement rocks laterally; however, some feldspar is reported in The Texas Company No. 1 Phillips, Edwards County, that cannot be explained in this manner. Mica is sporadically distributed in Phillips Petroleum Company No. 1 Wilson, Val Verde County. This is an anomalous occurrence possibly introduced by contamination during crushing; only one other sample—8,360 to 8,370 feet in Humble Oil & Refining Company No. 1-C Alma Cox, Crockett County—was found to contain mica. Sphalerite was found in only one sample, from 6,840 to 6,850 feet in Humble Oil & Refining Company No. 1 J. D. Harrison, Sutton County.

The curve showing the amount of insoluble residue varies erratically, and no correlative value for the curve could be detected. However, such curves might be quite valuable for local correlation. Insoluble residue data from which these curves were constructed, as well as data from other wells, are tabulated in Appendix K.

Some variation in distribution of the insoluble constituents does exist. However, any correlation based on these variations is not exact, and several hundred feet difference in correlation would probably be found if these logs were correlated independently by several geologists. That this is true is indicated by the comparison shown in Plate 17 with correlations made by Barnes using all available data.

Insoluble residues were examined from the following additional ten wells but no obvious correlation was found.

- Cities Service Oil Company No. 1-E Foster, Ector County
- Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County
- Humble Oil & Refining Company No. 1 J. D. Harrison, Sutton County
- Humble Oil & Refining Company No. 1 Miller, Collin County
- Phillips Petroleum Company No. 1 Glenna, Pecos County
- Phillips Petroleum Company No. 1-C Puckett, Pecos County
- Phillips Petroleum Company No. 1 Wilson, Val Verde County
- Shell Oil Company No. 7 Ratliff & Bedford, Andrews County
- Sinclair Oil & Gas Company No. 9 McElroy, Upton County
- The Texas Company No. 1 Phillips, Edward County

PREVIOUS WORK

Basic work on insoluble residues which strongly influenced all subsequent work was published in 1931 by McQueen. He found that the various geological units in the lower part of the Paleozoic system of Missouri have characteristic residues. A strong tendency has been shown by some subsequent workers to try to recognize these units far beyond the borders of Missouri. Cole (1942), for example, on the basis of insoluble residues correlated west Texas subsurface Ellenburger with Missouri Cambrian and Ordovician units.

Vanderpool (1950) in a brief note correlated the El Paso formation using insoluble residues. In his figure 14 he placed the base of the Ordovician at the base of the Honeycut equivalent, although many genera of Ordovician fossils have been identified below this level in many places in the Franklin Mountains. Some elements of the insoluble residues of the Gorman equivalent in the Franklin Mountains are similar to some elements of the insoluble residues of the Wilberns formation in the Llano region, but the abundant paleontologic evidence shows that the Gorman of the Franklin Mountains is not the same age or in the same stratigraphic position as the Wilberns of the Llano area.

Hendricks (1952) gave detailed information about the insoluble residues in the surface sections in central Texas measured by Cloud and Barnes (1948) and correlated the rocks of the subsurface with those at the surface. The only consistent feature that can be seen in the surface sections, Hendricks' Plate 2, is the sandiness of the Gorman with a sharp break to the nonsandy Tanyard beneath and a gradational change to the much less sandy Honeycut above.

The change from predominantly smooth chert to predominantly granular chert takes place anywhere from the top of the Tanyard to 350 feet down in the Tanyard. If the contact between the granular and nongranular chert zones fluctuates 350 feet in the outcrop area, then it is likely that it fluctuates as much or more in the subsurface. The top of Hendricks' silty, argillaceous zone is even more erratic, ranging from 130 to 900 feet below the top of the Tanyard. No indication can be seen of a change in the character of the insoluble residues at the Cambrian-Ordovician boundary. Hendricks does not suggest a correlation with Missouri strata; in fact, little can be seen that is common to the two areas at any corresponding stratigraphic level.

Cole (1942) on the basis of insoluble residues, as mentioned above, correlated the west Texas Ellenburger with strata in Missouri (fig. 35), and, as can be seen by comparison with Hendricks' interpretation, which is confirmed in a general way elsewhere in this publication, Cole's correlation is incorrect.

Ireland (1936) pointed out that the various formations southwestward in Oklahoma are not as easy to recognize as in Missouri and that they continue to change toward the Arbuckle and Wichita Mountains. The work of Hendricks (1940, 1952), Crowley and Hendricks (1945), and in this paper shows that the zonation found in Missouri does not apply in Texas. Many of the residues in Missouri and Texas are similar, but it is unlikely that they will be in the same order of occurrence or will coincide in time. The presence of similar residues in the two areas is not proof that the rocks are exactly or even approximately of the same age.

CONCLUSIONS

Among oil companies, at least one appears to be having success with the use of insoluble residues in conjunction with other evidence. The units recognized are closely parallel to those recognized in central Texas by Cloud and Barnes (1948). Some organizations, however, favor an attempt to try to recognize a large number of so-called "correlation points" and use them

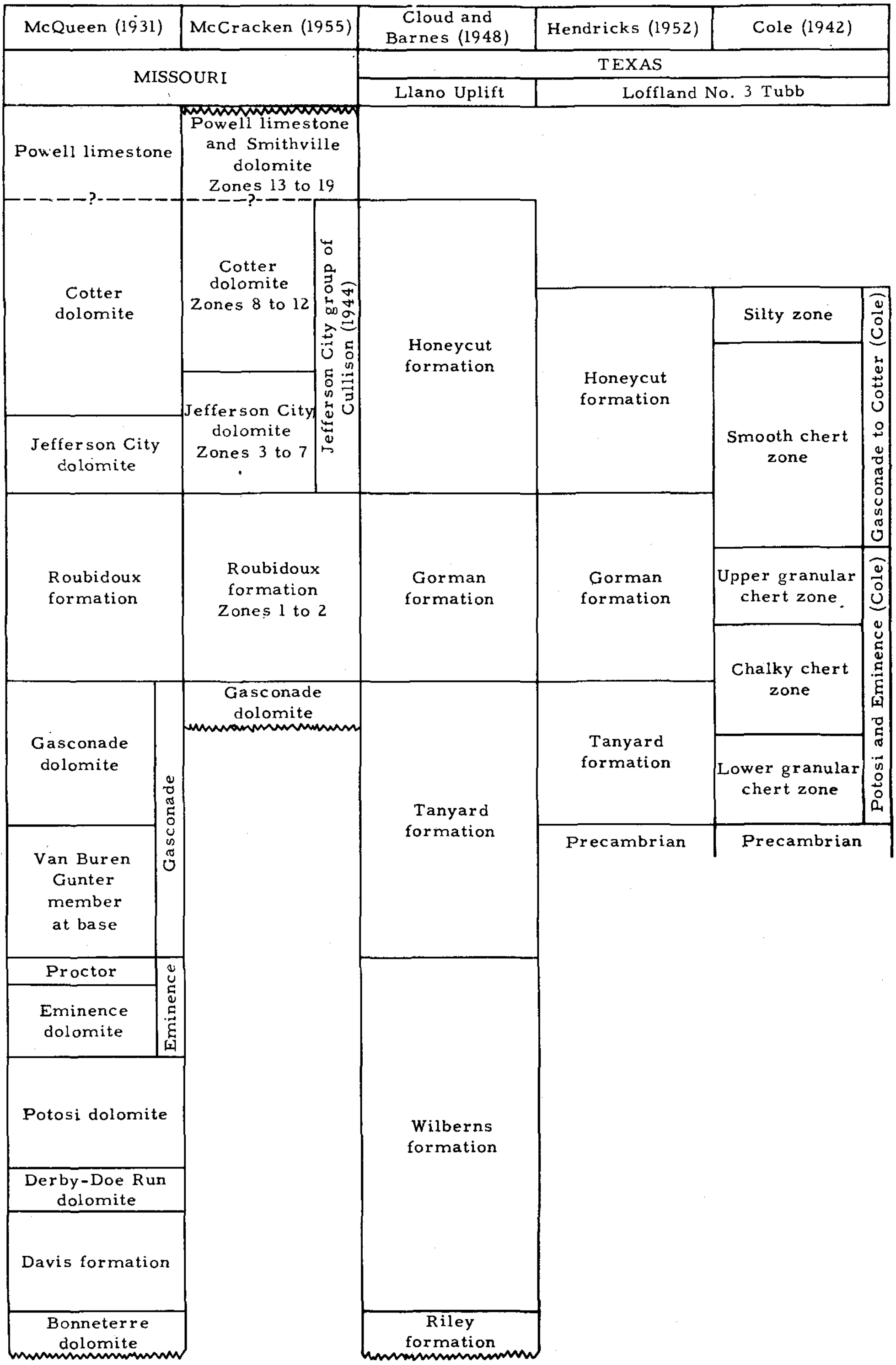

FIG. 35. Diagram showing the approximate correlation, by various workers, of pre-Simpson units in Missouri and Texas.

over long distances. This is not a realistic approach to the use of insoluble residues. Locally a large number of characteristic residues may be usable; laterally many of these will disappear and others will appear. Until insoluble residues have been examined from a great number of wells throughout the entire Ellenburger area of occurrence, it will not be possible to designate those which are purely local, any that extend throughout the area of deposition, and those that occupy certain positions within the area of deposition.

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Plates 18–65

PLATE 18

Photographs of cores from the Honeycut and Gorman formations, Ellenburger group, Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas

(Natural size)

A. Dolomite from about 210 feet above the base of the Honeycut formation (depth 9,051 feet).
The dolomite is intermixed fine and very fine grained as if it were deformed while soft. Vugs lined by white, coarse-grained dolomite are filled by olive-gray to olive-black clay. An indistinct stylolite is in upper part, and a faint nearly vertical fracture is in lower part.

B. Dolomite from about 185 feet above the base of the Honeycut formation (depth 9,074 feet).
The dolomite, on the border of fine and medium grained, is distinctly bedded, indistinctly oolitic, and shows some original depositional irregularities. A stylolite is along the bedding in upper part.

C. Dolomite from about 115 feet above the base of the Honeycut formation (depth 9,147 feet).
The dolomite is coarse grained, slightly sandy, indistinctly bedded, vuggy, and fractured. The open fracture and vugs are in part filled by very dark gray clay. A stylolite is in lower part.

D. Dolomite from about 105 feet above the base of the Honeycut formation (depth 9,155 feet).
The dolomite is coarse grained, contains numerous vugs, a few open fractures, both of which are in part filled by very dark gray clay; some steeply inclined "lattice-work" structure and indistinct stylolites of large amplitude.

E. Dolomite from about 80 feet above the base of the Honeycut formation (depth 9,180 feet).
The dolomite is in part medium to coarse grained and in part near the middle fine grained; both types interfinger along stylolites. A vug is in part filled by very dark gray clay. Open fractures are very tight.

F. Dolomite and chert from about 55 feet below the top of the Gorman formation (depth 9,316 feet).
Two types of dolomite, both very fine grained, are separated by a stylolite against which white dolomite veins terminate. The dolomite in the lower part is banded by finely disseminated pyrite, and that in the upper part was originally a granular slightly sandy sediment, probably with grains and granules (intraclasts) of aphanitic limestone in an aphanitic groundmass. The ghosts of the grains and granules are rather faintly preserved.
The chert, upper right, is oolitic, slightly translucent, preserves an oolitic texture, and objects in the dolomite tend to conform to the chert boundary. The chert was probably a rather loosely cemented limestone intraclast at the time it was incorporated, as indicated by an isolated chert ooid near the border of the chert and a rather minutely ragged boundary.
From the photograph it is impossible to determine if chertification preceded, followed, or was concomitant with dolomitization; the banding in the lower dolomite may have developed during dolomitization, followed by veining, and finally the formation of a stylolite.

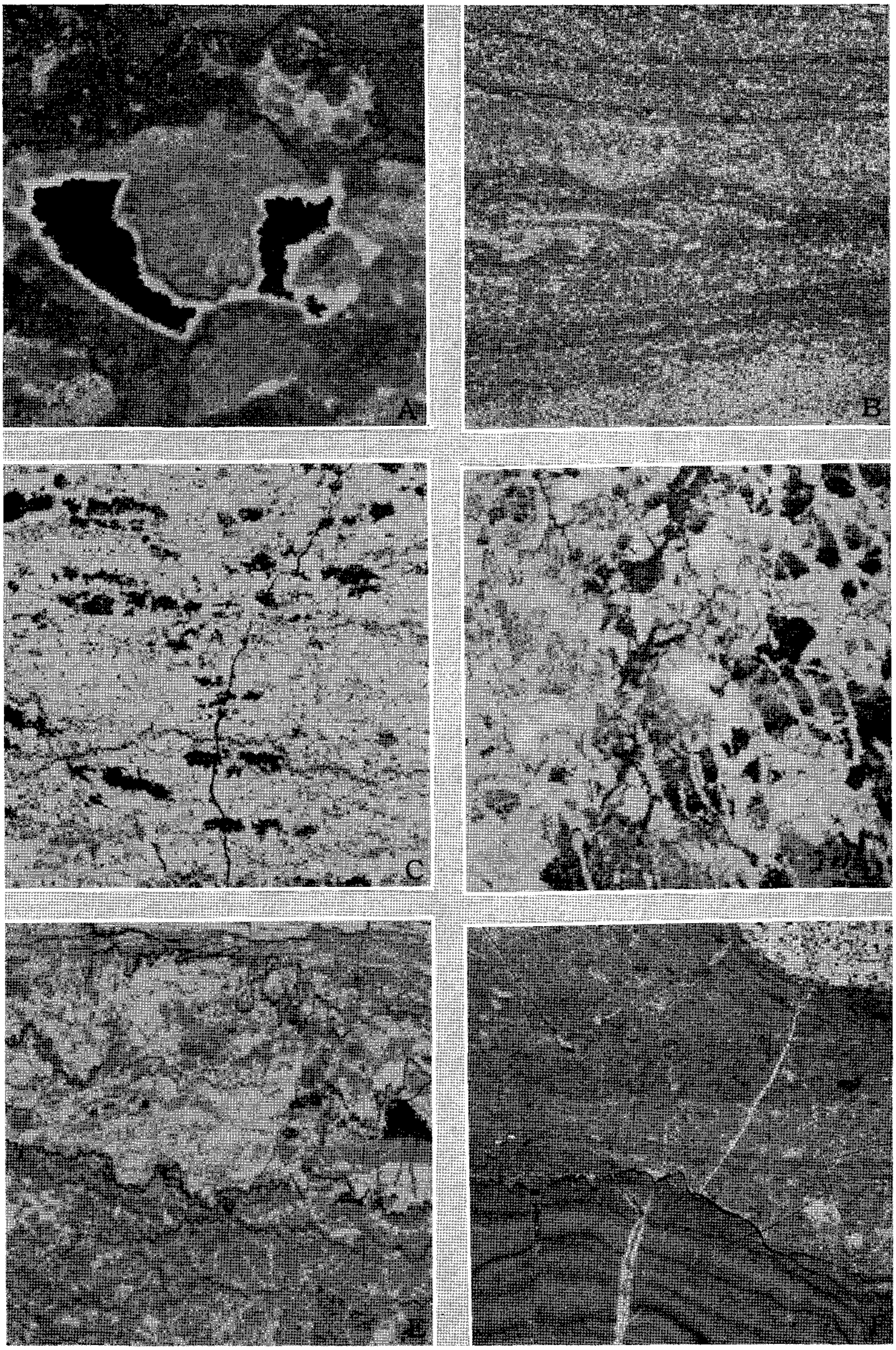
A
B
C

PLATE 19

Photographs of cores from the Honeycut formation, Ellenburger group, Gulf Oil Corporation No. 1 Texas "000," Andrews County, Texas

(Natural size)

A. Dolomite from about 120 feet above the base of the Honeycut formation (depth 12,580 feet).

The dolomite is fine grained in upper part and medium grained in lower part, the two types separated by a stylolite along which is much very dark gray shale. Before the stylolite formed, this shale was perhaps essentially horizontal and similar to but thinner than the shale bed shown near the bottom of the photograph. The void near the top is in coarse-grained dolomite which partly fills a space between breccia fragments. Similar dolomite in a vein is terminated by a stylolite.

B. Dolomite from about 117 feet above the base of the Honeycut formation (depth 12,583 feet).

The very fine-grained dolomite in the upper part is separated from the microgranular dolomite in the lower part by a stylolite having large amplitude. Some white, coarse-grained dolomite fills vugs and veins, the latter terminated by stylolites. Open fractures formed later than the stylolites.

C. Dolomite breccia from about 115 feet above the base of the Honeycut formation (depth 12,585 feet).

The dolomite breccia fragments are mostly fine to very fine grained, a few are bedded, some are mottled by finely disseminated pyrite, and all are in a coarser grained, argillaceous dolomite matrix. Many of the breccia fragments are in part bounded by stylolites along which they interfinger.

D. Dolomite from about 92 feet above the base of the Honeycut formation (depth 12,608 feet).

The coarse-grained dolomite, faintly bedded horizontally, has a peculiar cellular(?) structure suggesting either an organic origin or possibly poorly preserved ooids. An open fracture is to the left.

E. Dolomite breccia from about 29 feet above the base of the Honeycut formation (depth 12,671 feet).

The fragments are microgranular, in part color banded, and the matrix is white, coarse grained, and with many voids. A large void, lower left, was in part filled by microgranular dolomite with graded bedding and the remaining space by clay. The graded bedding indicates that this is the proper orientation for the core and that there has been no tilting since the void was filled.

Similar filled voids and vugs have been described in other wells which are tilted in the same direction as the bedding, indicating that they were filled before the beds were deformed.

F. Dolomite from about 8 feet above the base of the Honeycut formation (depth 12,692 feet).

The fine-grained, nearly horizontally bedded dolomite is in part bleached. The boundary between the bleached and non-bleached rock is inclined about 15°. An open fracture is to the left.

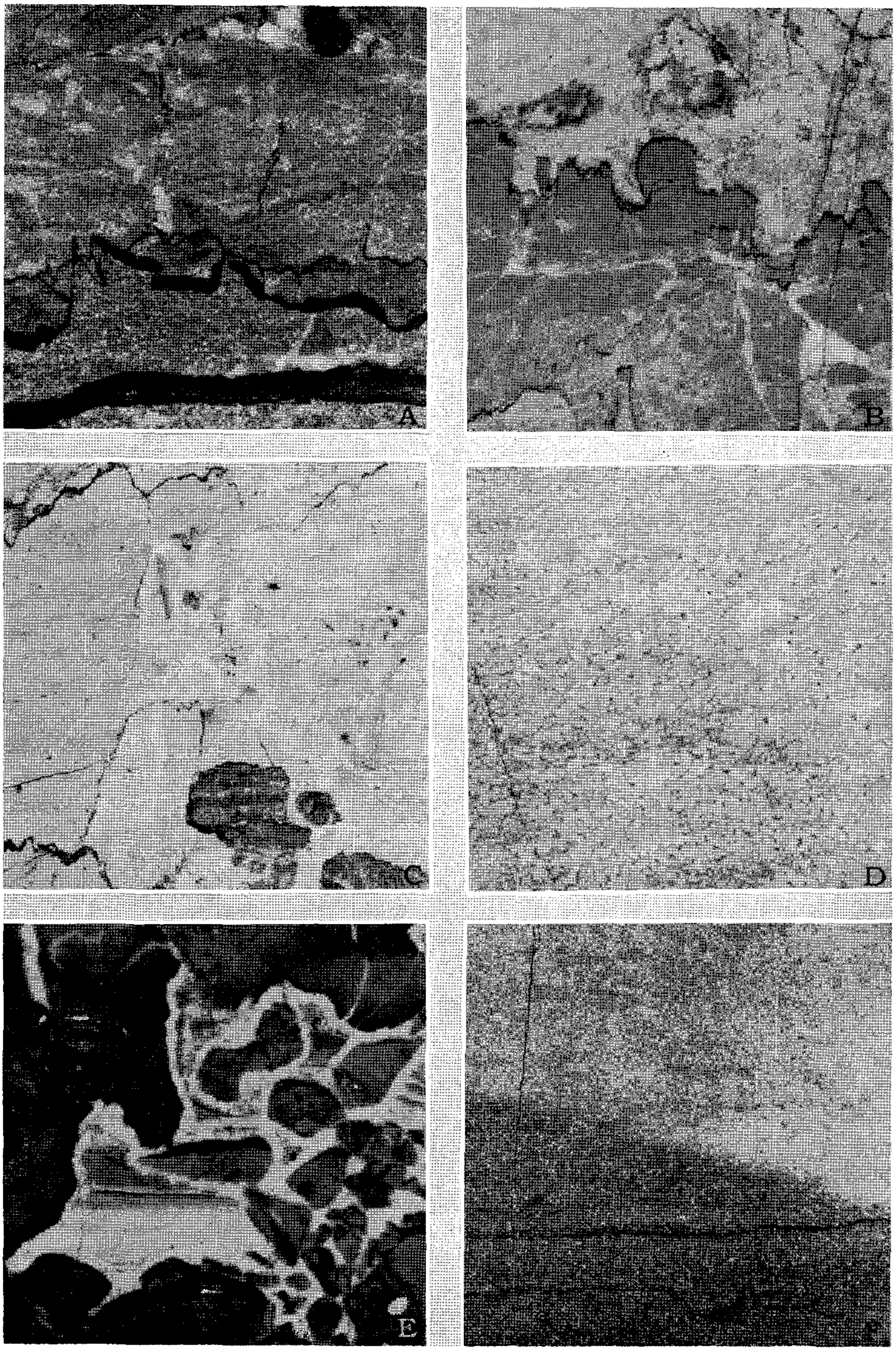
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PLATE 20

Photographs of cores from the B2a′ unit and the Honeycut formation, Ellenburger group, Gulf Oil Corporation No. 1 McElroy-State, Upton County, Texas

(Natural size)

A. Conglomerate from about 276 feet above the base of the B2a′ unit (depth 11,664 feet).

The green and gray shale pebbles, some of which are bent, others ragged, are in a dolomitic sandstone matrix. Such material definitely appears to have been deformed before it was completely consolidated.

B. Dolomitic sandstone and dolomite from about 154 feet above the base of the B2a′ unit (depth 11,686 feet).

The sandy dolomite at the top of the photograph is separated by a stylolite from the argillaceous, dolomitic, smeared-out sandstone beneath, composed of medium gray and very light greenish-gray components. A sandstone pebble or rounded breccia fragment is near bottom of photograph.

Figures A and B are of rock from a 105-foot conglomeratic zone, containing Ellenburger pebbles, which was very much deformed before lithification was complete. This zone is overlain by 37 feet of perfectly normal Ellenburger. Possibly post-Ellenburger conglomerate, shales, and sandstones were involved in a submarine slide, followed by the sliding of a sheet of Ellenburger across the whole.

C. Dolomite breccia from about 120 feet above the base of the B2a′ unit (depth 11,820 feet).

The microgranular dolomite fragments, mostly very steeply inclined, are in a white, coarse-grained dolomite matrix. Some of the fragments interfinger along a stylolite against which dolomite veins terminate. The veins have multiple fillings with white, fine-grained dolomite at the sides followed by darker dolomite of about the same grain size and white, very coarse-grained dolomite in the center. The open fracture probably formed after the stylolite.

D. Dolomite and chert from about 18 feet below the top of the Honeycut formation (depth 11,958 feet).

The dolomite, bordering on fine and medium grained, is argillaceous, and a dark area of very fine-grained dolomite may fill a vug. The chert, mostly translucent, is speckled and clouded by minute inclusions and rimmed by a quarter-inch band of white, opaque chert. An open fracture is in the chert.

E. Brecciated and deformed dolomite from about 57 feet below the top of the Honeycut formation (depth 11,997 feet).

Disrupted bedding lamellae and ragged fragments of medium-grained dolomite in a darker, fine-grained matrix suggest deformation while the rock was still soft. The white, coarse-grained, vuggy dolomite at lower left may be later.

F. Brecciated dolomite from about 121 feet below the top of the Honeycut formation (depth 12,061 feet).

The microgranular dolomite fragments are in a fine-grained, sandy, dolomite matrix; the remaining space is filled by white, coarse-grained dolomite.

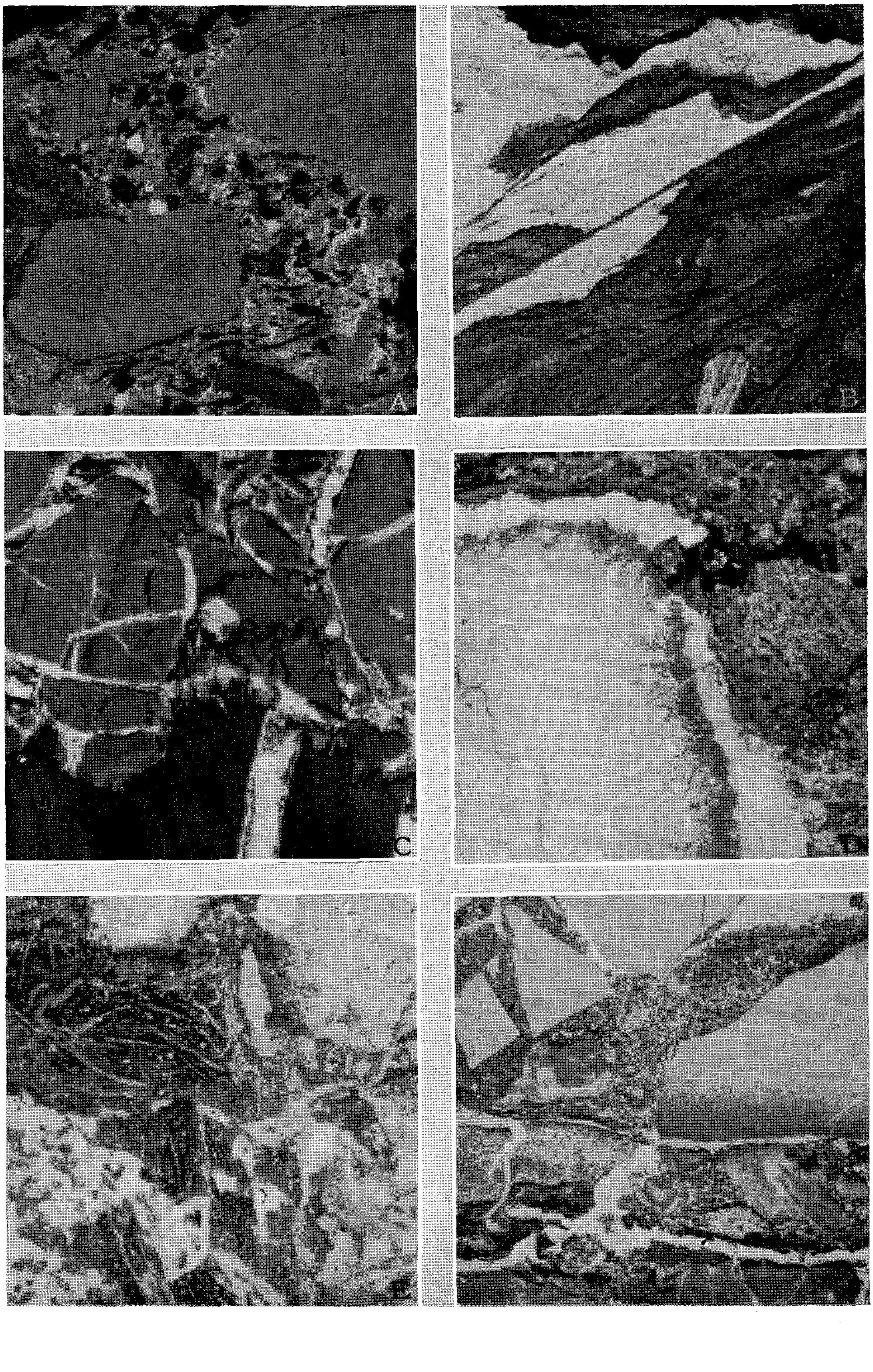
A
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PLATE 21

Photographs of cores from the Honeycut formation, Ellenburger group, Gulf Oil Corporation No. 1 McElroy-State, Upton County, Texas

(Natural size)

A. Dolomite from about 548 feet above the base of the Honeycut formation (depth 12,112 feet).

The very fine-grained dolomite was originally a granular (intraclastic) sediment, in part an intraformational conglomerate. A nearly horizontal, white dolomite vein is in the lower part of the photograph and a steeply inclined, open fracture is near the middle.

B. Dolomite and anhydrite from about 469 feet above the base of the Honeycut formation (depth 12,191 feet).

Very fine-grained dolomite breccia fragments lined on one side by white, coarse-grained dolomite are in a coarse-grained anhydrite matrix. The anhydrite crystals up to one-half inch long, easily distinguished in the core, cannot be seen in the photograph.

C. Brecciated dolomite from about 409 feet above the base of the Honeycut formation (depth 12,251 feet).

Very fine-grained, angular dolomite breccia fragments with faint outlines of gastropods, coarse-grained frayed dolomite fragments, a few olive-black shale fragments, and in lower part a large ragged chert fragment are in a fine to medium-grained, dark-colored, very argillaceous dolomite matrix. Deformation of this type takes place while the rock is in part soft. The chert replaces a granular, oolitic sediment. The veins are of white, coarse-grained dolomite.

D. Mud-cracked dolomite from about 405 feet above the base of the Honeycut formation (depth 12,254 feet).

The microgranular dolomite in upper part of photograph, color banded from very finely disseminated pyrite, rests on fine-grained, very sandy dolomite. Sandy dolomite of slightly different appearance cuts the microgranular dolomite in one place and penetrates it deeply in another. A horizontal surface reveals that the sand is filling mud cracks in the microgranular dolomite.

E. Dolomite from about 398 feet above the base of the Honeycut formation (depth 12,262 feet).

The microgranular dolomite with nearly horizontal beds is color banded by finely disseminated pyrite nearly parallel to the beds. Larger pyrite specks are near the vertical stylolite. The fractures probably formed during coring.

F. Dolomite and chert from about 337 feet above the base of the Honeycut formation (depth 12,323 feet).

The microgranular dolomite retains faint ghosts indicating that it was formerly a granular (intraclastic) sediment containing a few intraformational conglomerate pebbles. The dolomite interfingers with chert along a stylolite. The chert, mostly opaque except for vugs(?) filled by white, banded chert with centers of quartz, appears to have replaced a granular sediment similar to that replaced by the dolomite.

G. Dolomite and chert from about 321 feet above the base of the Honeycut formation (depth 12,339 feet).

The very fine-grained, faintly bedded dolomite interfingers with opaque chert, which appears to have replaced a deformed sediment. Thin dolomite veins in the dolomite terminate at the stylolite.

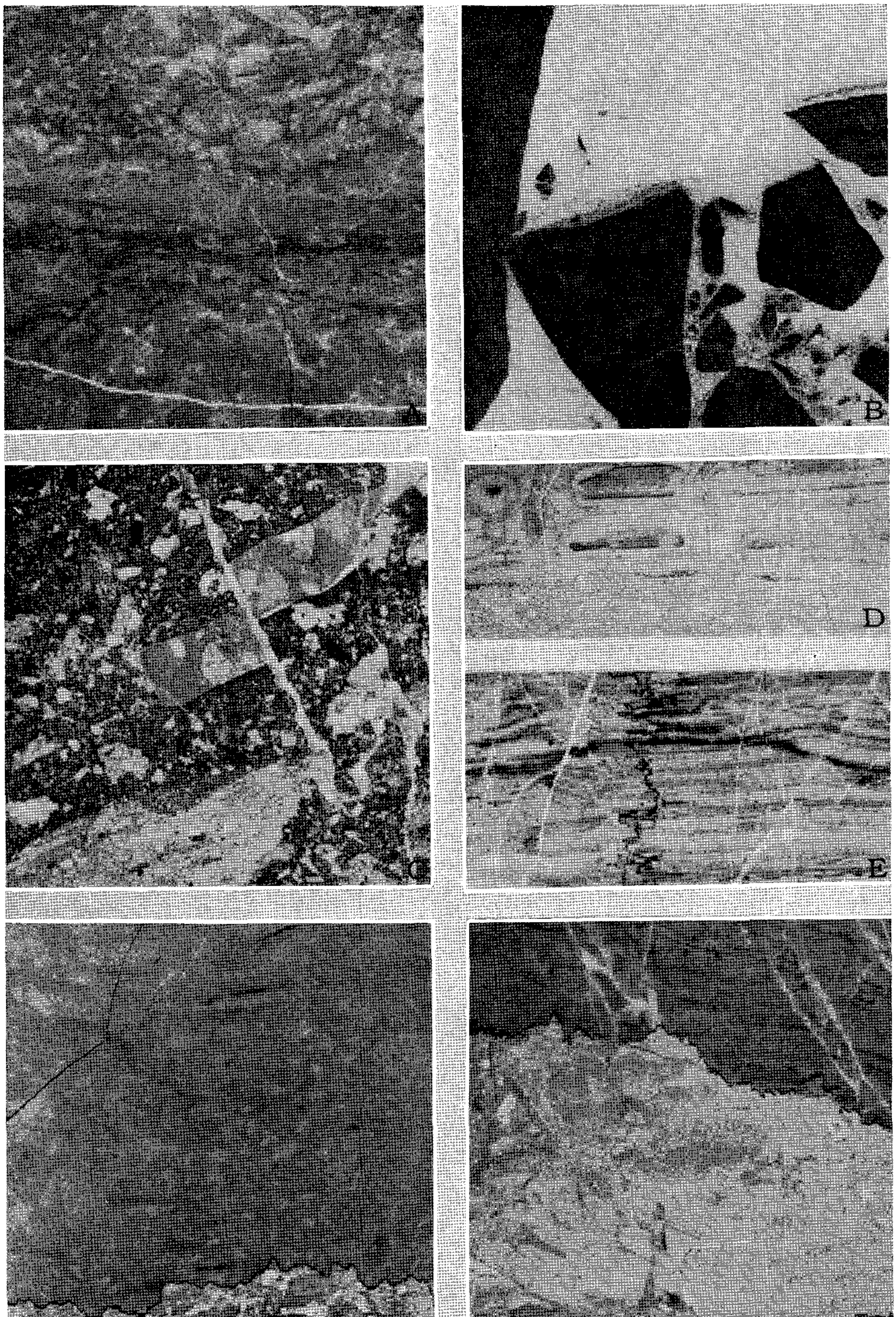
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PLATE 22

Photographs of cores from the Honeycut and Gorman formations, Ellenburger group, various wells, Midland and Upton counties, Texas

(Natural size)

GULF OIL CORPORATION NO. 1 MCELROY-STATE, UPTON COUNTY

A. Dolomite intraformational conglomerate from about 60 feet above the base of the Honeycut formation (depth 12,600 feet).

Fine-grained pebbles mostly stacked on edge, some piled horizontally, are in a coarse-grained, vuggy matrix. A faint stylolite is in lower part and an open fracture is to the left.

B. Dolomite and chert from about 9 feet below the top of the Gorman formation (depth 12,669 feet).

The dolomite, very fine, fine, and medium grained, is rather crudely interbedded and perhaps somewhat deformed while soft. Delicate spires of white, opaque chert interfinger with dolomite along a stylolite in the lower part of the photograph. Some irregular veins are in part filled by white coarse-grained dolomite.

C. Dolomite and chert from about 20 feet below the top of the Gorman formation (depth 12,680 feet).

The dolomite, mostly fine grained, in part verging on medium grained, is fairly distinctly bedded with the beds outlined by finely disseminated pyrite. More pyritiferous areas are mostly in the lower part. The bedding shows some tendency to conform to the opaque chert nodules. One of the nodules, as well as the beds, is offset by a small reverse fault.

D. Chert and dolomite from about 100 feet below the top of the Gorman formation (depth 12,760 feet).

The chert, occupying most of the photograph, probably replaced a sediment deformed while soft. Near the top it interfingers with sandy dolomite along a stylolite with both sand and chert dissolved along the stylolite. The stylolites within the chert may have been present at the time of chertification; some in the lower part may have been reactivated since chertification.

MAGNOLIA PETROLEUM COMPANY NO. 2-A WINDHAM, MIDLAND COUNTY

E. Dolomite breccia from about 62 feet above the base of the Honeycut formation (depth 12,928 feet).

A large, fine-grained, sandy fragment, in upper part with nearly vertical bedding and faint stylolites, is separated by a prominent stylolite from breccia composed of light-colored, opaque chert and fine to very fine-grained dolomite fragments in an argillaceous dolomite matrix.

F. Dolomite from about 54 feet below the top of the Gorman formation (depth 13,044 feet).

Some initial depositional irregularities are in the distinctly bedded, microgranular dolomite, which in the lower part is somewhat bleached in the vicinity of white dolomite veins. The amount of thinning by solution along the stylolite, if the vein is perpendicular to the sawed surface, can be demonstrated graphically to be about one-quarter inch.

WILSHIRE OIL COMPANY NO. 23–118 WINDHAM, UPTON COUNTY

G. Deformed dolomite from about 35 feet above the base of the Honeycut formation (depth 12,695 feet).

A bent, frayed, fine-grained dolomite bed in the lower part is in a matrix of smaller dolomite fragments, a few small dark shale fragments, and a dolomite "paste," indicating deformation while the rock was soft.

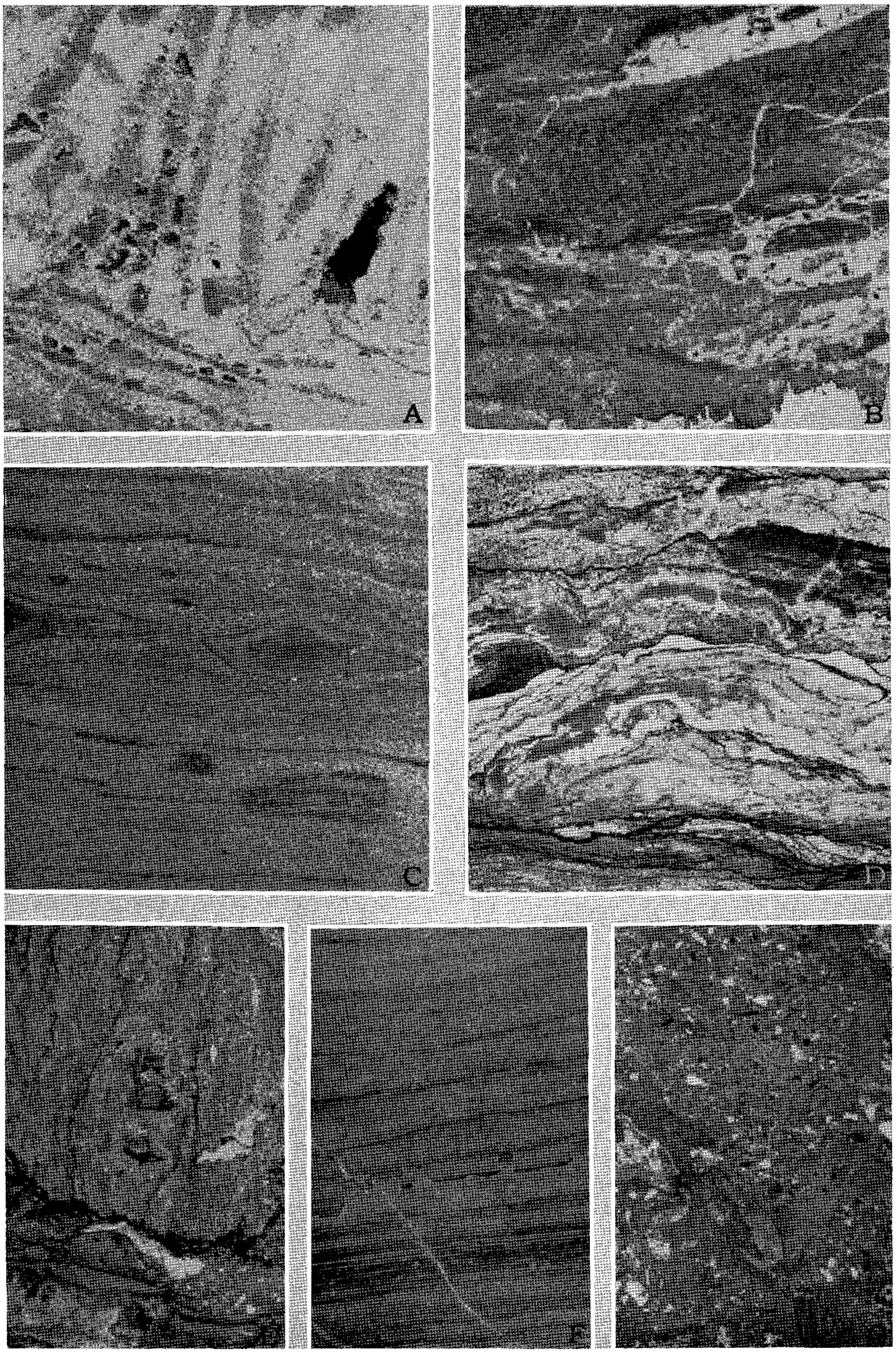
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PLATE 23

Photographs of cores from the Honeycut and Gorman formations, Ellenburger group, various wells, Andrews and Crockett counties, Texas, and Lea County, New Mexico

(Natural size)

SHELL OIL COMPANY NO. 12 LOCKHART, ANDREWS COUNTY

A. Dolomite breccia from about 86 feet above the base of the Honeycut formation (depth 8,694 feet).

A large, light-colored, fine to medium-grained fragment interfingers along a stylolite with very fine to microgranular fragments which in turn interfinger with each other along stylolites. Some fine-grained dolomite matrix is at upper left.

B. Dolomite from about 63 feet below the top of the Gorman formation (depth 8,843 feet).

Microgranular dolomite (top) interfingers with a lenticular area of very fine-grained dolomite, and both interfinger with fine-grained dolomite along stylolites. The fine-grained dolomite was originally a granular (intraclastic) sediment composed of small pebble intraformational conglomerate. Part of a dolomite vein parallel to the bedding is missing along a stylolite, and a white, coarse-grained dolomite vein with a dark center terminates against the stylolite.

SHELL OIL COMPANY NO. 5 STATE, LEA COUNTY

C. Chert and limestone from about 20 feet below the top of the Gorman formation (depth 7,820 feet).

A dark limestone bed in lower part is next to a quarter-inch, light-colored limestone bed in contact with concentrically color-banded chert. The chert is broken and spread, and in some manner a fragment of the light-colored limestone bed moved into the crack, the rest of which is mostly filled by white, coarse-grained dolomite. Chert in the upper half inch is sandy, calcareous, and has replaced a granular sediment.

HUMBLE OIL & REFINING COMPANY NO. 2 EVELYN LINEBERRY, ANDREWS COUNTY

D. Dolomite breccia from about 89 feet below the top of the Gorman formation (depth 10,479 feet).

White, opaque chert, and microgranular, in part argillaceous dolomite fragments in upper part are in a sandstone matrix and in lower part in a shaly dolomite matrix. Material of this type suggests solution and collapse, with infiltration of material foreign to the Ellenburger.

HUMBLE OIL & REFINING COMPANY NO. 1-D ALMA COX, CROCKETT COUNTY

E. Limestone from about 153 feet above the base of the Honeycut formation (depth 7,647 feet).

The limestone was originally a granular (intraclastic) sediment composed of aphanitic granules cemented by clear calcite. Some "dead oil" or argillaceous materials is in lower part.

F. Limestone from about 133 feet above the base of the Honeycut formation (depth 7,667 feet).

The aphanitic limestone was originally mostly a granular (intraclastic), fossiliferous sediment with aphanitic grains and granules in part in clear calcite and in part in an aphanitic matrix. A few irregular aphanitic beds were originally probably lime-mud. The fossils are gastropods.

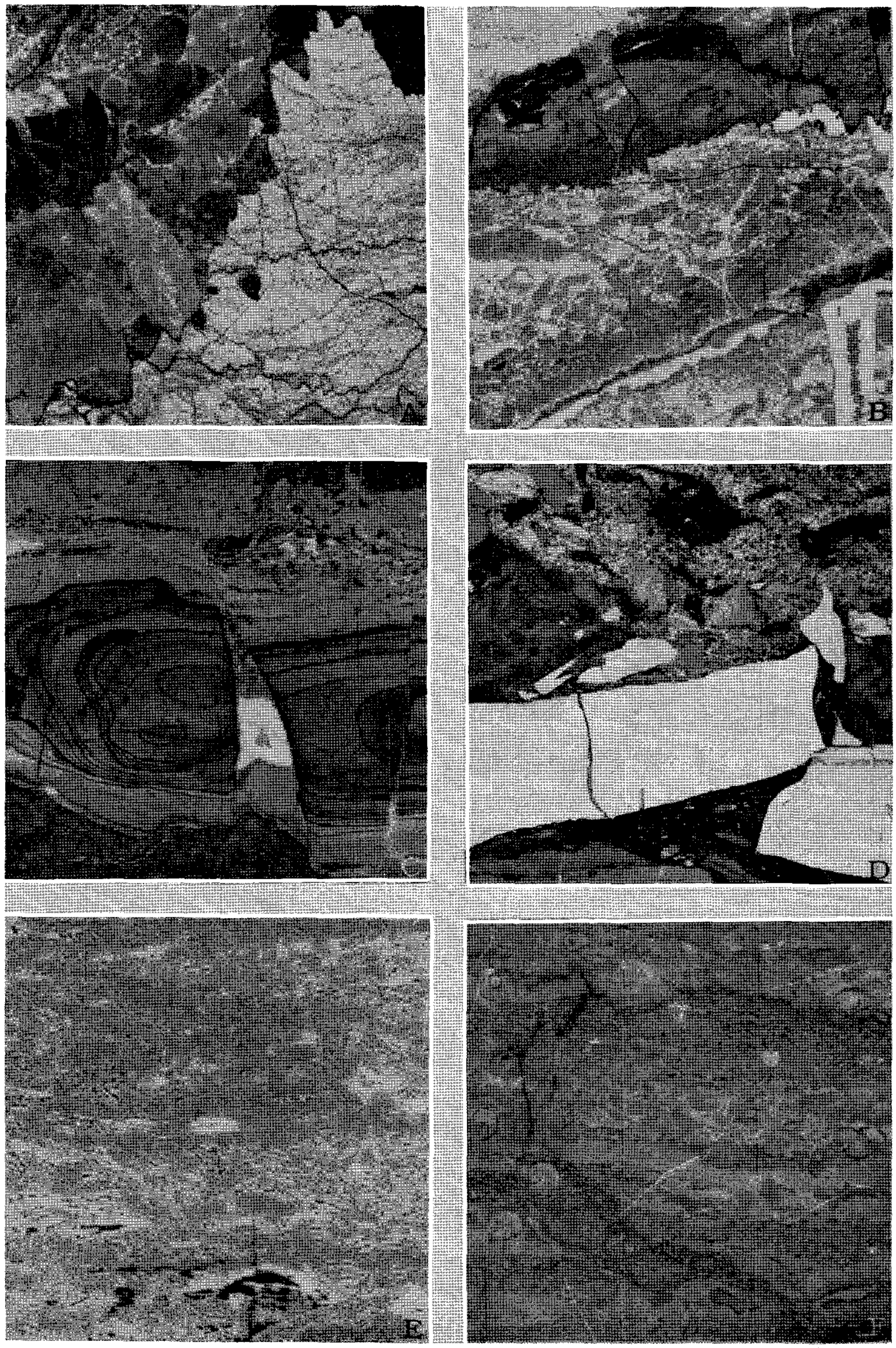
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PLATE 24

Photographs of cores from the C′, B2b′, and B2a′ units and the Honeycut formation, Ellenburger group, Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas

(Natural size)

A. Dolomite from about 27 feet above the base of the C′ unit (depth 15,417 feet).

The microgranular dolomite, with some original depositional irregularities and graded bedding, is distinctly bedded. It is slightly brecciated with matrix and veins of calcite next to which the wall rock is in part bleached. The small dark spots are accumulations of finely disseminated pyrite.

B. Dolomite from about 4 feet above the base of the B2b′ unit (depth 15,621 feet).

The dark gray, microgranular dolomite was veined by very fine-grained, very light greenish-gray dolomite, followed by vertical veins of white, coarse-grained dolomite and anhydrite. The stylolite at the upper edge of the thicker vein is younger than either set of veins.

C. Breccia from about 79 feet above the base of the B2a′ unit (depth 15,681 feet).

The fine-grained, medium gray dolomite fragments enclosed by very fine-grained, very light greenish-gray dolomite producing rounded forms are in a matrix of white to medium light gray anhydrite.

D. Dolomite from about 64 feet above the base of the B2a′ unit (depth 15,696 feet).

The dolomite, mostly very fine-grained, is veined by dolomite, and the veins terminate at a stylolite. Remnants of another vein, or possibly a light-colored bed, are along the stylolite.

E. Microgranular dolomite from about 61 feet below the top of the Honeycut formation (depth 15,821 feet).

Diffusion bands and dendrites of finely disseminated pyrite are bleached along fractures. The vertical fracture has a faint stylolite along it.

F. Microgranular dolomite from about 63 feet below the top of the Honeycut formation (depth 15,823 feet).

Diffusion bands and dendrites of finely disseminated pyrite are numerous.

G. Dolomite from about 65 feet below the top of the Honeycut formation (depth 15,825 feet).

Fracturing in the dolomite controls the pattern of the finely disseminated pyrite, diffusion bands.

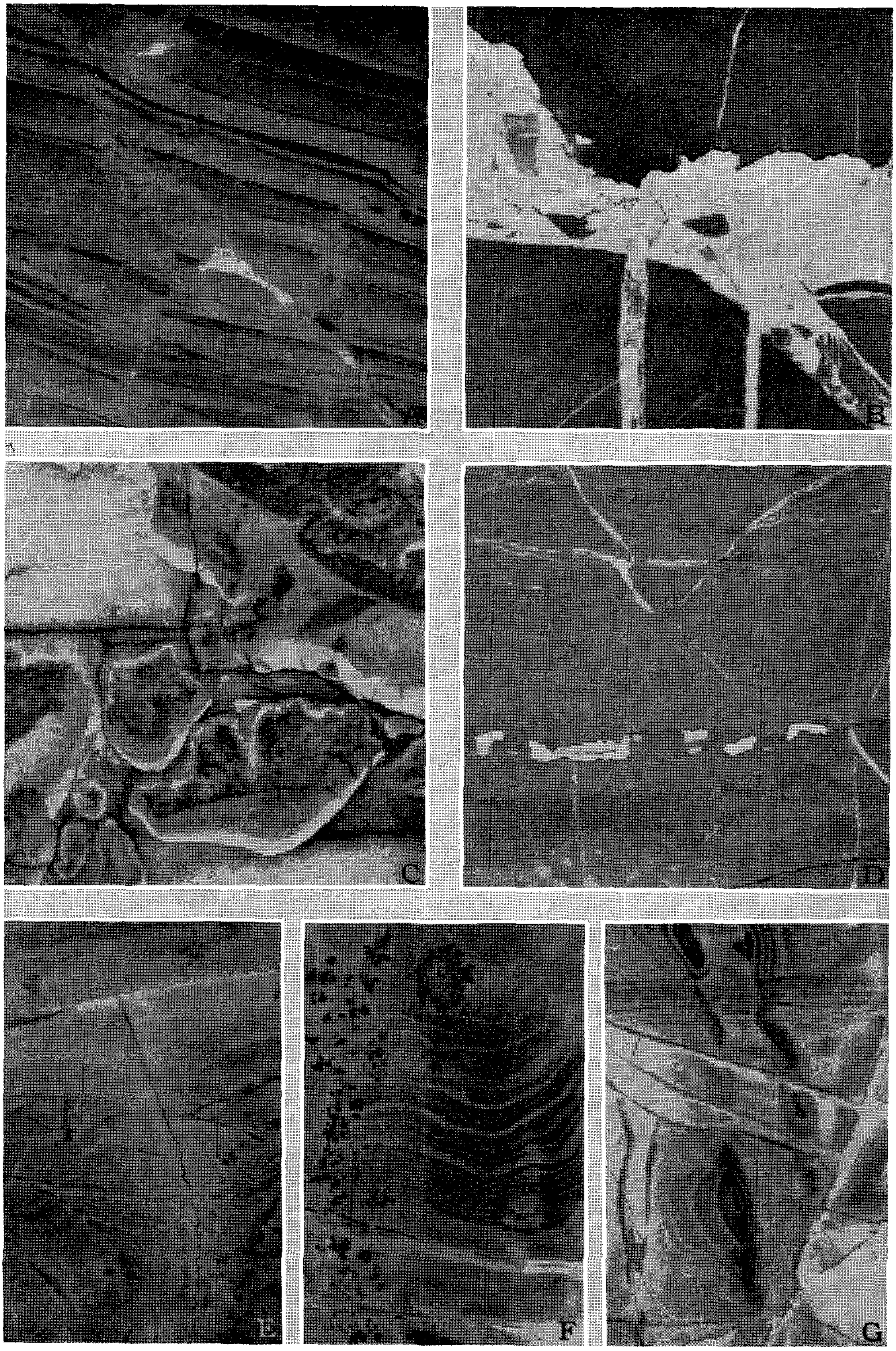
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PLATE 25

Photographs of cores from the B2a′ and B2b′ units and the Honeycut formation, Ellenburger group, Phillips Petroleum Company No. 1 Glenna, Pecos County, Texas

(Natural size)

A. Dolomite from about 133 feet above the base of the B2b′ unit (depth 13,967 feet).

The distinctly and very thinly bedded dolomite with some original depositional irregularities has some graded bedding, which indicates that the core is now correctly oriented. The bedding is slightly offset along white, coarse-grained dolomite veins. One of the later fractures in part follows a vein.

B. Dolomite breccia from about 54 feet above the base of the B2b′ unit (depth 14,056 feet).

The dolomite is similar to that in figure A except that it is brecciated. The rather scant matrix is white, coarse-grained dolomite. A few very dark dolomite veins and some very tight fractures are nearly vertical.

C. Intraformational conglomerate from about 52 feet above the base of the B2a′ unit (depth 14,188 feet).

The dolomite in upper part is fine grained. The rest is medium-grained, intraformational conglomerate pebbles (intraclasts) in a fine to very fine-grained, in part oolitic matrix. The dark dolomite veins are nearly horizontal.

D. Dolomite from about 42 feet above the base of the B2a′ unit (depth 14,188 feet).

The fine verging on very fine-grained dolomite is mottled from burrows. Some indistinct bedding is nearly horizontal.

E. Dolomite from about 9 feet above the base of the B2a′ unit (depth 14,221 feet).

The mostly very fine-grained dolomite is distinctly bedded; the very thinly bedded dark zone in lower part is sandy, the microgranular dolomite in lower part is slightly sandy. The dark areas just below center are concentrations of very finely disseminated pyrite, and the bed beneath was originally a granular sediment composed of granules and smaller grains. In this bed a few tiny chert nodules may have replaced granules. Several types of dolomite fragments in the breccia zone bordered by stylolites are in various attitudes. The zone is between essentially undisturbed beds suggesting that the breccia may have been injected followed by the formation of stylolites.

F. Contorted dolomite from about 126 feet below the top of the Honeycut formation (depth 14,356 feet).

The very fine-grained dolomite is distinctly and very thinly bedded. Some small masses of white, coarse-grained dolomite in lower part may fill vugs.

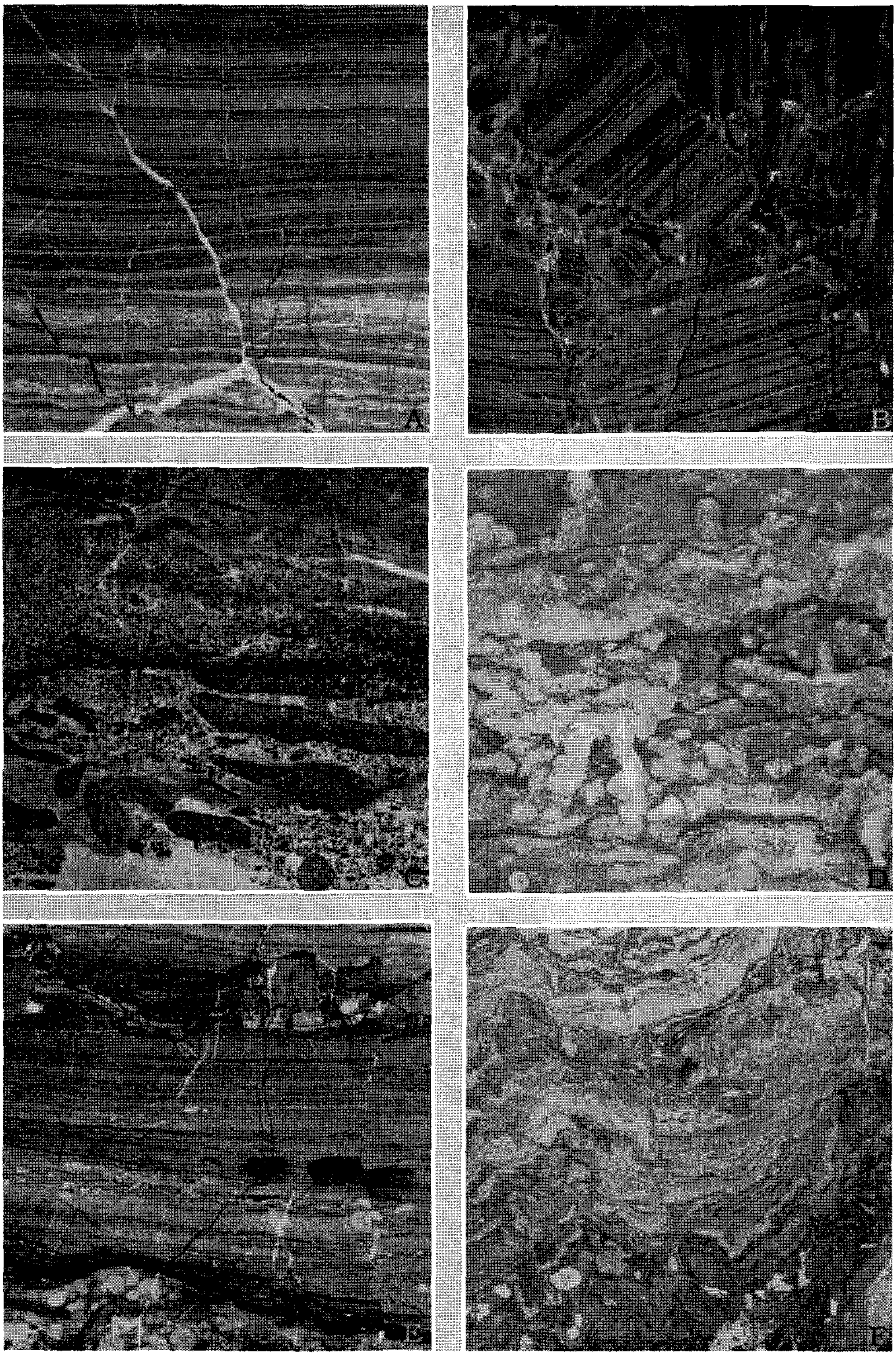
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PLATE 26

Photographs of cores from the C′ and B2b′units, Ellenburger group, various wells, Pecos County, Texas

(Natural size)

PHILLIPS PETROLEUM COMPANY NO. 1-C PUCKETT

A. Intraformational conglomerate from about 61 feet above the base of the C′ unit (depth 13,339 feet).

Very fine-grained dolomite pebbles (intraclasts) with bleached borders are in a slightly coarser matrix. The outlines of the smaller grains are very indistinctly preserved.

B. Dolomite from about 22 feet below the top of the B2b′ unit (depth 13,422 feet).

The very fine-grained dolomite is very thinly and distinctly bedded, slightly color banded, in part bleached, and the beds appear to be in part graded. The numerous veins of olive-gray clay, dolomite, and calcite contain a few voids.

STANDARD OIL COMPANY OF TEXAS NO. 2-1 CLAUDE OWENS

C. Dolomite from about 56 feet above the base of the C′ unit (depth 9,414 feet).

The microgranular dolomite with some graded beds is banded and mottled by finely disseminated pyrite. Irregular veins of dark dolomite are common, and to the left an open fracture is in part filled by white dolomite.

D. Dolomite from about 54 feet above the base of the C′ unit (depth 9,416 feet).

The microgranular dolomite with graded beds is somewhat mottled along the bedding by finely disseminated pyrite. The beds are slightly offset along a stylolite which interfingers horizontally.

E. Dolomite from about 32 feet above the base of the C′ unit (depth 9,438 feet).

The microgranular dolomite with graded beds is banded and mottled by finely disseminated pyrite. A zone of disturbance to the left and others near the bottom were probably formed by burrowing organisms.

F. Dolomite from about 25 feet above the base of the C′ unit (depth 9,445 feet).

The microgranular dolomite with very thin, graded beds is color banded by very finely disseminated pyrite in a rather confusing pattern. The irregularly color-banded area to the right is associated with a barely visible vertical fracture.

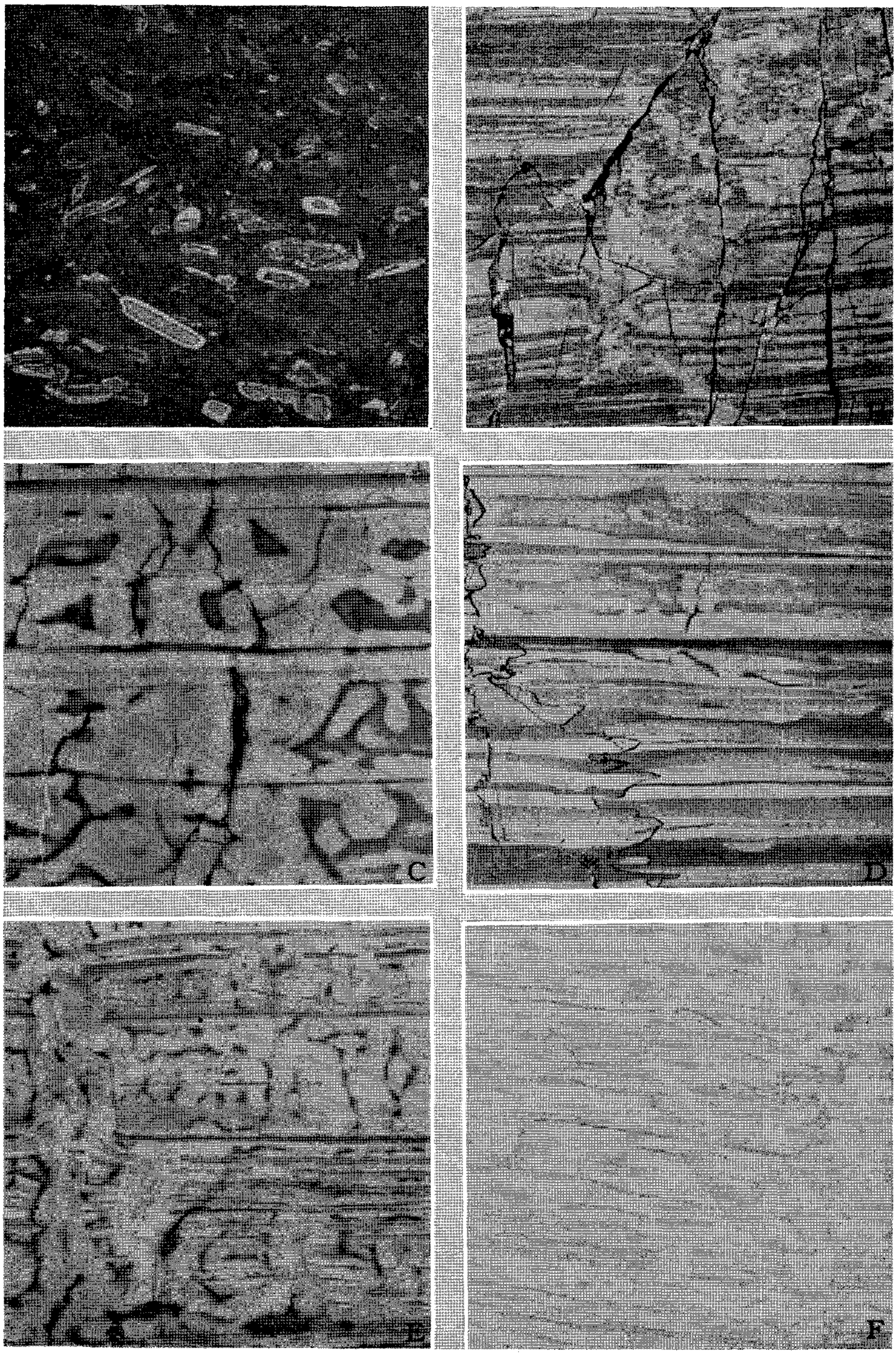
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PLATE 27

Photographs of cores from the Honeycut and Gorman formations, Ellenburger group, The Superior Oil Company No. 1–27 University, Crockett County, Texas

(Natural size)

A. Dolomite from about 46 feet above the base of the Honeycut formation (depth 7,149 feet).

The dolomite, very fine grained verging on microgranular, of two colors, interfingers along a stylolite of large amplitude. Some thin, white chert films are in the upper faintly bedded dolomite, and white dolomite veins terminate at the stylolite.

B. Dolomite from about 42 feet above the base of the Honeycut formation (depth 7,153 feet).

The very fine-grained dolomite in the upper part interfingers with fine-grained dolomite in the lower part along a stylolite of large amplitude. The lower dolomite has a faint texture suggesting that it was originally a granular, bedded sediment. Very dark chert to the right caps one of the downward-pointing stylolite columns. The white irregular beds in upper part are silty dolomite, and the open fractures are very tight.

C. Dolomite from about 34 feet below the top of the Gorman formation (depth 7,229 feet).

The fine-grained dolomite in upper part, originally a granular sediment, interfingers along a stylolite with very fine-grained, structureless dolomite. White dolomite veins with small breccia fragments terminate at the stylolite. Even where veins appear to match across the stylolite, dark gray clay along the stylolite shows a cross-cutting relationship.

D. Dolomite and chert from about 55 feet below the top of the Gorman formation (depth 7,250 feet).

The very fine-grained dolomite in the upper part is separated from the microgranular dolomite in the lower part by bedded chert. The whole is brecciated with little movement between the fragments. The matrix is mostly dolomite and some calcite. A stylolite is mostly in the dolomite and penetrates the chert in at least one place.

E. Brecciated dolomite from about 137 feet below the top of the Gorman formation (depth 7,332 feet).

The very fine-grained breccia fragments are in a medium-grained, argillaceous, dolomite matrix. The white is calcite of continuous optical orientation which appears to have formed before the brecciation. Much rock, demonstrated by the interfingering of breccia fragments, has been removed by solution along the stylolite.

F. Dolomite from about 142 feet below the top of the Gorman formation (depth 7,337 feet).

The fine-grained dolomite grades upward into medium-grained dolomite. Some graded beds are near the middle, and beds are mostly faint and slightly offset along white dolomite veins which terminate at a stylolite.

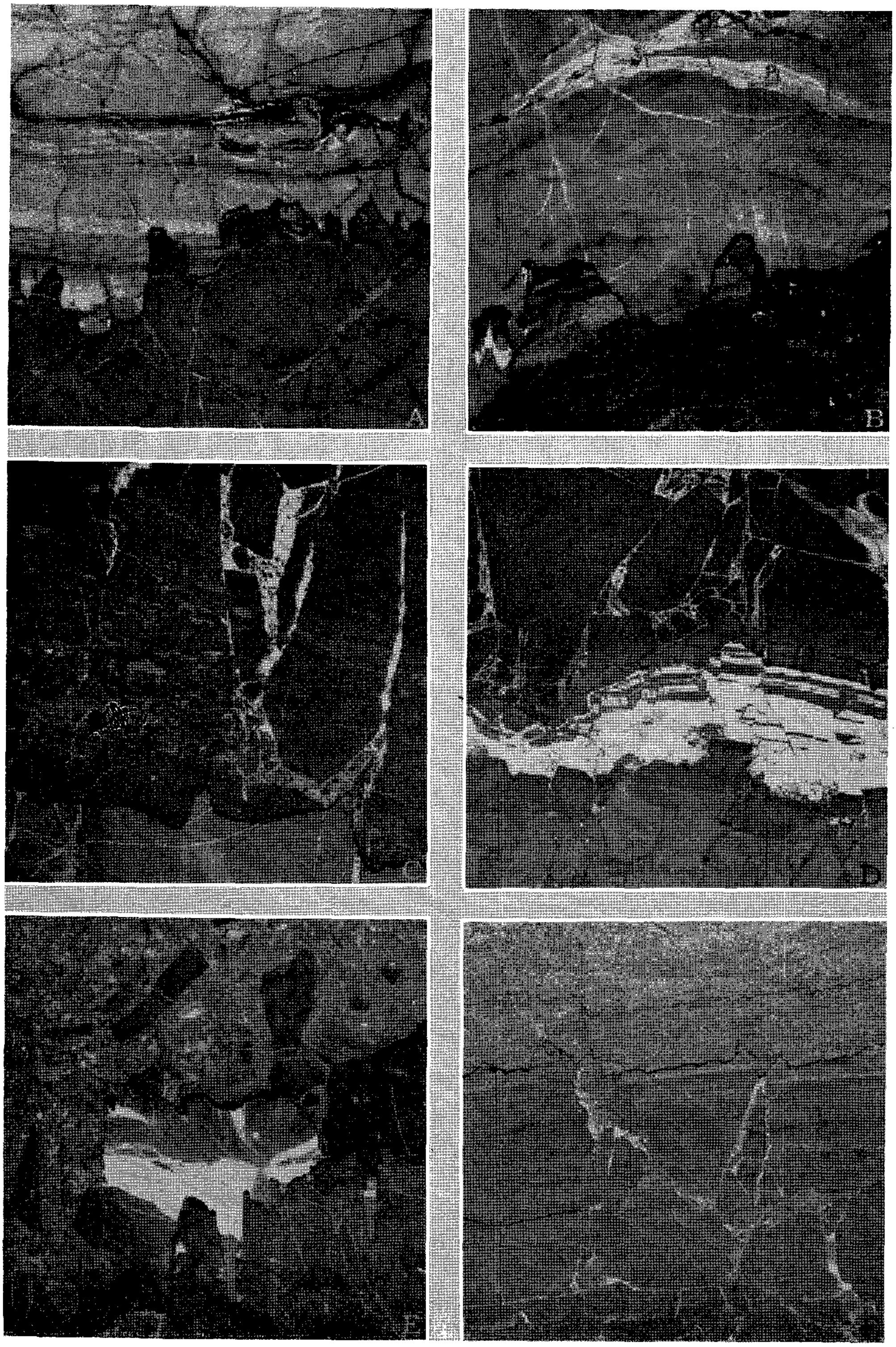
A
B
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PLATE 28

Photographs of cores from the Honeycut formation, Ellenburger group, Magnolia Petroleum Company No. 1 Below, Kendall County, Texas

(Natural size)

A. Limestone and dolomite from about 518 feet above the base of the Honeycut formation (depth 4,012 feet).

Aphanitic limestone breccia fragments in a medium-grained, argillaceous, dolomite matrix. The limestone when the whole core was viewed appears to be a 6- or 8-inch mass with the shaly dolomite swirling around it. A few isolated dolomite rhombs are in the limestone.

B. Dolomite and chert from about 316 feet above the base of the Honeycut formation (depth 4,214 feet).

The dolomite is very fine grained and faintly bedded horizontally. The opaque, color-banded chert in a spool-like mass has plume-like masses of calcite terminating at its borders. The calcite which may have replaced dolomite is lighter colored in the spindle of the spool. The numerous fractures are very tight.

C. Limestone and dolomite from about 292 feet above the base of the Honeycut formation (depth 4,238 feet).

Aphanitic limestone is irregularly and incompletely replaced by very fine-grained dolomite. In part the dolomite and limestone interfinger along stylolites. The irregularity of the dolomitic areas suggests that it may have formed along and spread out from burrows which were probably more permeable than the adjacent lime-mud. The limestone was originally a granular, fossiliferous sediment. The bed at the bottom of the photograph is chert slightly offset along a dolomite vein, and the dark area at the right may have been originally a burrow as beds just out of the photograph bend toward this area.

D. Limestone and dolomite from about 284 feet above the base of the Honeycut formation (depth 4,246 feet).

The very fine-grained, calcitic dolomite is in irregular, wavy layers and encloses eyes of limestone. Rather faint stylolites are in the upper, less dolomitic limestone.

E. Limestone and dolomite from about 280 feet above the base of the Honeycut formation (depth 4,250 feet).

The aphanitic limestone contains a few shell fragments and is irregularly replaced by very fine-grained dolomite. The replacement, even in the areas which appear to be dolomite, is not complete. The irregularity of the replacement suggests that dolomitization took place along and outward from burrows. Stylolites are numerous, and some dolomitization appears to have taken place along them.

F. Limestone and dolomite from about 279 feet above the base of the Honeycut formation (depth 4,251 feet).

The aphanitic limestone was originally a granular fossiliferous sediment composed of aphanitic grains in a minimum of clear calcite cement. The limestone is irregularly replaced along the bedding by very fine-grained dolomite, and the two are mostly separated by stylolites. It seems likely that the dolomite in the dolomitic beds formed before the next limestone bed was deposited, thus indicating a short period of alternation between conditions favorable for the production of limestone and of dolomite. The interface between the beds furnished a permeable zone for the passage of solution to form the stylolites. The irregularity of the dolomite-limestone pattern is caused by differential solution along the stylolites.

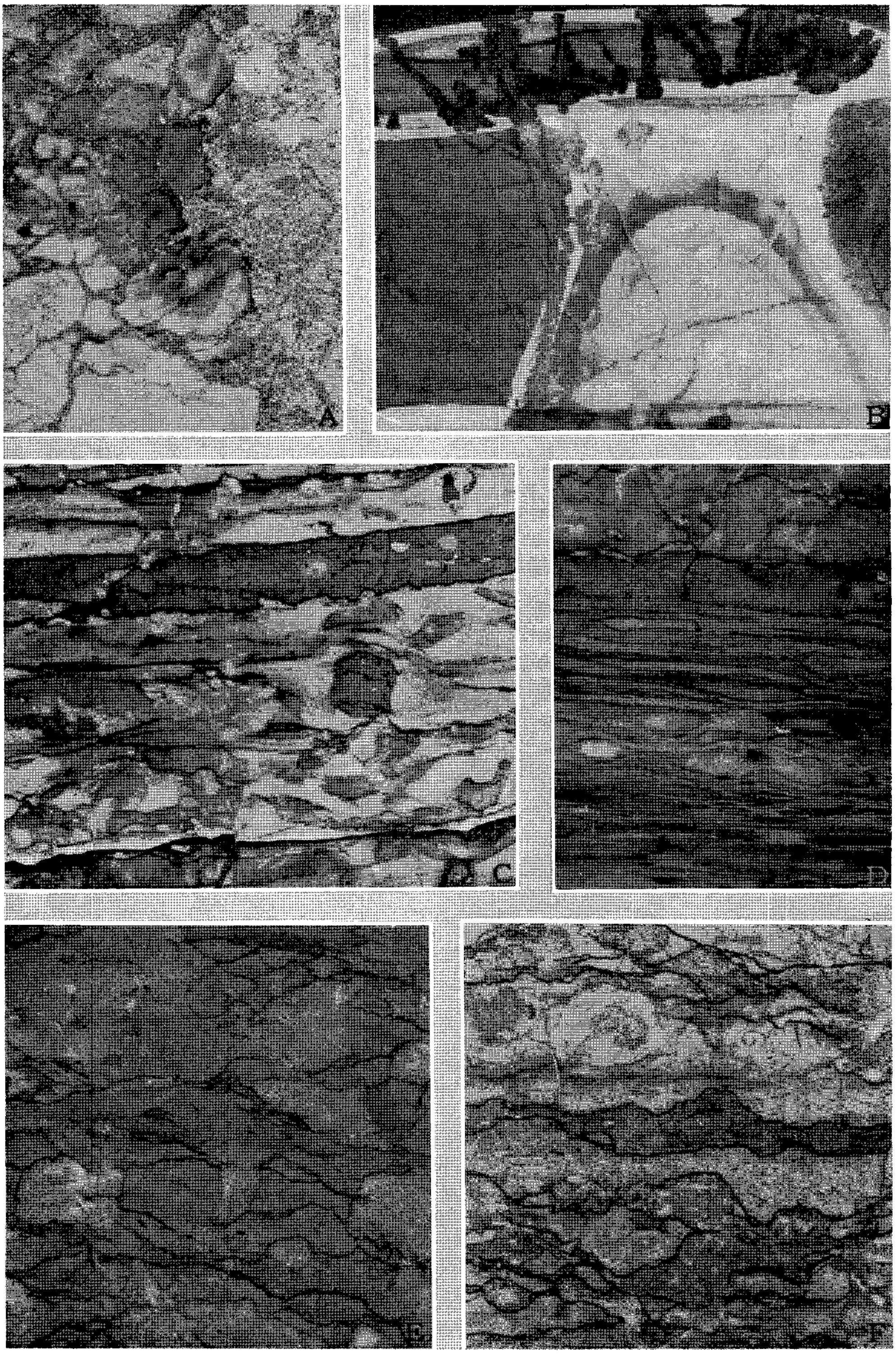
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PLATE 29

Photographs of cores from the Honeycut formation, Ellenburger group, and from the Wilberns and Riley formations, Kendall and Kerr counties, Texas

(Natural size)

MAGNOLIA PETROLEUM COMPANY NO. 1 BELOW, KENDALL COUNTY

A. Dolomite from about 266 feet above the base of the Honeycut formation (depth 4,264 feet).

The microgranular, very faintly bedded dolomite in part perhaps color banded has very distinct stylolites of large amplitude. The chert at the lower right is part of a nodule almost entirely replaced by calcite. A very tiny fracture is to the left.

B. Dolomite from about 181 feet above the base of the Honeycut formation (depth 4,349 feet).

The microgranular dolomite is very thinly and distinctly bedded with graded beds. The disturbance to the left happened while the beds were very soft. The beds are offset along the white dolomite-clear calcite vein. A slight displacement is along the black stylolite.

C. Deformed dolomite from about 110 feet above the base of the Honeycut formation (depth 4,420 feet).

The thinly bedded, microgranular dolomite was very soft when deformed.

D. Limestone and greensand from near the base of the Wilberns formation (depth 6,338 feet).

The light-colored, coarse-grained, fossiliferous, sandy, glauconitic limestone occurs as irregular lenses within the greensand in much the same manner as trilobite coquinite masses occur in the greensand of the Lion Mountain sandstone member of the Riley formation in the Llano region. This sample, however, contains Wilberns fossils and is interpreted as being in the transitional zone between the Morgan Creek limestone and the Welge sandstone of the Wilberns formation. The greensand contains an abundance of quartz sand and many fossil fragments.

E. Greensand and limestone from near the base of the Wilberns formation (depth 6,346 feet).

Numerous large fossil fragments are in the upper coarser grained greensand; the finer grained greensand below is less calcareous; in both, quartz sand is abundant. The interbedded slightly glauconitic, white limestone is a coqunite of Wilberns trilobites. Stylolites are in the upper bed.

G. L. ROWSEY NO. 2 NOWLIN, KERR COUNTY

F. Oolitic limestone from 128 feet below the top of the Cap Mountain limestone member of the Riley formation (depth 7,368 feet).

The limestone is sandy with some rather large quartz grains and one microcline granule near the stylolite.

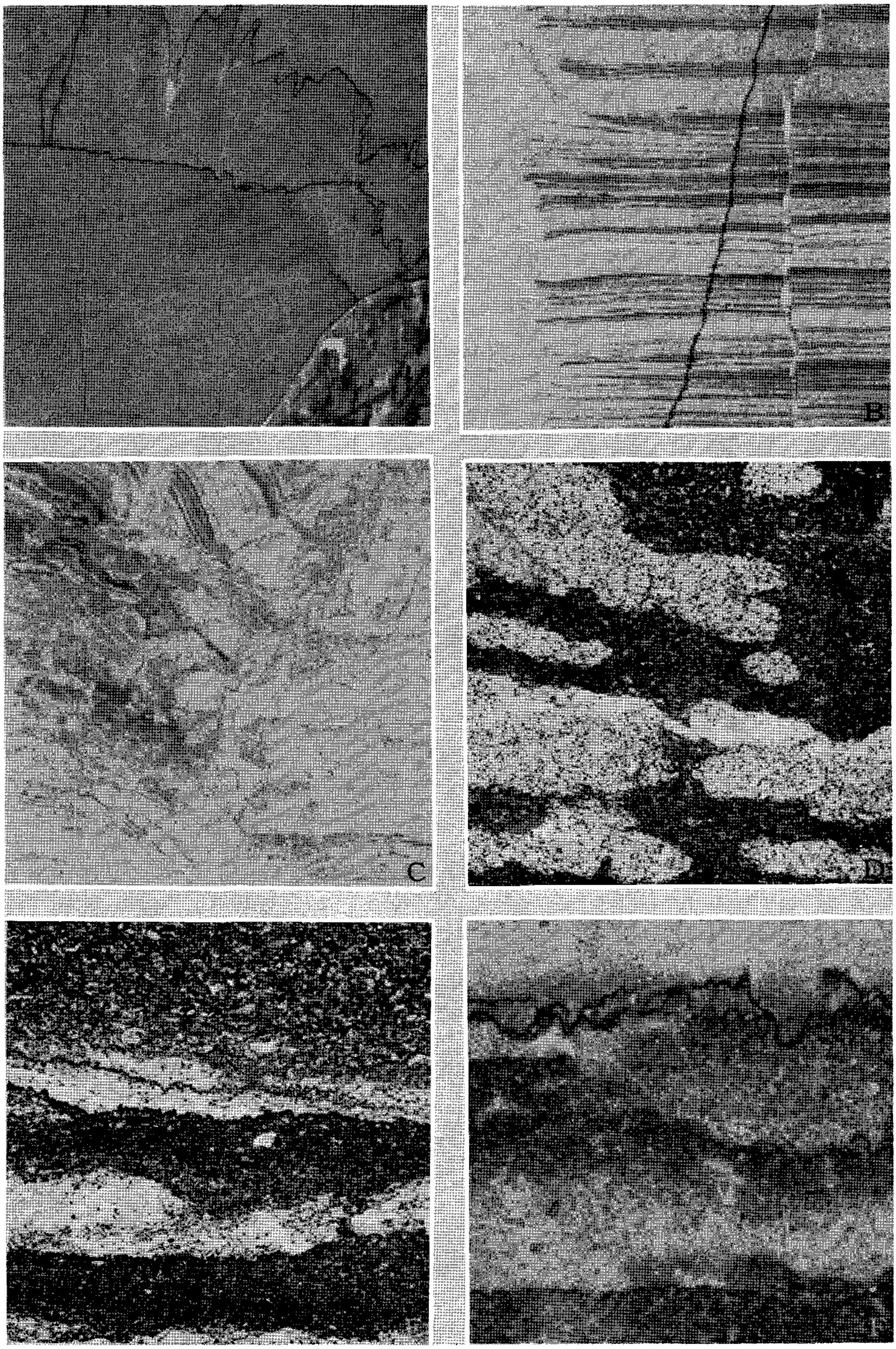
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PLATE 30

Photographs of cores from the Riley and Wilberns(?) formations, Kerr and Nolan counties, Texas

(Natural size)

TUCKER DRILLING COMPANY NO. 1 DR. ROY E. PERKINS, KERR COUNTY

A. Oolitic limestone from about 266 feet below the top of the Cap Mountain limestone member of the Riley formation (depth 2,846 feet).

Much of the upper part of the Cap Mountain is oolitic limestone mostly of lighter color and with smaller ooids than seen in this specimen. The uniformly dark grains are glauconite; the white areas of calcite may fill vugs. The stylolites wander about rather aimlessly.

B. Sandstone and shale from about 90 feet below the top of the Hickory sandstone member of the Riley formation (depth 3,320 feet).

The medium dark gray, silty, micaceous shale alternates with irregular zones of fine-grained sandstone. Much of the sandstone appears to have followed burrows into the shale. The shale is otherwise little disturbed.

C, D. Sandstone and shale from about 92 feet below the top of the Hickory sandstone member of the Riley formation (depth 3,322 feet).

Both the sandstone and shale are similar to that in "B" above, except for a medium-grained sandstone bed near the top of "C." About half of the sandstone in "C" is in beds that show some original depositional irregularities and the rest follows burrows. The sandstone and shale in "D" are very little disturbed by burrows and have been little disturbed since their deposition.

E. Sandstone from about 93 feet below the top of the Hickory sandstone member of the Riley formation (depth 3,323 feet).

The sandstone is coarse grained and somewhat disturbed as can be seen by the irregularity of the shaly streaks. The dark grains are olive-gray, clay pellets.

HONOLULU OIL CORPORATION NO. 6 WHITAKER, NOLAN COUNTY

F. Dolomite from about 6 feet above the sandstone in the San Saba member of the Wilberns formation (depth 5,614 feet).

The fine-grained, argillaceous, somewhat pyritiferous dolomite is mottled by irregular, shaly, bedding plane streaks. A fault to the left has about one-half inch throw. The dolomite is probably Lower Ordovican in age.

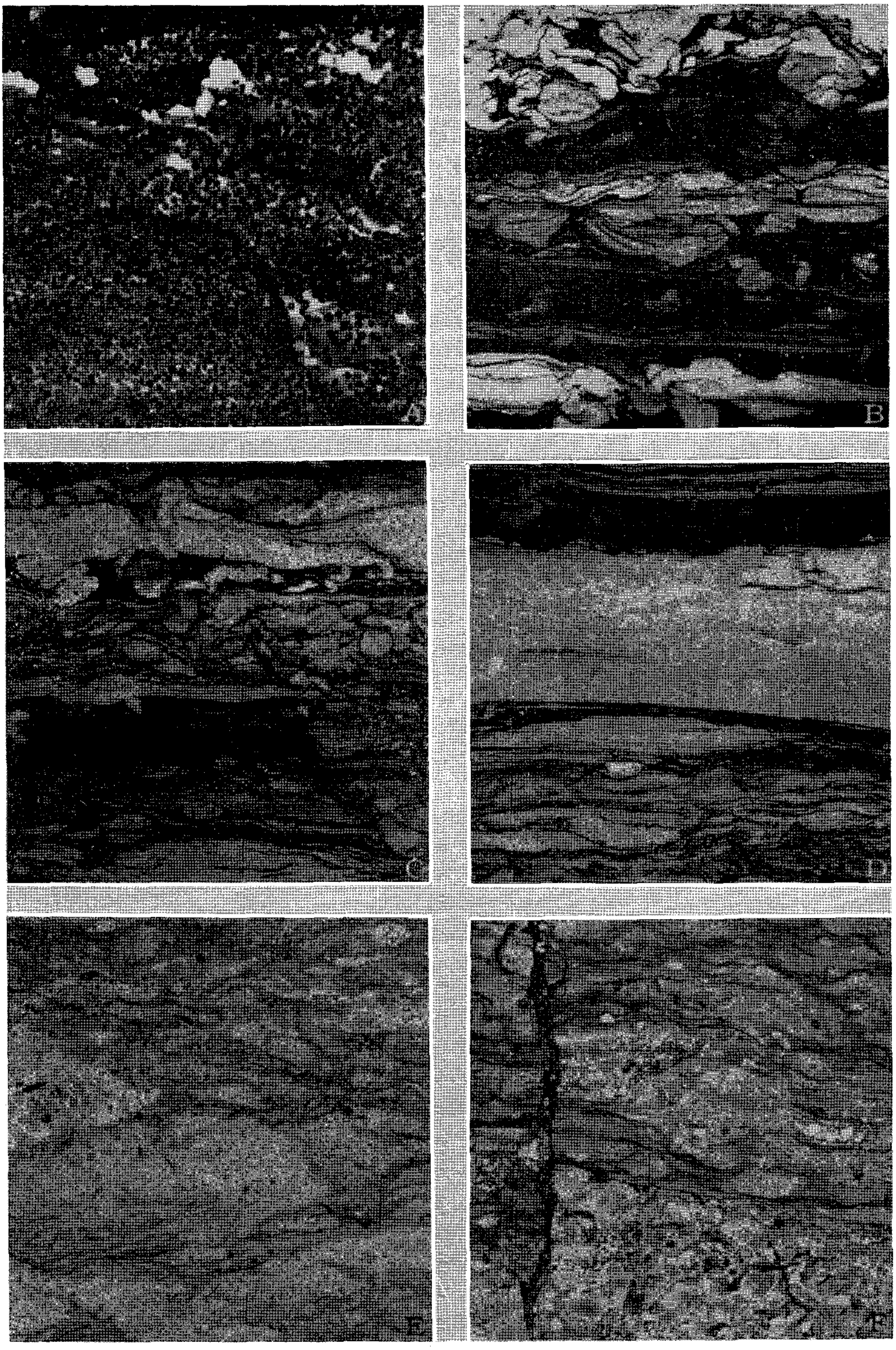

PLATE 31

Photographs of cores from the Wilberns and Riley formations, G. L. Rowsey No. 2 Fee, Bandera County, Texas

(Natural size)

A. Limestone from about 161 feet above the base of the Morgan Creek limestone member of the Wilberns formation (depth 6,269 feet).

The limestone is composed of coarse fossil debris and some rounded objects which may be small pebbles or algal masses. Above the lowest stylolite is a pelmatozoan columnal. The vertical fracture has a stylolite along it.

B. Limestone from about 154 feet above the base of the Morgan Creek limestone member of the Wilberns formation (depth 6,276 feet).

The fine-grained limestone is cross-bedded, glauconitic, and stylolitic.

C. Limestone from about 128 feet above the base of the Morgan Creek limestone member of the Wilberns formation (depth 6,302 feet).

The reddish limestone is mostly composed of coarse-grained fossil debris embedded in secondary calcite. Glauconite is common and stylolites are prominent to indistinct. The rounded objects may be algal masses or possibly intraformational conglomerate pebbles.

D. Limestone from about 126 feet above the base of the Morgan Creek limestone member of the Wilberns formation (depth 6,304 feet).

The limestone is similar to that in figure C except that algal(?) balls are very much more common. The one at the upper left has a median streak which may have served as an object around which the algae(?) grew. White pelmatozoan debris is common.

E. Sandstone from the Hickory sandstone member of the Riley formation (depth 6,767 feet).

The fine to very fine-grained, silty, argillaceous sandstone is indistinctly bedded horizontally. The dark line is a crack which probably formed along a shaly streak. A few linear, dark objects along the bedding are fragments of corneous brachiopods.

F. Intraformational conglomerate from the Hickory sandstone member of the Riley formation (depth 6,780 feet).

The fine and very fine-grained, slightly calcareous pebbles are color banded parallel to their periphery and are in a medium to coarse-grained, argillaceous sandstone matrix. At least two pebbles in the field of view are composed of an earlier-formed intraformational conglomerate.

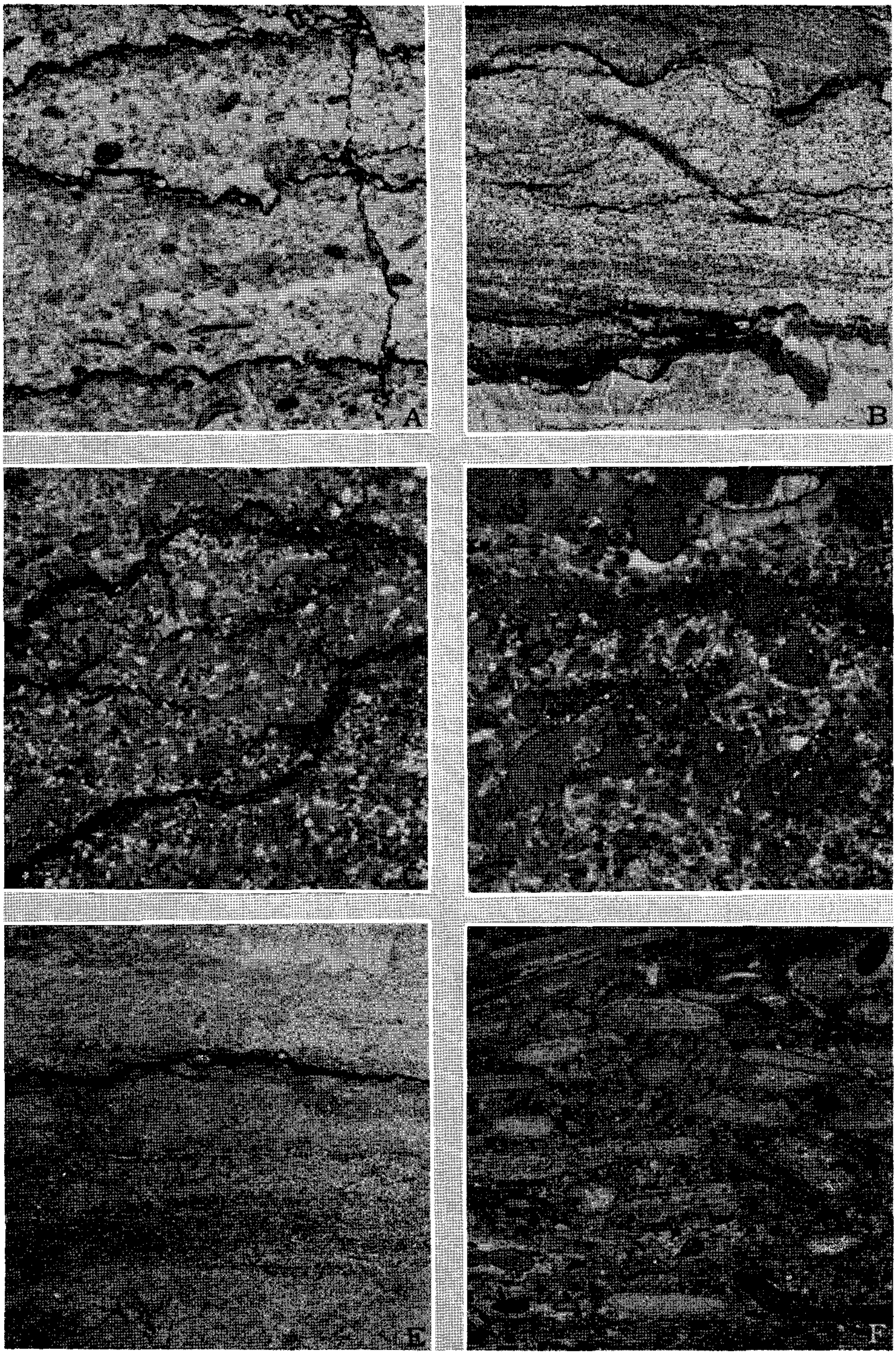
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PLATE 32

Photographs of cores from the Wilberns and Riley formations, Humble Oil & Refining Company No. F-90 Odom, Coke County, Texas.

(Natural size)

A. Shale and sandstone from about 20 feet below the top of the Morgan Creek member of the Wilberns formation (depth 6,130 feet). (The position of formation and member boundaries was estimated from electrical logs. The dip for the entire core from this well averages about 60°.)

The interbedded fine-grained sandstone and very silty shale display a peculiar pattern of faulting.

B. Shale and sandstone from about 31 feet below the top of the Morgan Creek member of the Wilberns formation (depth 6,141 feet).

The thinly interbedded fine-grained sandstone and silty shale are similar to those in figure A except that faulting is absent and more of the sandstone is along burrows.

C. Shale and sandstone from about 58 feet below the top of the Morgan Creek member of the Wilberns formation (depth 6,168 feet).

Medium to coarse-grained sandstone beds are interbedded with silty shale. Only a few small masses of sandstone follow burrows.

D. Shale and sandstone from about 63 feet below the top of the Morgan Creek member of the Wilberns formation (depth 6,173 feet).

The fine to coarse-grained sandstone is in part interbedded with silty shale and in part follows burrows in the shale. The sandstone and shale to the right are dragged along a fault.

E. Sandstone from about 37 feet below the top of the Riley formation (depth 6,257 feet).

The fine to very coarse-grained sandstone beds are very poorly sorted, and some grains are of granule size.

F. Sandstone from about 42 feet below the top of the Riley formation (depth 6,262 feet).

The sandstone is similar to that from 6,257 feet except that the white (bleached) sandstone shows an irregular cross-cutting relationship.

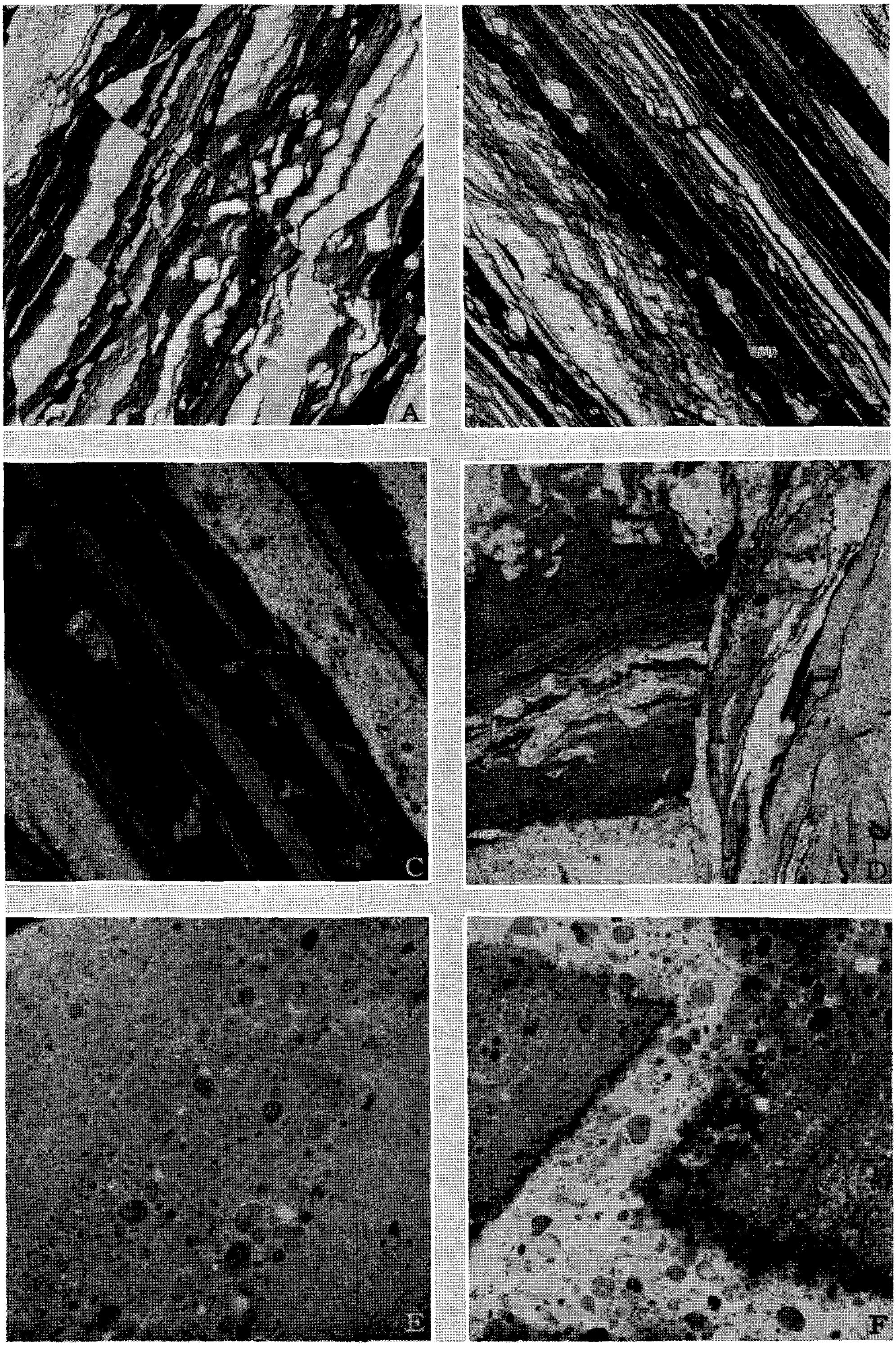
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PLATE 33

Photgraphs of cores from above and in the Ellenburger and Arbuckle groups, Nolan and Collin counties, Texas

(Natural size)

Skelly Oil Company No. 1 Ater, Nolan County, Texas

A. Chert and shale from about 25 feet above the Ellenburger (depth 7,062 feet).

Masses and streaks of white chert are irregularly interbedded with green indurated shale or clay. Some of the shale or clay may be along stylolites.

B. Chert and shale from about 21 feet above the Ellenburger (depth 7,066 feet).

The bedded shale at upper right grades into indurated shale or clay similar to that in figure A which in turn appears to grade into chert. It seems likely that the shale has been in part replaced by chert. The small white area of opaque chert near the top contains a few translucent areas. In lower part stylolites are common in the chert.

C. Chert possibly from the Gorman formation of the Ellenburger group (depth 7,134 feet).

The mostly opaque, in part brecciated chert of several types interfingers along stylolites. Color-banded chert is in upper part and a few translucent nodules, one of which is spiculiferous, are in lower part.

Humble Oil & Refining Company No. 1 Miller, Collin County

D. Dolomite from about 877 feet above the base of the West Spring Creek formation of the Arbuckle group (depth 9,388 feet).

Original deposition features are preserved in the mostly very fine-grained dolomite. The darker areas are calcitic.

E. Limestone from about 903 feet above the base of the West Spring Creek formation of the Arbuckle group (depth 9,362 feet).

The aphanitic limestone is structureless except for some slightly darker, thin, argillaceous beds. A stylolite has formed along a vertical fracture. The limestone was replaced by dolomite adjacent to the stylolite, and in a circular area at the upper left dolomite possibly followed a burrow.

F. Limestone and shale from about 6 feet below the top of the Cool Creek formation of the Arbuckle group (depth 11,166 feet).

The aphanitic limestone is interbedded with dolomitic, calcitic, pyritiferous shale. The peculiar structure may possibly be caused by slumping of slightly indurated rocks into a solution cavity. Collapse materials are abundant at the top of the corresponding formation (Gorman) of central Texas.

G. Limestone and chert from about 50 feet below the top of the Cool Creek formation of the Arbuckle group (depth 11,210 feet).

The aphanitic limestone is in part in rounded intraformational conglomerate pebbles. The matrix is translucent, very light gray, oolitic chert. A stylolite in lower part forms a boundary between chert and limestone.

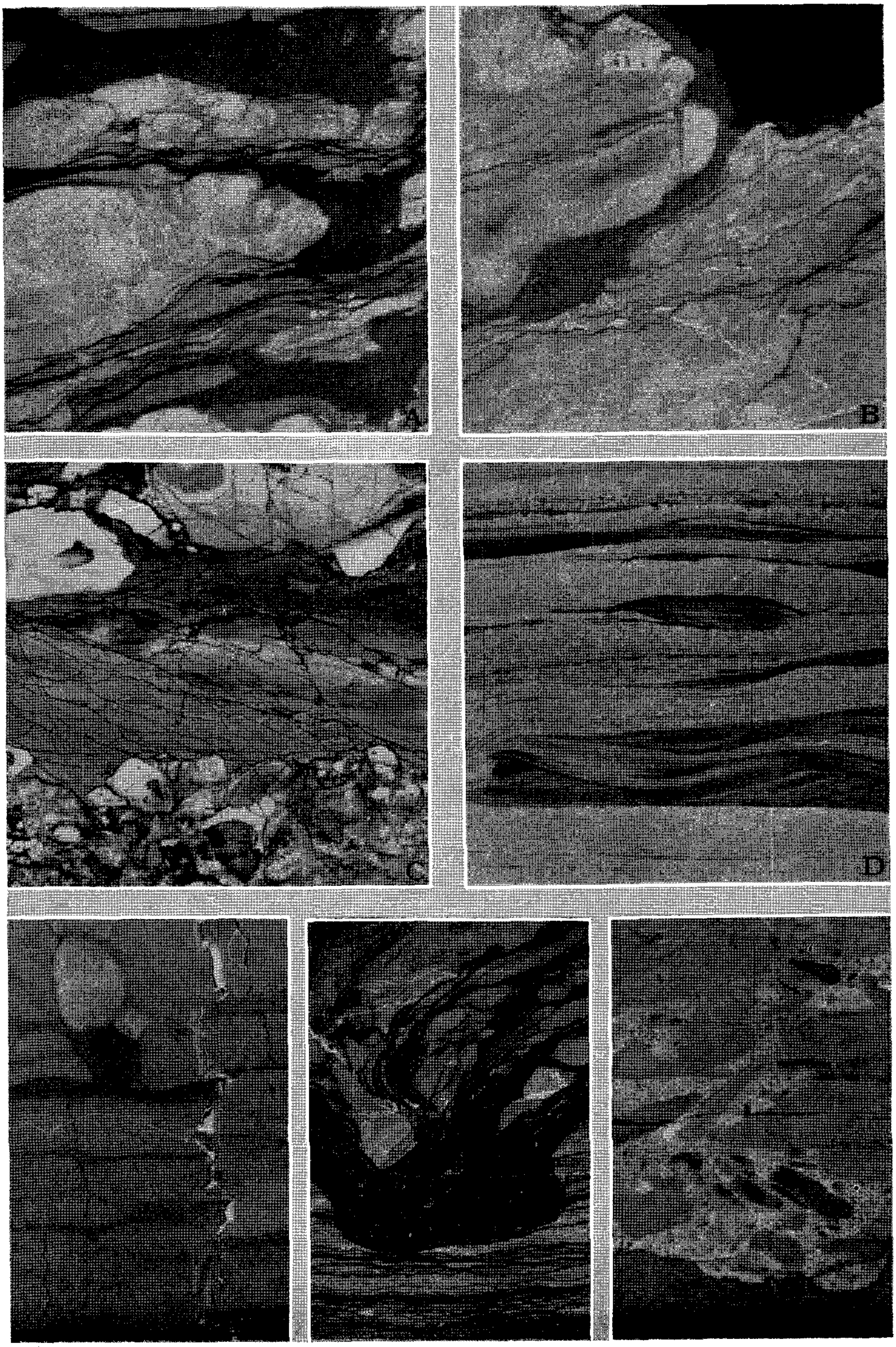
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PLATE 34

Upper Cambrian fossils from Wilberns and Riley formations, various wells and surface sections, central Texas

FIGURES—

1,2. *Chancelloria*-type spicules (x10) from the upper part of the Cap Mountain limestone member of the Riley formation, at 504 feet in Morgan Creek section. UT-32191d, e.

3–5. *Kinsabia variegata* Lochman (x10) from the lower part of the Cap Mountain limestone member of the Riley formation, at 850 feet in Threadgill Creek section. UT-32190a-c.

6–8. *Apsotreta expansa* Palmer (x10) from the Lion Mountain sandstone member of the Riley formation, at 599 feet in Threadgill Creek section.
- 6. Interior of brachial valve. UT-32194a.
- 7, 8. Internal and profile views of pedicle valves. UT-32194b, c.

9, 11. Merostome fragment from the upper portion of the Wilberns formation, 6,248 feet below surface, General Crude Oil Company No. 1 George Cave, Nolan County. USNM 127236.
- 9. Detail of fragment of telson, x4.
- 11. Appearance of specimen natural size in core, x1. Other fragments are absent.

10, 13. *Huenella texana* (Walcott) from the Morgan Creek limestone member of the Wilberns formation, 6,302 feet below surface, G. L. Rowsey No. 2 Fee, Bandera County. USNM 127237.
- 10. Detail of specimen, x4.
- 13. Appearance of specimen in core, x1. Other fossils are absent.

12, 14. Saukiid trilobite from the upper part of the Wilberns formation, 7,649 feet below surface, American Trading & Production Corporation No. 1 Sauer, Schleicher County. USNM 127238.
- 12. Close-up of specimen, x4.
- 14. Appearance of specimen in core, x1. Impressions of other trilobite fragments are in lower right corner.

15, 16. *Labiostria conveximarginata* Palmer from Lion Mountain sandstone member of the Riley formation, 6,370 feet below surface, Magnolia Petroleum Company No. 1 Below, Kendall County. USNM 127239.
- 15. Close-up of specimen, x4.
- 16. Appearance of specimen in core, x1. Trilobite material is abundant, a feature characteristic of limestone from this part of the section.

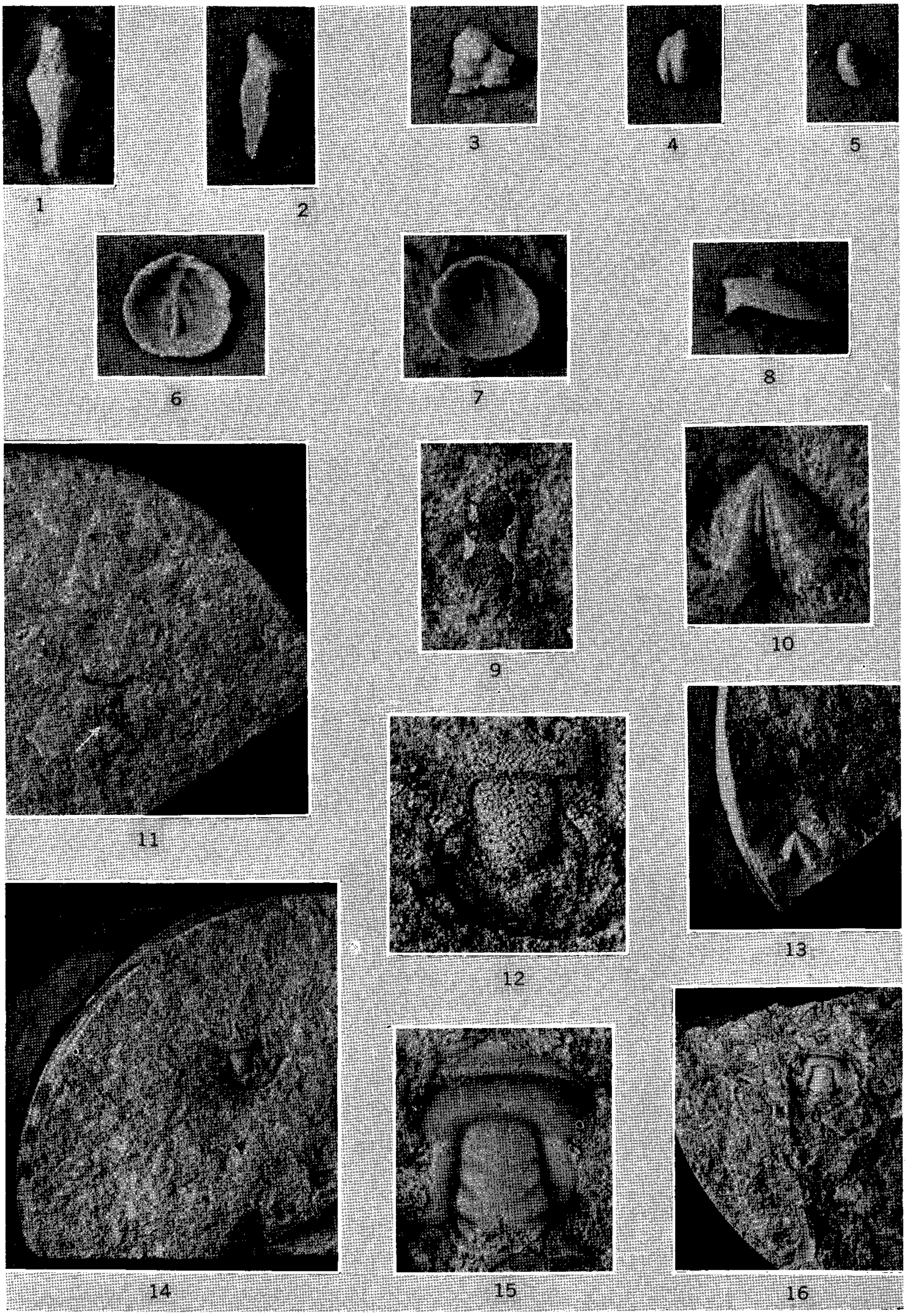
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PLATE 35

Lower Ordovician fossils from Ellenburger and Arbuckle groups, various wells, various parts of Texas

FIGURES—

1. *Polytoechia* cf. *P. alabamensis* Ulrich and Cooper, x1, pedicle valve from high Lower Ordovician (high West Spring Creek) beds at 9,335 to 9,336 feet in Humble Oil & Refining Company No. 1 Miller, Collin County. USNM 127240.

2. *Pomatotrema*, x1, pedicle valve from same level and locality as figure 1. USNM 127241.

3. *Pomatotrema*, x2, brachial valve from high Lower Ordovician (high West Spring Creek) beds at 7,868 to 7,869 feet in The Superior Oil Company No. 1 S.L. Privette, Grayson County. USNM 127242.

4–6. *Diparelasma*, pedicle valves (x2) and brachial valve (x3) from same level and locality as figure 1. USNM 127243a-c.

7. *Liospira*-like gastropod, x2, from beds of probable Honeycut age at 4,469 feet in Magnolia Petroleum Company No. 1 Mary Ball, Schleicher County. USNM 127244.

8. *Eoleperditia*?, x3, from high Lower Ordovician (high West Spring Creek) beds at 9,348 feet in Humble Oil & Refining Company No. 1 Miller, Collin County. USNM 127245.

9, 10. *Hormotoma*, x1, from beds of probable Honeycut age at 4,469 and 4,515 feet in Magnolia Petroleum Company No. 1 Mary Ball, Schleicher County. USNM 127246a, b.

11. *Euconia*, x1, from beds of probable Honeycut age at 11,371 to 11,372 feet in Phillips Petroleum Company No. 2 Delp, Gray County. USNM 127247.

12. *Orospira*? of type of *O. gainesvillensis* Cullison, or high-spired *Ophileta* (*Ozarkispira*), x1, from beds of probable Honeycut age at 12,150 to 12,152 feet in Gulf Oil Corporation No. 1 McElroy-State, Upton County. USNM 127248.

13. *Orospira*, x2, from beds of Honeycut age at 5,225 to 5,226 feet in The Texas Company No. 1 Phillips, Edwards County. USNM 127249.

14, 15. *Archaeoscyphia*, x1, x5, from beds of Honeycut age at 4,457 to 4,458 feet in Magnolia Petroleum Company No. 1 Mary Ball, Schleicher County. USNM 12750a, b.

16. Coiled nautiloid cephalopod, probably a tarphyceratid, x1, from beds of Honeycut age at 4,010 feet in Humble Oil & Refining Company No. 1 J. H. Guthrie, Edwards County. USNM 127251.

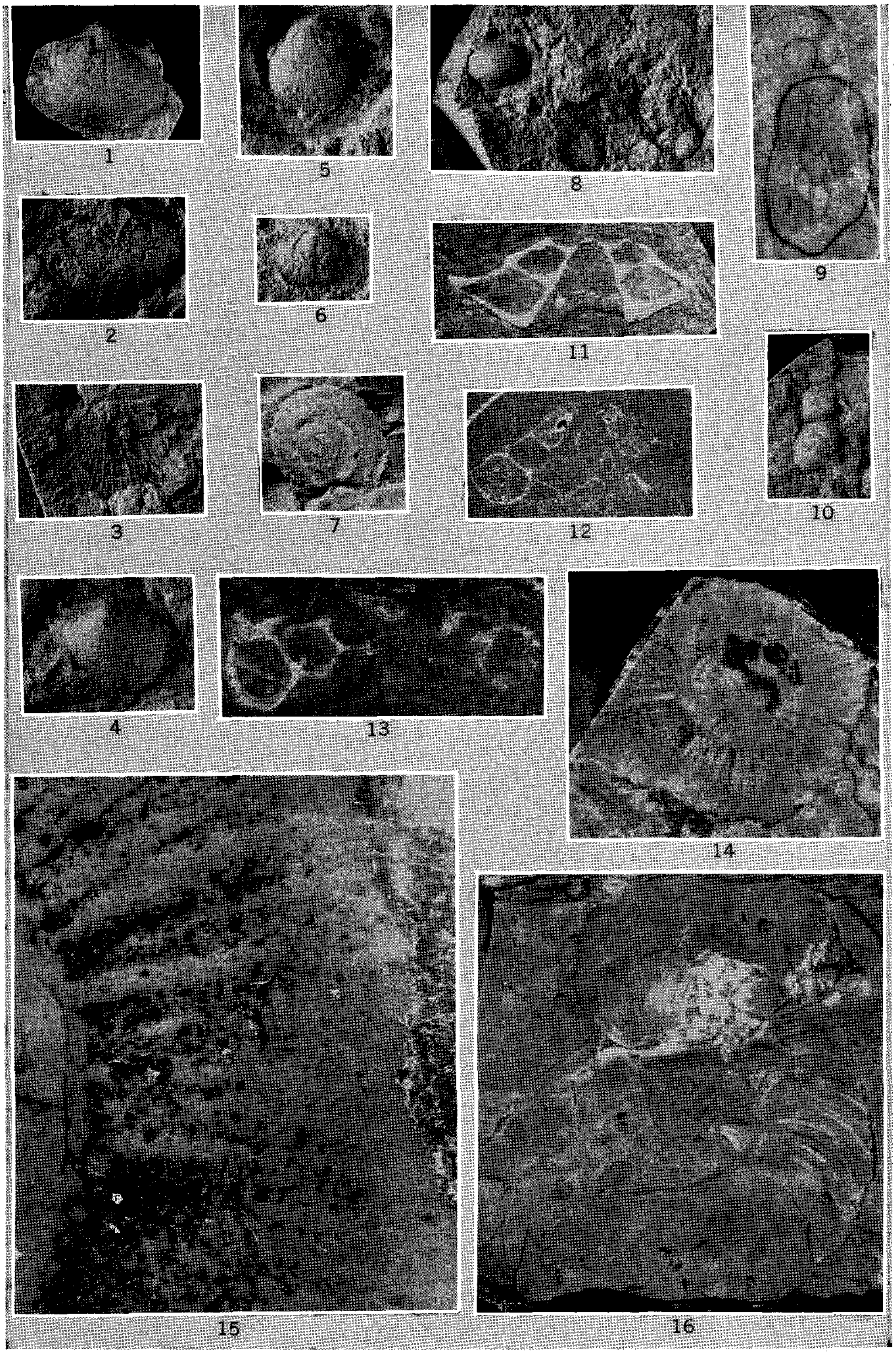

PLATE 36

Photomicrographs of Ellenburger and Arbuckle rocks

A. Well-rounded orthoquartzite-type sand in dolomite (p. 100). Skelly Oil Company No. 1 Ater, Nolan County, Texas, 7,094 feet. (x42)

B. Well-rounded sand consisting entirely of quartz (supermature orthoquartzite); weak tendency for bimodal size distribution; a few dark, elliptical intraclasts (pp. 100, 782). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 10,260 feet. (x42)

C. Submature arkose consisting of poorly sorted, angular microcline, orthoclase, and quartz cemented by calcite (pp. 101, 754). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,451 feet. (x60, crossed nicols)

D. Immature arkose, consisting of abundant angular microline and quartz in a clayey matrix (pp. 101, 102, 757). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,556 feet. (x34, crossed nicols)

E. Well-rounded quartz sand grains embedded in dolomite; large clear patch of barite in center (pp. 101, 778). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,369 feet. (x34, crossed nicols)

F. Supermature orthoquartzite, consisting of well-rounded grains of plutonic quartz; one grain of feldspar (high relief) with an authigenic overgrowth is shown (p. 101). Phillips Petroleum Company No. 1 Wilson, Val Verde County, Texas, 16,456 feet. (x42)

G. Clayey laminae in medium crystalline dolomite (p. 101). Skelly Oil Company No. 1 Ater, Nolan County, Texas, 7,124 feet. (x16)

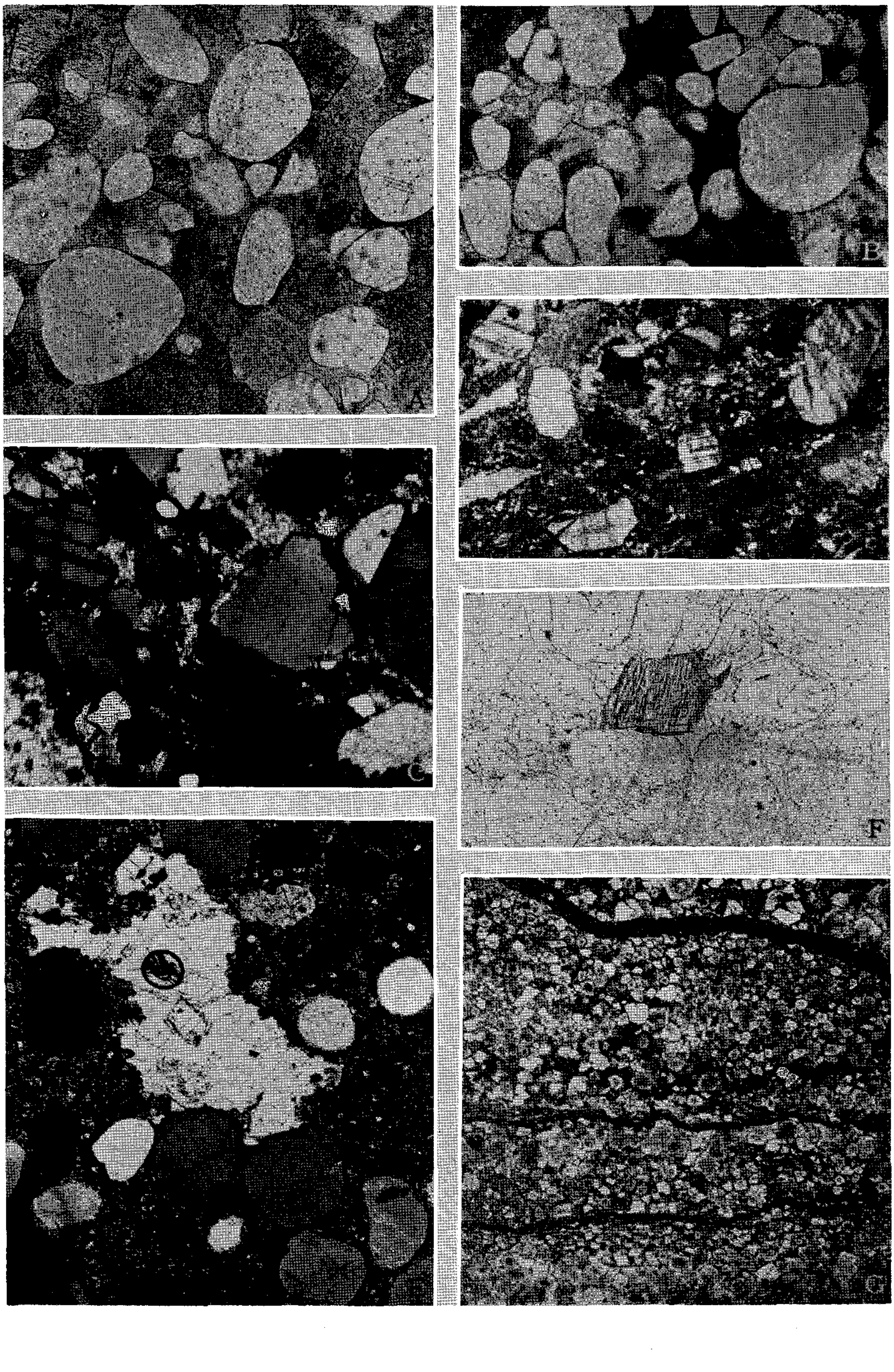
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PLATE 37

Photomicrographs of Ellenburger and Arbuckle rocks

A. Idiomorphic, zoned crystals of dolomite embedded in clay; black specks are pyrite (pp. 102, 108, 753). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,415 feet. (x75)

B. Well-sorted and well-rounded quartz sand embedded in dolomite (p. 103). Phillips Petroleum Company No. 1 Glenna, Pecos County, Texas, 14,079 feet. (x42)

C. Bimodal mixture of coarse sand with silt (p. 103). Richardson & Bass No. 1 Federal-Cobb, Eddy County, New Mexico, 16,212 feet. (x34, crossed nicols)

D. Intraclastic limestone which has been partially replaced by a large mass of chert which "spills over" and transects part of a large intraclast; the replaced area is clear, the calcitic part is dark (pp. 105, 110). Cherokee Creek section, 822 feet above base. (x28)

E. Intraclasts in sparry calcite cement (pp. 105, 107). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,697 feet. (x23)

F. Intraclastic limestone with area between intraclasts occupied by dolomite which has "spilled over" and replaced the edges of the intraclasts (p. 105). Cherokee Creek section, 934 feet above base. (x28)

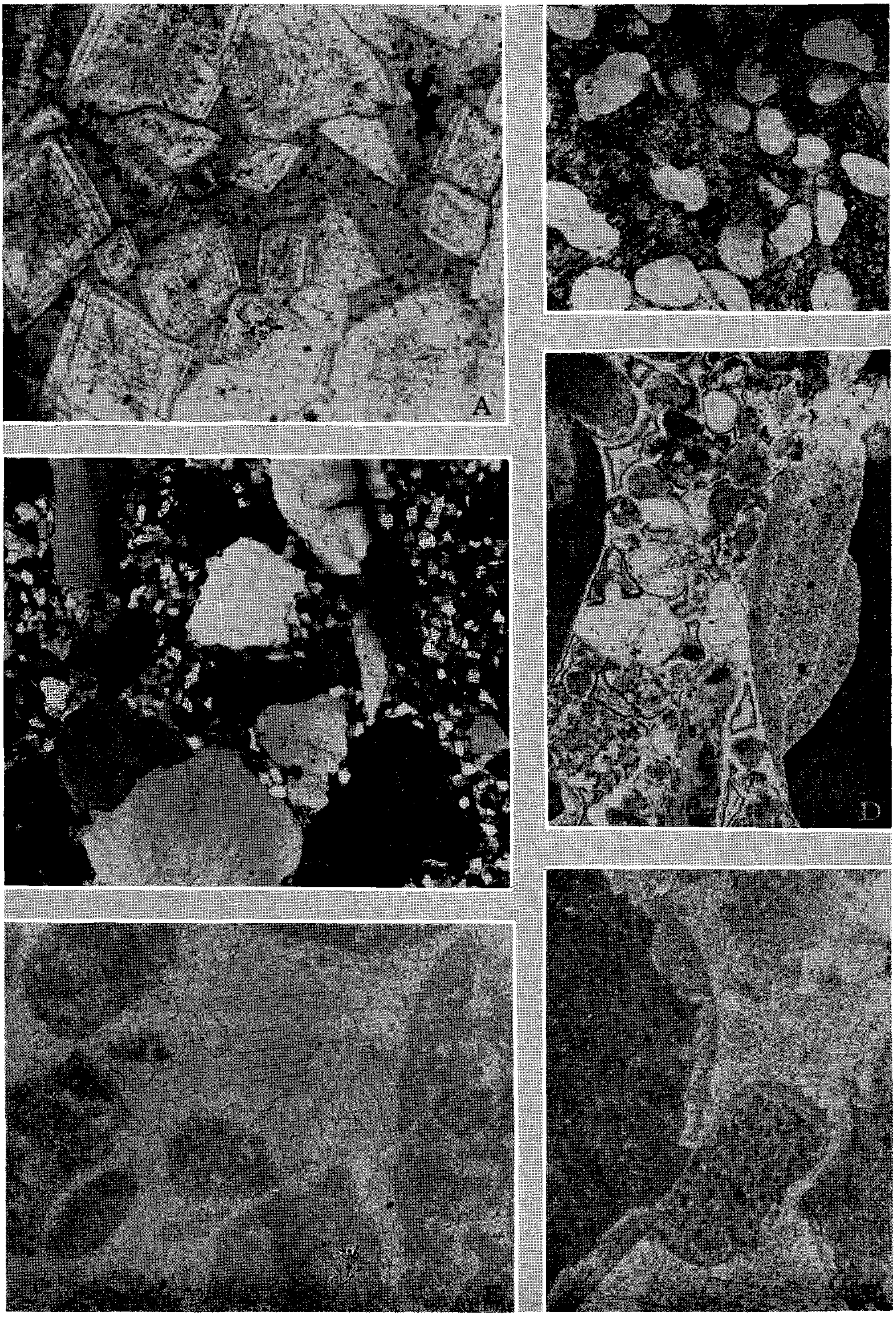
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PLATE 38

Photomicrographs of Ellenburger and Arbuckle rocks

A. Vague allochem ghosts transected by medium crystalline dolomite; allochem ghosts probably represent replaced intraclasts (pp. 105, 109, 744). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,077 feet. (x42)

B. Oolites showing concentric structure and replacement of the original microcrystalline calcite bands by fibrous calcite (pp. 106, 107). Humble Oil & Refining Company No. 1-C Alma Cox, Crockett County, Texas, 8,417 feet. (x42, crossed nicols)

C. Contact between oolitic limestone (upper right) and oolitic chert nodule (clear, lower left). One oolite (lower right corner) only partially replaced by chert; the dark is calcite (pp. 106, 110, 775). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,414 feet. (x50)

D. Oolite ghosts in coarsely crystalline dolomite (pp. 106, 109). Skelly Oil Company No. 1 Ater, Nolan County, Texas, 7,107 feet. (x75)

E. Pellets, probably of fecal origin, cemented by sparry calcite (p. 106). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,718 feet. (x42)

F. Elliptical chert nodule, preserving the pellet structure of the surrounding darker carbonate rock; concentric banding is apparently a later diffusion phenomenon (p. 106). Cherokee Creek section, 900 feet above base. (x11)

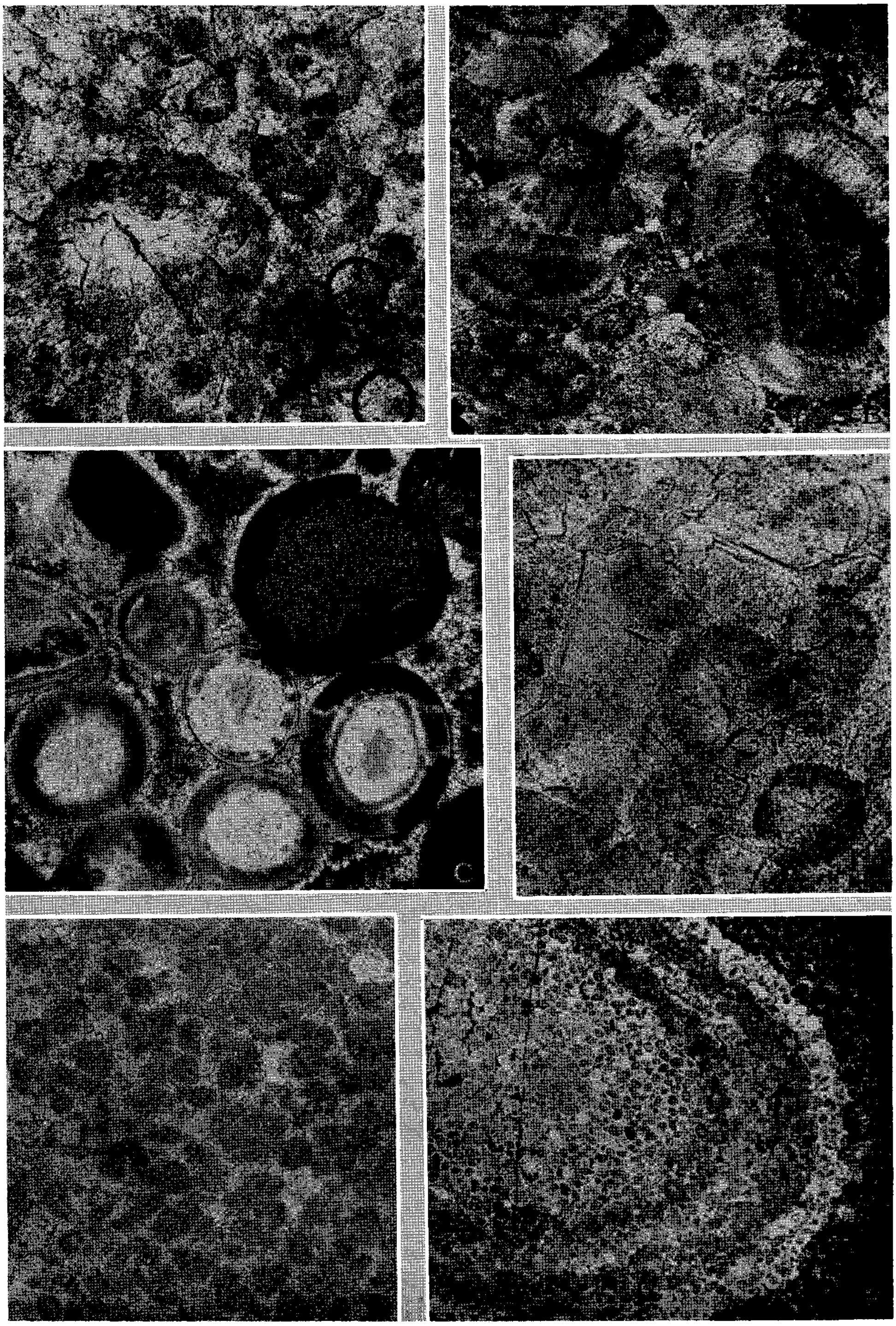

PLATE 39

Photomicrographs of Ellenburger, Arbuckle, Chappel, and Marble Falls rocks

A. Pellet ghosts (darker, nearly circular spots) in finely crystalline dolomite (pp. 106, 107, 109, 730). Gulf Oil Corporation No. 1 Mitchell Bros. —State, Presidio County, Texas, 15,367 feet. (x75)

B. The dark particles are largely fossils, but one oolite and several intraclasts are shown; rock is cemented by sparry calcite; probably Marble Falls limestone (Lower Pennsylvanian) (p. 106). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 3,905.5 feet. (x42)

C. Fossil hash, largely crinoid fragments (large, clear pieces) with some small brachiopods; Chappel limestone (Mississippian) (p. 106). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 3,963.5 feet. (x42)

D. Algal reef (?) limestone, showing rude banding (p. 106). Continental Oil Company No. 1 Burger B-28, Lea County, New Mexico, 9,267 feet. (x16)

E. Algal reef (?) composed of finely crystalline calcite with vague banding brought out by changes in crystal size; one thin calcite veinlet (p. 106). Continental Oil Company No. 1 Burger B-28, Lea County, New Mexico, 9,267 feet. (x42)

F. Microcrystalline calcite traversed by a few thin clay laminae which are slightly disturbed (pp. 102, 106). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 10,233 feet. (x42)

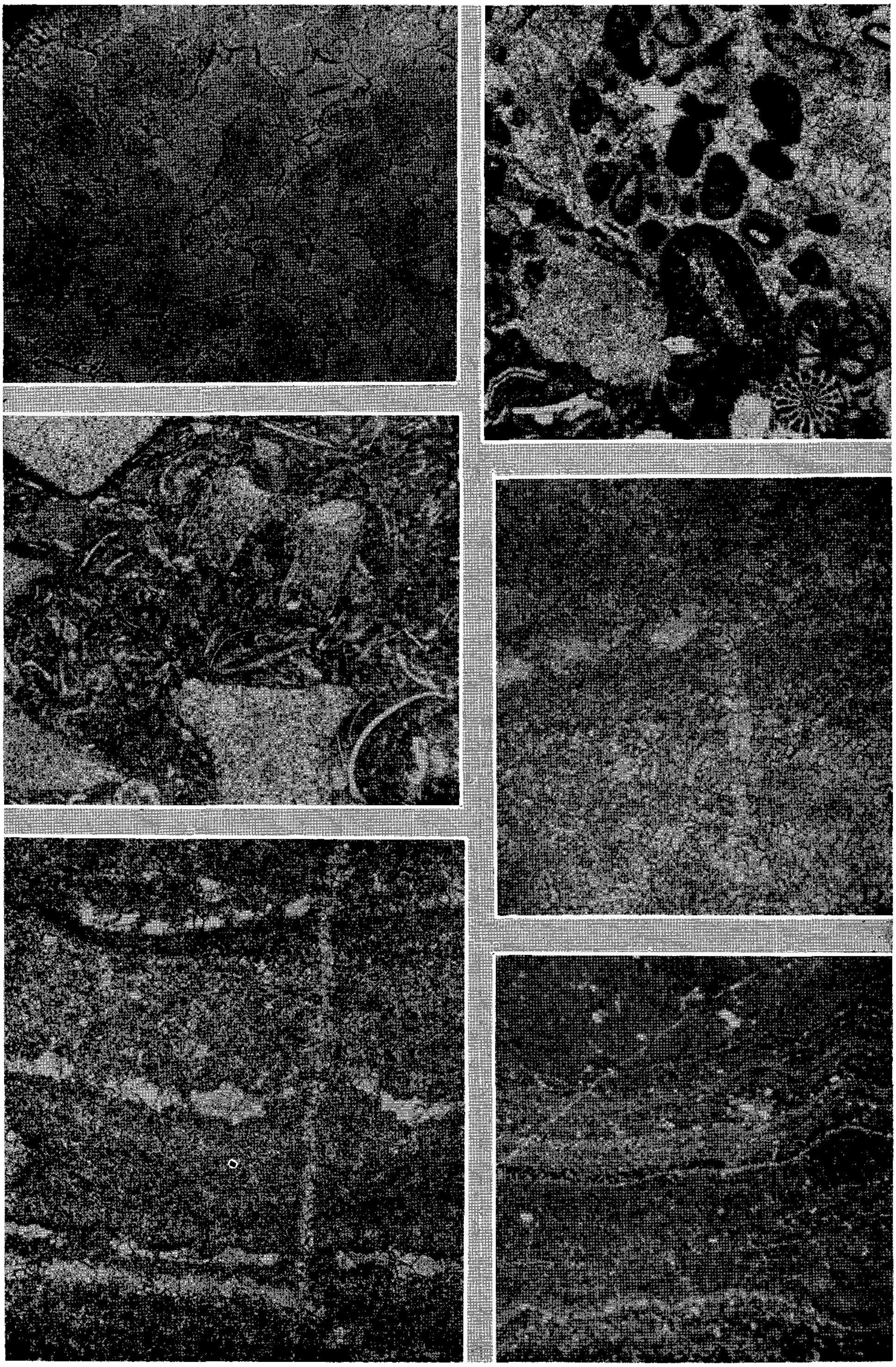

PLATE 40

Photomicrographs of Ellenburger and Arbuckle rocks

A. Arcuate fossil fragments in microcrystalline calcite (p. 106). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,682 feet. (x42)

B. Microcrystalline limestone apparently disturbed by animal burrows (this type of limestone is designated dismicrite) (p. 106). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,256.5 feet. (x42)

C. Collapsed oolites cemented by sparry calcite (pp. 106, 779). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,396 feet. (x28)

D. Oolites with the original concentrically banded microcrystalline calcite which made up the oolites replaced by radial fibers of calcite, although some dark microcrystalline calcite remains (p. 107). Humble Oil & Refining Company No. 1-C Alma Cox, Crockett County, Texas, 8,417 feet. (x42)

E. Very finely crystalline dolomite with vague horizontal laminae (pp. 107, 109). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,301 feet. (x42)

F. Very finely crystalline hypidiomorphic dolomite, a very common Ellenburger rock type (pp. 107, 109). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,301 feet. (x75)

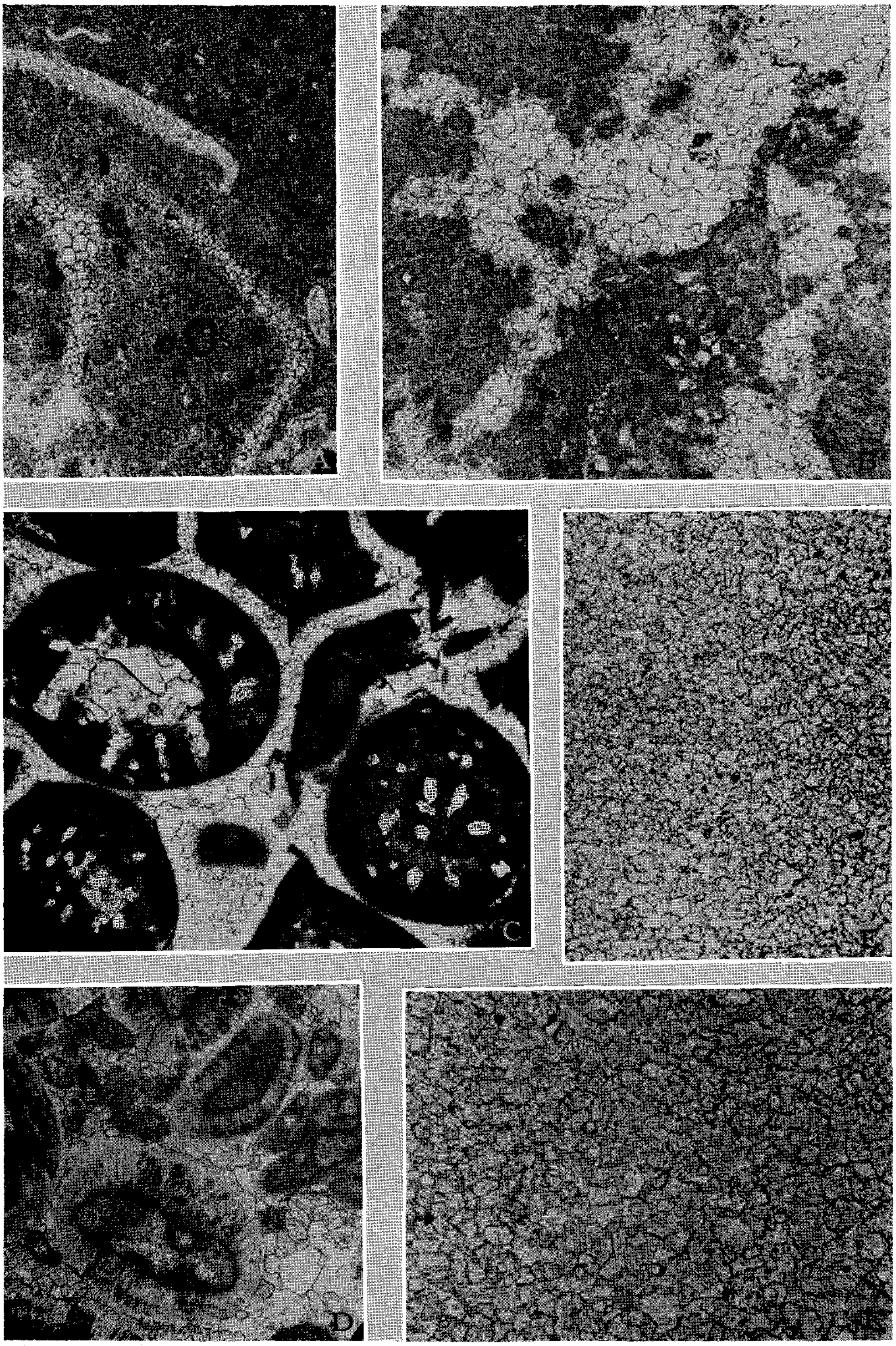
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PLATE 41

Photomicrographs of Ellenburger rocks

A. Vague allochem ghosts in hypidiomorphic, medium crystalline dolomite; there is a tendency for some of the ghosts to assume a rhomb-shaped zone within the dolomite (pp. 107, 109, 115, 743). The black interstitial areas are dead oil. Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,033 feet. (x42)

B. Zoned dolomite with idiomorphic crystals embedded in a clay matrix (p. 108). Gulf Oil Corporation No. 1 Texas "000," Andrews County, Texas, 12,495 feet. (x28)

C. Small dolomite rhombs embedded in chert composed of microcrystalline quartz (dark groundmass). A few large dolomite crystals have later replaced the chert with the small dolomite crystals persisting as unaltered inclusions within the large dolomite crystals (pp. 108, 792). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,236 feet. (x60, crossed nicols)

D. Semicomposite, coarsely crystalline dolomite, showing ragged edges of large mosaics and the fine-grained blocky structure of the aggregate (pp. 108, 745). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,125 feet. (x60, crossed nicols)

E. Semicomposite, coarsely crystalline dolomite with oolite or intraclast ghosts (pp. 108, 109, 747). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,219 feet. (x42, crossed nicols)

F. Zoned, hypidiomorphic dolomite crystals; darker central zone caused by abundant liquid-filled vacuoles (pp. 108, 771). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,079 feet. (x75)

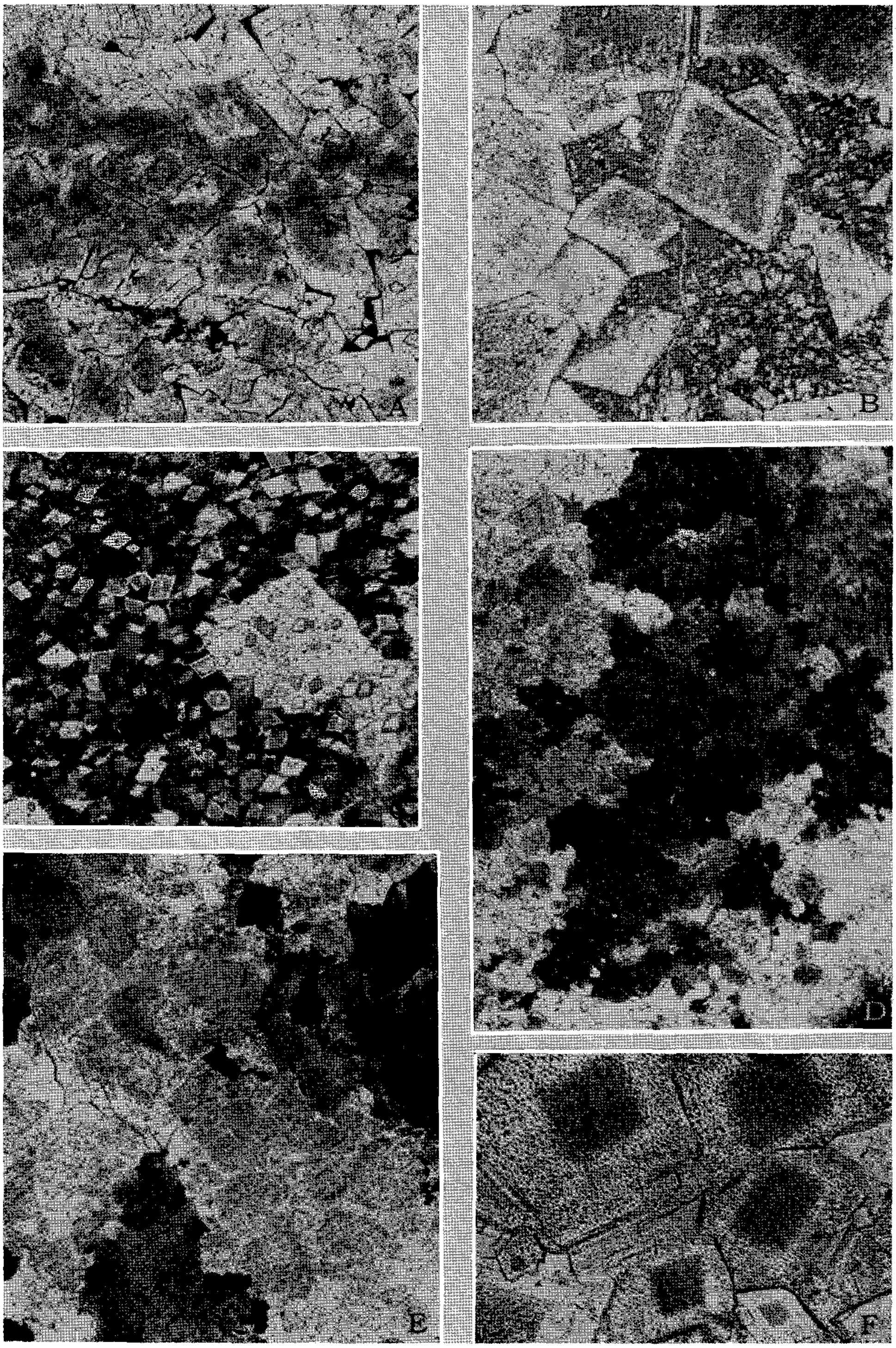
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PLATE 42

Photomicrographs of Ellenburger rocks

A. Zoned dolomite crystal (p. 108). Continental Oil Company No. 1 Burger B-28, Lea County, New Mexico, 9,288 feet. (x200)

B. Zoned dolomite (pp. 108, 770). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,001 feet. (x75)

C. Intraclast ghosts preserved as "cloudy" (actually bubbly) inclusions in large dolomite rhomb; ghosts have been destroyed in the finely crystalline dolomite surrounding the large rhomb. This illustrates the principle that allochem structures in a limestone may be preserved on replacement by coarse dolomite but obliterated if the rock is replaced by finer dolomite (pp. 109, 794). Wilshire Oil Company No. 23–118 Windham, Upton County, Texas, 12,701 feet. (x42)

D. Same as "C." Wilshire Oil Company No. 23–118 Windham, Upton County, Texas, 12,701 feet. (x34, crossed nicols)

E. Intraclastic limestone replaced by coarsely crystalline dolomite with intraclast ghosts preserved only in centers of dolomite crystals; ghosts have vanished in the rims of the crystals (pp. 109, 742). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 8,955 feet. (x34, crossed nicols)

F. Large dolomite crystal replacing calcitic pellets and intraclasts; ghosts are preserved only in central part of the crystal and are obliterated in the outer rim (pp. 109, 742). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 8,955 feet. (x50)

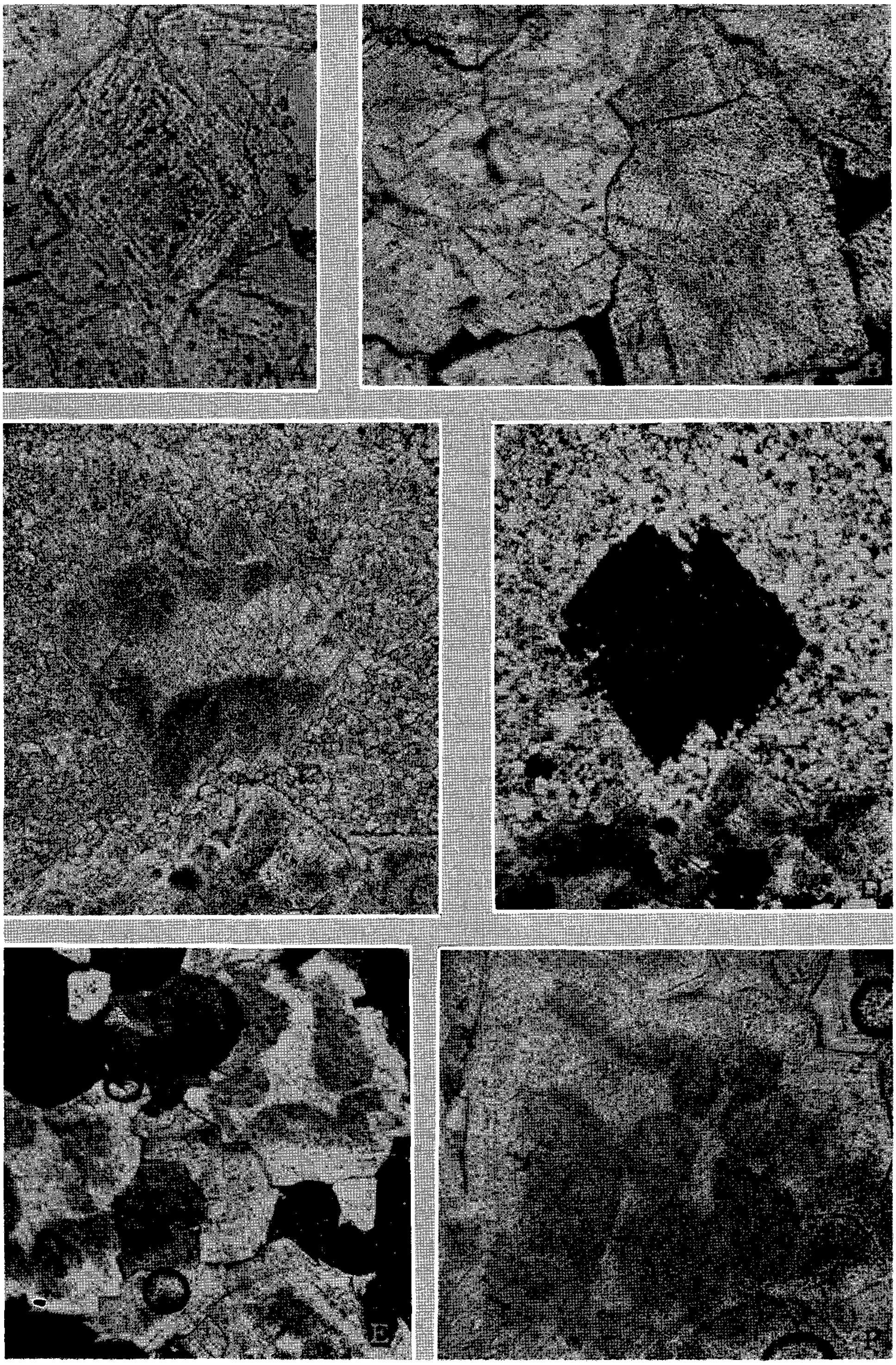

PLATE 43

Photomicrographs of Ellenburger rocks

A. Coarsely crystalline dolomite replacement of a pellet limestone. Pellet ghosts are preserved only in central rhombic zones of dolomite crystals (preservation visible because of a swarm of undigested microcrystalline calcite inclusion in the dolomite). The outer rhombic zone of the dolomite crystals is clear. This photograph illustrates the principle that a previous limestone structure sometimes is preserved and sometimes is destroyed by dolomitization, with a difference in degree of preservation even within the very same dolomite crystal (pp. 109, 790). The Superior Oil Company No. 1-27 University, Crockett County, Texas, 7,068 feet. (x75)

B. Chert (microcrystalline quartz) with large dark intraclasts, formerly limestone. Spaces between intraclasts are filled with megaquartz in radiating crusts, indicating that silicification of the intraclasts took place prior to cementation by calcite (pp. 110, 789). Gulf Oil Corporation No. 1 Texas "000", Andrews County, Texas, 12,689 feet. (x34, crossed nicols)

C. Chert oolites (some with quartz sand grain nuclei) surrounded by a thin rim of radiating quartz crystals; remaining space between oolites filled with sparry calcite deposited after the quartz. Oolites were apparently replaced by chert before being cemented (p. 110). The Superior Oil Company No. 1-27 University, Crockett County, Texas, 7,238 feet. (x42)

D. Same as "C." The Superior Oil Company No. 1-27 University, Crockett County, Texas, 7,238 feet. (x34, crossed nicols)

E. Chert replacement of a limestone originally consisting of pellets (pelsparite). The strip along the right margin of the photograph is dolomite, and here the original pellet texture is obliterated (pp. 110, 772). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,186.5 feet. (x34, crossed nicols)

F. Chert showing vague ghosts of the pellet texture of the original limestone, which it has replaced. The faint gently curving near-vertical arcs are banding concentric with the margin of the chert nodule and have developed after replacement by some diffusion process (p. 110). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,186.5 feet. (x16)

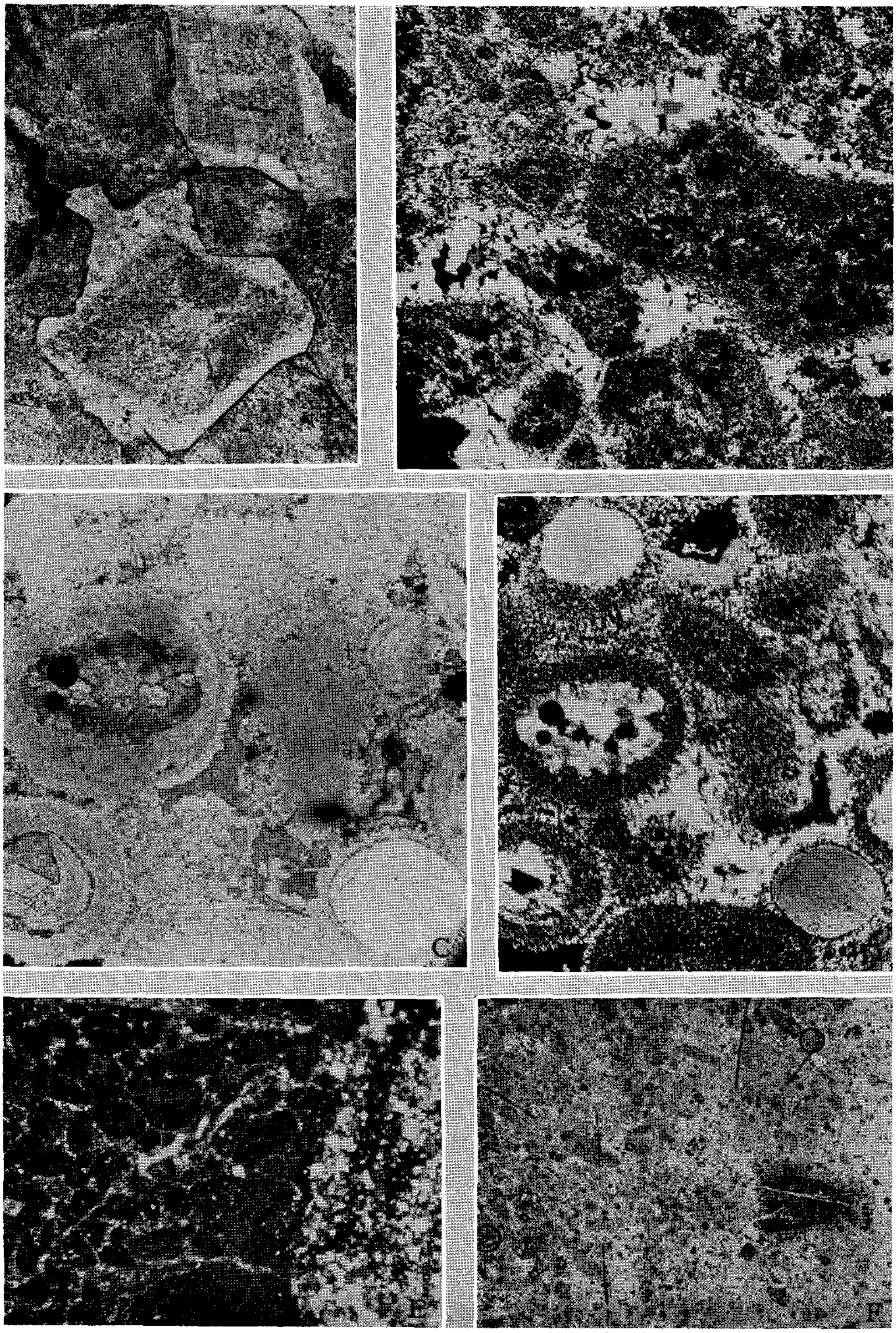
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PLATE 44

Photomicrographs of Ellenburger rocks

A. Concentrically banded chert nodule (left half of photograph) embedded in dolomite. Bedding continues almost horizontally through chert and is not deflected in approaching the margin of the nodule; this indicates that the chert formed in situ by replacement. The concentric banding is not caused by a "snowballing" method of accretion but is an epigenetic feature, probably similar in origin to diffusion banding. The bedding in the dolomite bends in passing over the chert, indicating the chert was probably less compactable (pp. 110, 796). Phillips Petroleum Company No. 1 Glenna, Pecos County, Texas, 13,977 feet. (x4)

B. Quartz spherulites (clear) with intricately scalloped margins, replacing dolomite (p. 111). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,204 feet. (x16)

C. Detail of a quartz spherulite replacing dolomite (p. 111). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,204 feet. (x28)

D. Same as "C." The quartz spherulite has flamboyant structure. The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,204 feet. (x23, crossed nicols)

E. Quartz spherulite with radial structure (pp. 111, 737). Gulf Oil Corporation No. 1 Mitchell Bros. —State, Presidio County, Texas, 15,856 feet. (x12, crossed nicols)

F. Same as "E." Margins of the quartz spherulites are convex toward the dolomite. Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,856 feet. (x16, ordinary light)

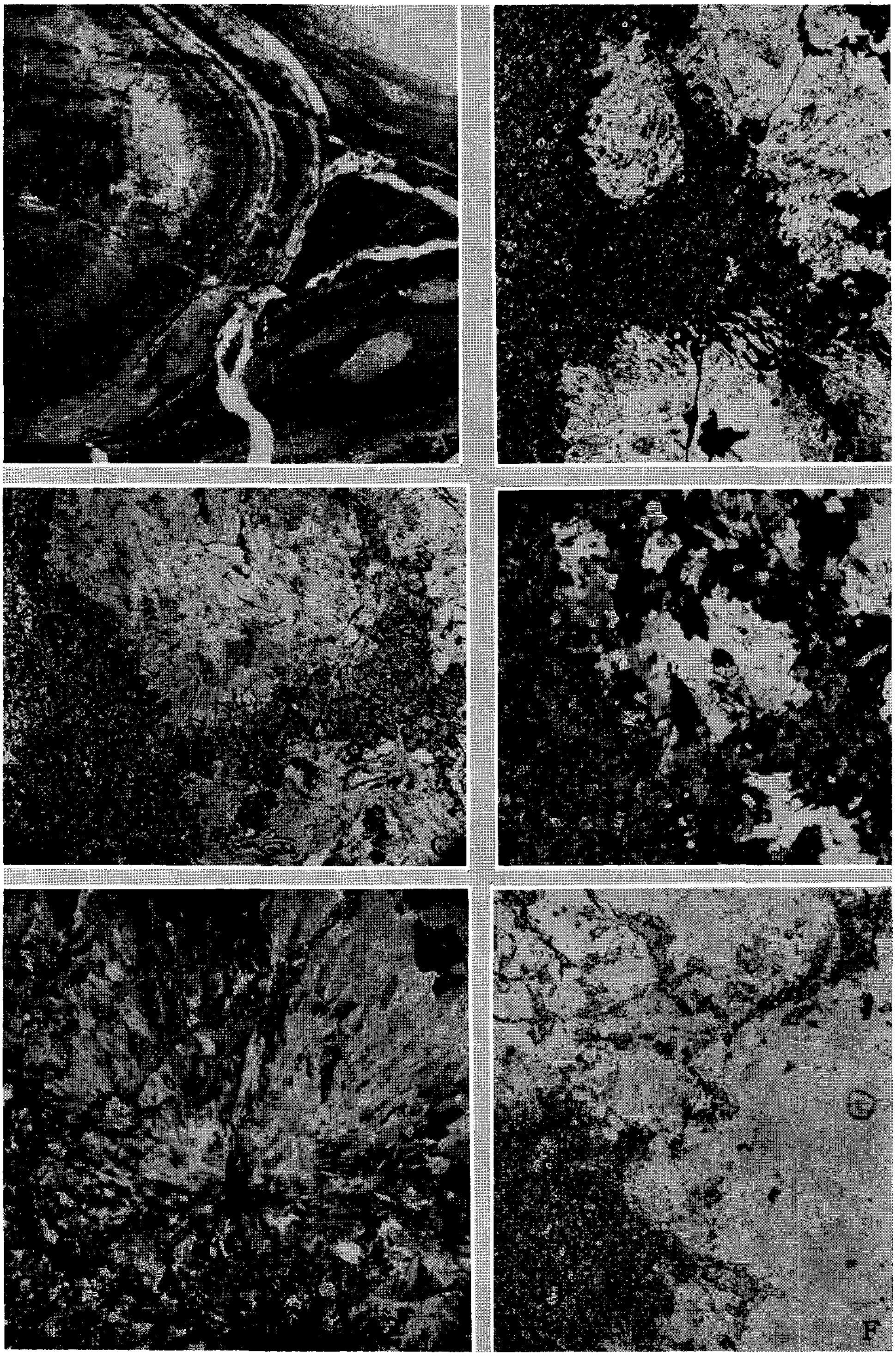
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PLATE 45

Photomicrographs of Ellenburger rocks

A. Typical quartz spherulite with flamboyant, radiating structure (pp. 111, 757). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,588 feet. (x34, crossed nicols)

B. Chert spherulites, composed of microcrystalline quartz, replacing dolomite. Spherulites have scalloped margins convex toward dolomite and contain concentric bubble bands (pp. 111, 747). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,227 feet. (x75)

C. Small chert spherulites with flamboyant to chalcedonic extinction, replacing dolomite (pp. 111, 747). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,227 feet. (x60, crossed nicols)

D. Chert composed of microcrystalline quartz replacing medium to finely crystalline dolomite. The chert shows many crenulate margins convex toward the dolomite (pp. 111, 114). Black specks are liquid-filled cavities. Sinclair Oil & Gas Company No. 9 McElroy, Upton County, Texas, 12,274 feet. (x42)

E. Chert composed of clear microcrystalline quartz replacing dolomite, with crenulate margin resulting from corrosion of the dolomite. A faint fibrous structure visible in the chert possibly indicates that the chert previously replaced gypsum (pp. 111, 114). Sinclair Oil & Gas Company No. 9 McElroy, Upton County, Texas, 12,274 feet. (x75)

F. Chert composed of microcrystalline quartz with pinpoint birefringence (upper part of photograph) replacing finely crystalline dolomite (pp. 111, 114). Sinclair Oil & Gas Company No. 9 McElroy, Upton County, Texas, 12,274 feet. (x34, crossed nicols)

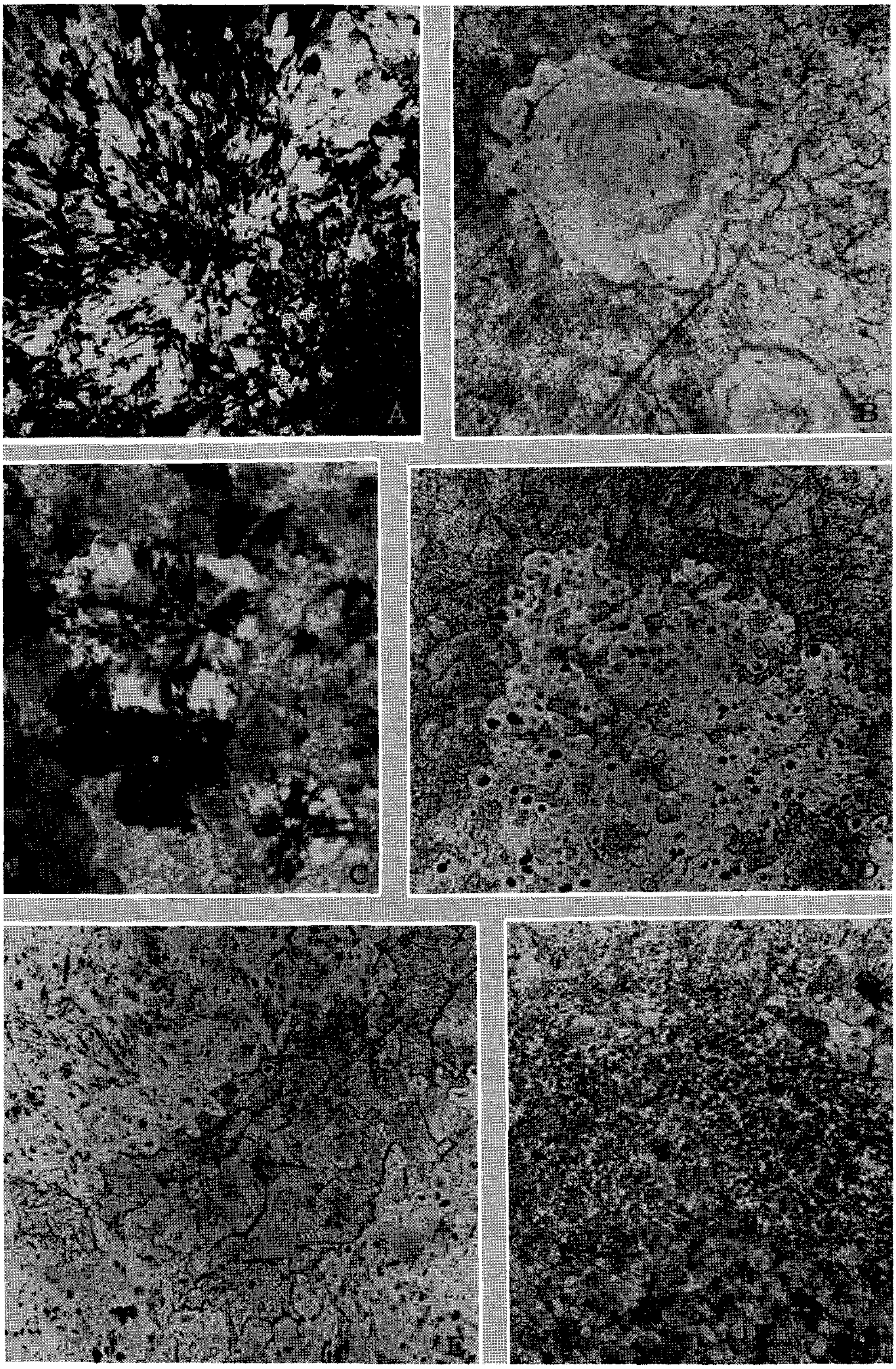
A
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PLATE 46

Photomicrographs of Ellenburger rocks

A. Radiating barite laths filling a cavity in dolomite (pp. 111, 792). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,321(?) feet. (x12, crossed nicols)

B. Cavity filled with anhydrite laths and rhombic dolomite crystals. Black and white speckled areas are small masses of microcrystalline quartz which have replaced the anhydrite (p. 111). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,829 feet. (thin section A, x60, crossed nicols)

C. Anhydrite laths filling a cavity in dolomite (pp. 111, 733). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,621 feet. (x34, crossed nicols)

D. Pseudomorphs of dolomite after an unknown mineral. Photograph shows general shape of the pseudomorphs with dark pellet ghosts concentrated along the bottom side of all pseudomorphs (p. 111). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,326 feet. (x7)

E. Pseudomorphs of dolomite after an unknown mineral. Pellet ghosts are clustered along the bottom side of the pseudomorph as if they had fallen as more insoluble material during solution of the original mineral. The pseudomorph is now filled with dolomite which only partially closes the cavity (p. 111). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,325 feet. (x11)

F. Pseudomorphs of dolomite after an unknown mineral. The centers of the pseudomorphs remain unfilled; the dolomite is of encrusting character and has mosaic extinction (p. 111). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,325 feet. (x8, crossed nicols)


C
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PLATE 47

Photomicrographs of Ellenburger and Arbuckle rocks

A. Biomicrite (consisting of arcuate fossils in a microcrystalline calcite matrix) now almost completely replaced by finely crystalline dolomite. Dolomite crystals tend to avoid but occasionally transect fossils (p. 108). Sinclair Oil & Gas Company No. 9 McElroy, Upton County, Texas, 12,197 feet. (x42)

B. A large patch of medium crystalline dolomite replacing microcrystalline calcite (micrite) (pp. 108, 783). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 10,679 feet. (x42)

C. Calcite replacing dolomite. The crystals have the rhombic external form of dolomite but now consist of a calcite mosaic. Every transition can be traced from relatively pure dolomite rhombs, to rhombs filled with calcite inclusions, to dolomite rhombs completely calcitized (pp. 112, 791). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,114 feet. (x75)

D. Dolomite rhombs replaced by a mosaic of sparry calcite. This rock at one time was composed of idiomorphic dolomite crystals embedded in chert (clear) (pp. 112, 792). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,238 feet. (x50)

E. Same as "D." The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,238 feet. (x42, crossed nicols)

F. Contact between pellet-bearing limestone (upper half of photograph) and chert nodule (lower half). The chert replaced the limestone and preserved the pellet structure (p. 112). Cherokee Creek section, 900 feet above base. (thin section A, x42)

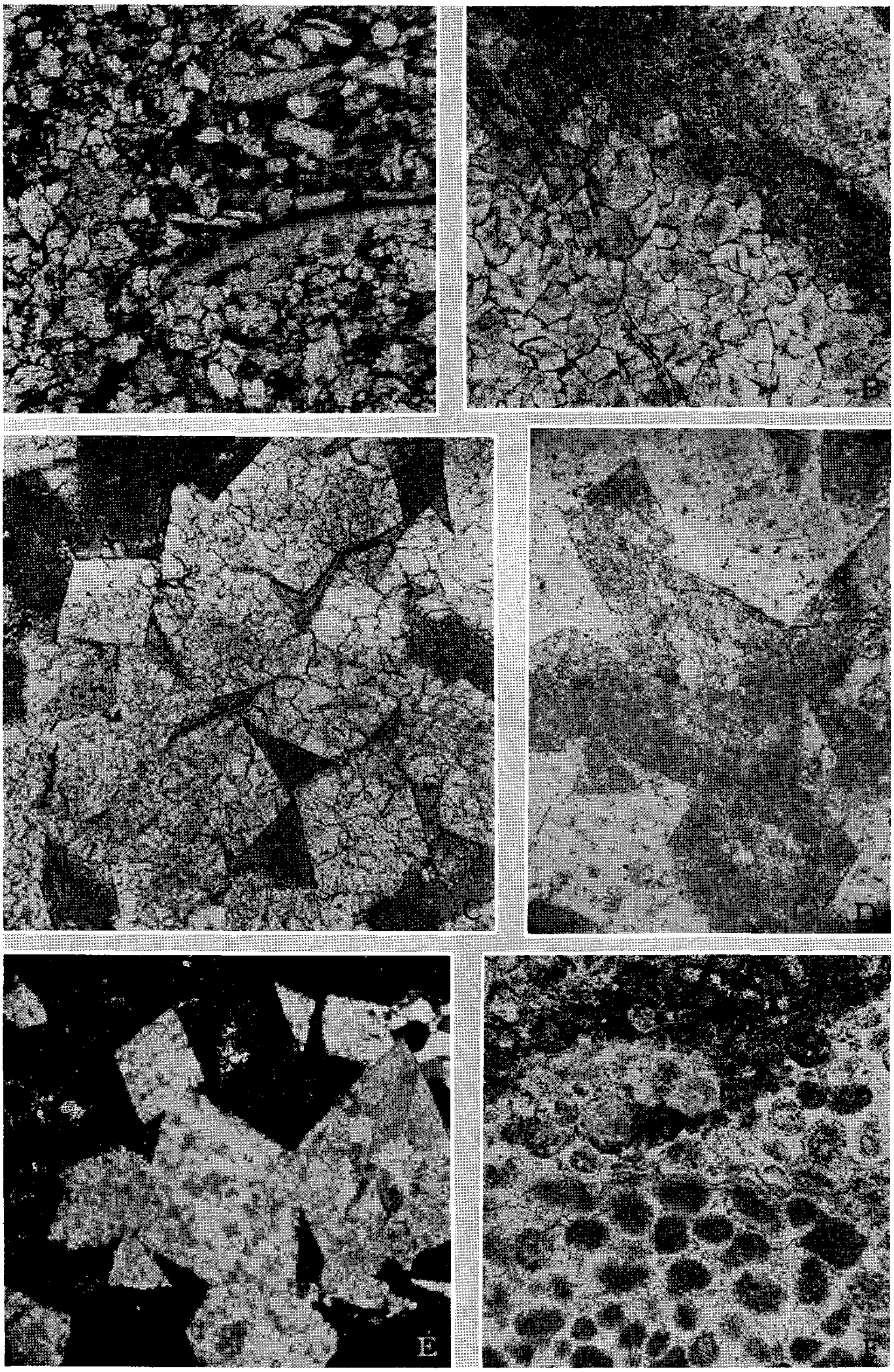
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PLATE 48

Photomicrographs of Ellenburger rocks

A. Chert replacement of an intraclastic limestone (pp. 112, 801). Skelly Oil Company No. 1 Ater, Nolan County, Texas, 7,084 feet. (x42)

B. Same as "A." The coarse quartz mosaic between the intraclasts, which are composed of microcrystalline quartz, is interpreted as having formed by direct precipitation of quartz into pore space, after the intraclasts were replaced by chert (p. 801). Skelly Oil Company No. 1 Ater, Nolan County, Texas, 7,084 feet. (x34, crossed nicols)

C. A chert nodule containing tiny inclusions of dolomite rhombs has been fractured; calcite has filled the fractures and "spilled out" to replace some of the adjoining chert (pp. 113, 772). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,126 feet. (x42)

D. Calcite vein (light band with parallel sides) transecting chert nodule. Calcite crystals have spread out from the vein and replaced the adjoining chert; this calcite appears nearly black because it contains abundant undigested chert inclusions, which cause a pseudo-pleochroism (pp. 113, 788). Gulf Oil Corporation No. 1 McElroy-State, Upton County, Texas, 12,145 feet. (x28)

E. Oolites, composed of microcrystalline quartz, surrounded by calcite bands, all in optical continuity (white areas); remaining pore space filled with megaquartz. Apparently calcite oolites were replaced by chert before being cemented; then the pores were filled by calcite, followed by quartz (pp. 113, 794). Wilshire Oil Company No. 23-118 Windham, Upton County, Texas, 12,724 feet. (x34, crossed nicols)

F. Chert oolites surrounded by a rim of tiny calcite crystals (high relief) and finally by megaquartz (pp. 113, 775). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,414 feet. (x50)

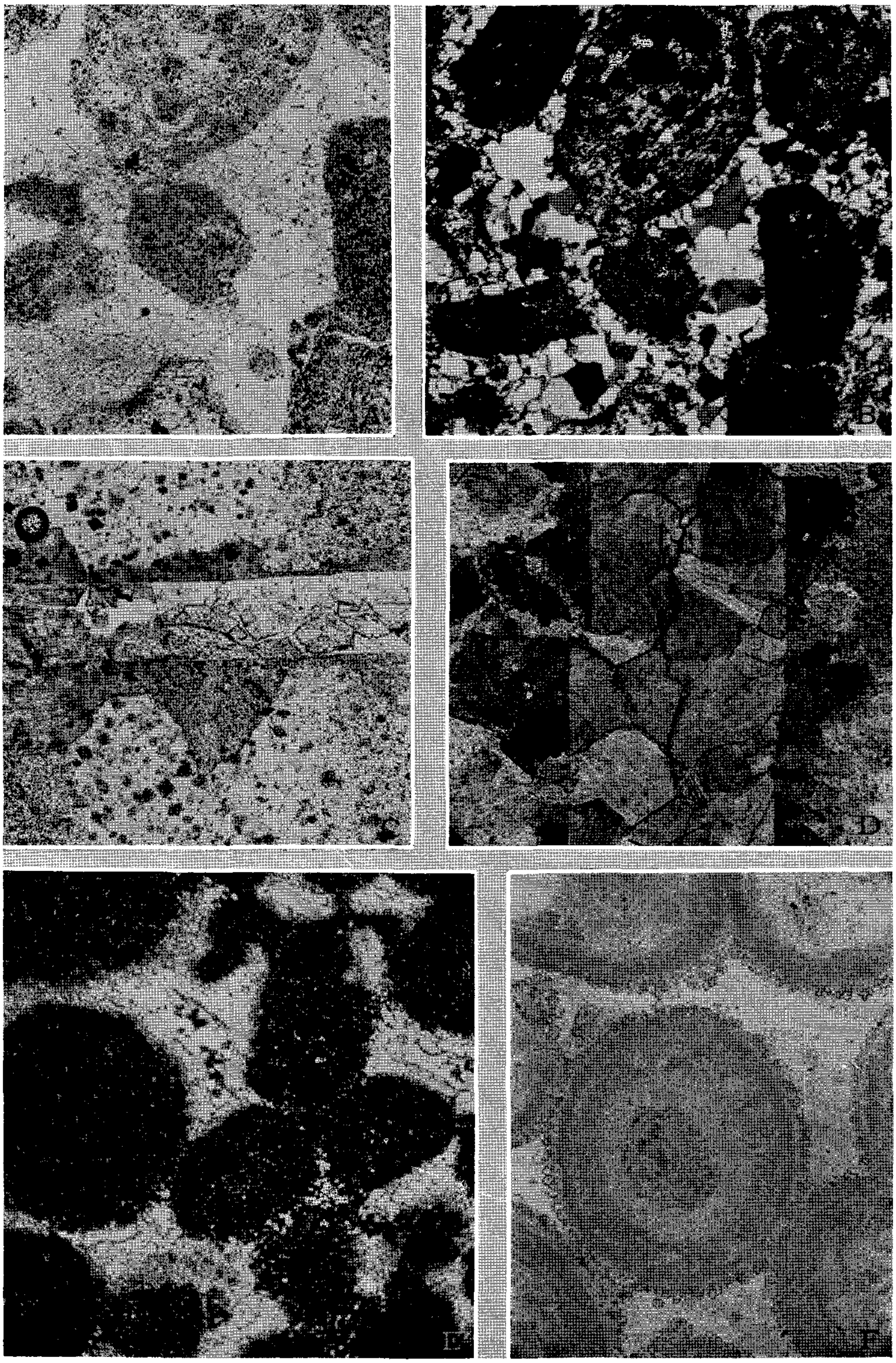
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PLATE 49

Photomicrographs of Ellenburger rocks

A. Fractured chert nodule (light gray groundmass) replaced by dolomite "spilling out" from fractures. The dolomite is intensely "pleochroic" (compare "B") because of abundant undigested chert inclusions (p. 113). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,323 feet. (x75)

B. Same as "A," stage rotated 90 degrees to illustrate "pleochroism." Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,323 feet. (x75)

C. Oolites, composed of microcrystalline quartz, cemented by large masses of calcite in optical continuity; the calcite has "spilled over" and replaced the edges of some of the oolites to form intensely "pleochroic" or spongy calcite crystals (dark) (p. 113). Wilshire Oil Company No. 23–118 Windham, Upton County, Texas, 12,724 feet. (x42)

D. Same as "C," stage rotated 90 degrees to illustrate "pleochroism." Wilshire Oil Company No. 23–118 Windham, Upton County, Texas, 12,724 feet. (x42)

E. Originally this was an oolitic limestone. The oolites were replaced by chert, then dark irregular areas of dolomite (in optically continuous units) replaced the chert, preserving the concentric structure of the chert (pp. 113, 748). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,233 feet. (x75)

F. Same as "E." The ragged dolomite areas have uniform optical orientation. Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,233 feet. (x60, crossed nicols)

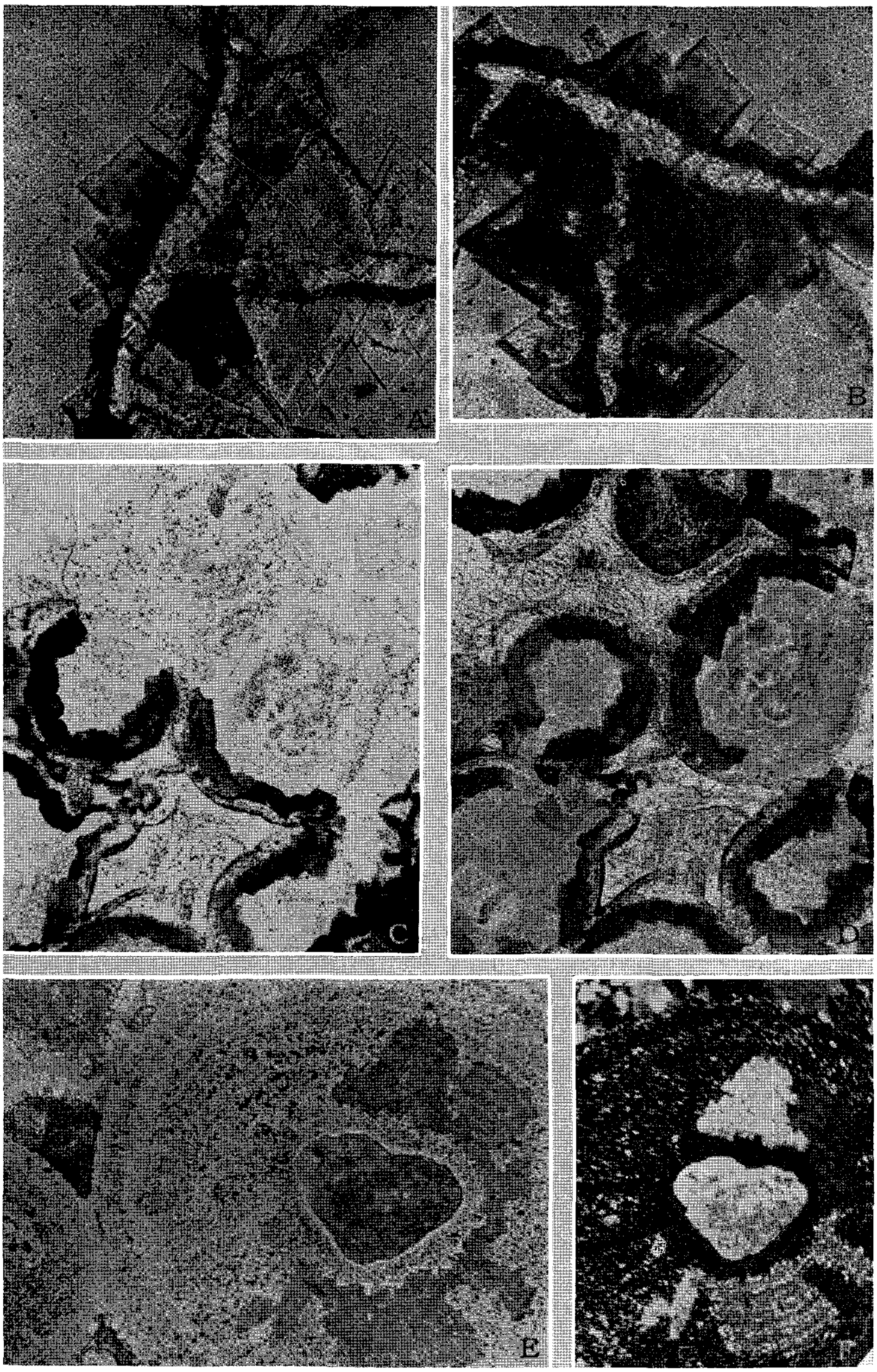
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PLATE 50

Photomicrographs of Ellenburger rocks

A. Microcrystalline quartz pseudomorphous after dolomite. Rhomb ghosts are plainly visible (pp. 113, 755). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,495 feet. (x75)

B. Coarse-grained microcrystalline quartz pseudomorphous after dolomite rhombs, embedded in a chert nodule composed of more finely grained microcrystalline quartz (pp. 113, 755). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,495 feet. (x60, crossed nicols)

C. Dolomite crystals in chert. Dolomite crystals consist of an outer, fairly idiomorphic "wall," separated by a "moat" of chert from a seemingly corroded dolomite nucleus (pp. 113, 752). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,373 feet. (x75)

D. Dolomite crystals in chert. The dolomite crystals contain a chert center or chert "moat" surrounding a dolomite nucleus (pp. 113, 752). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,373 feet. (x60, crossed nicols)

E. Dolomite crystals irregularly corroded and channeled because of replacement by chert, which forms the main part of the photograph (p. 114). Gulf Oil Corporation No. 1 Texas "000," Andrews County, Texas, 12,557 feet. (x75)

F. Dolomite rhombs corroded because of replacement by chert (p. 114). Gulf Oil Corporation No. 1 Texas "000," Andrews County, Texas, 12,542 feet. (x75)

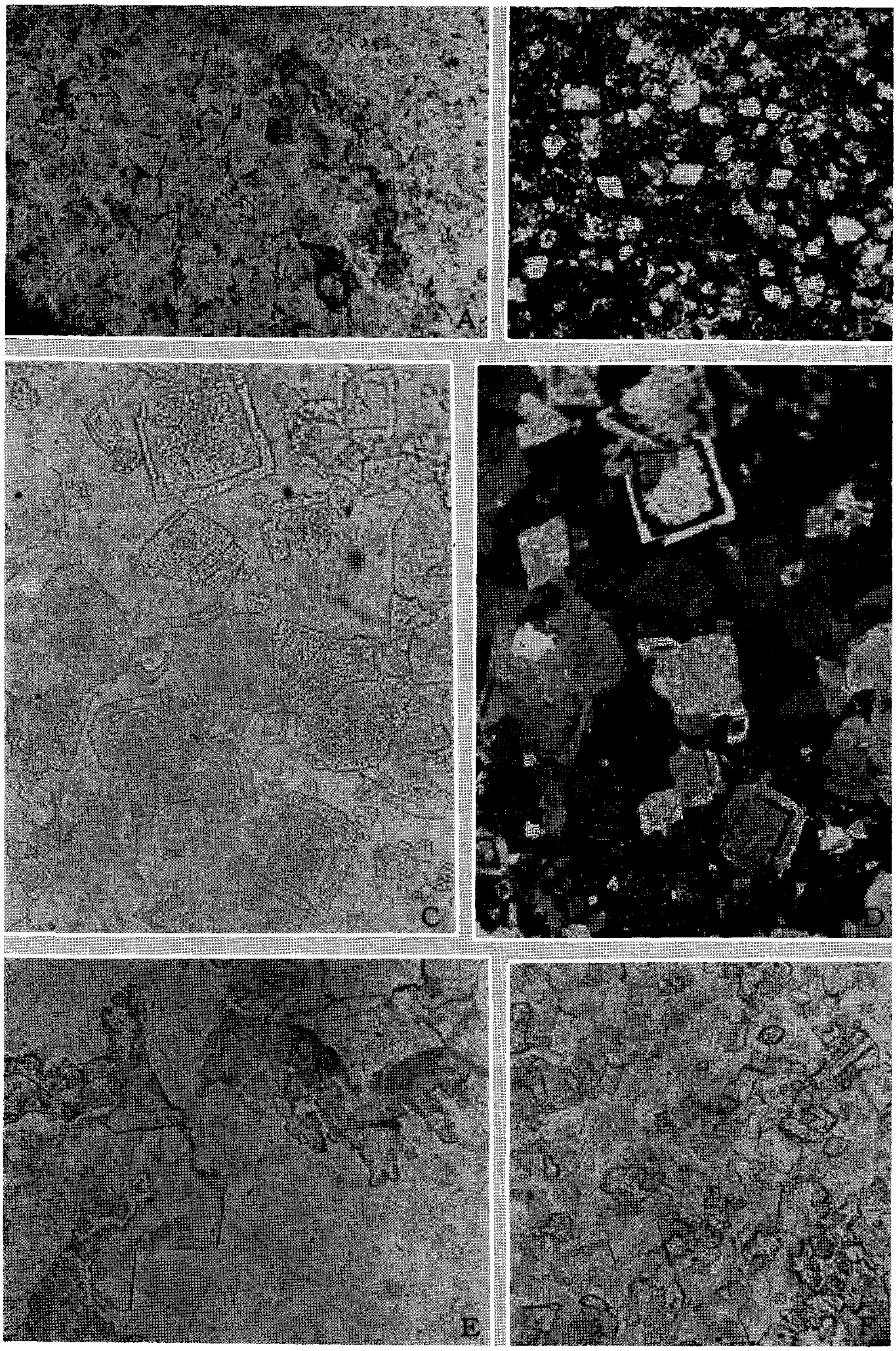
A
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PLATE 51

Photomicrographs of Ellenburger rocks

A. Typical laminated finely to very finely crystalline dolomite (p. 114). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,345 feet. (x16)

B. Slump structures in soft sediment, shown by varying crystal size of dolomite (p. 115). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,282 feet. (x11)

C. Tectonic fracture filled with quartz crystals growing perpendicular to fissure walls (p. 115). Magnolia Petroleum Company No. 2-A Windham, Midland County, Texas, 13,058 feet. (thin section A, x23, crossed nicols)

D. Phantom quartz crystals showing flamboyant extinction. This is a tectonic vein filling (pp. 115, 752). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,330 feet. (x23, crossed nicols)

E. Slumped or brecciated dolomite (p. 115). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,301 feet. (x28)

F. Brecciated chert, probably a tectonic vein filling (p. 115). The Superior Oil Company No. 1-27 University, Crockett County, Texas, 7,243 feet. (x42)

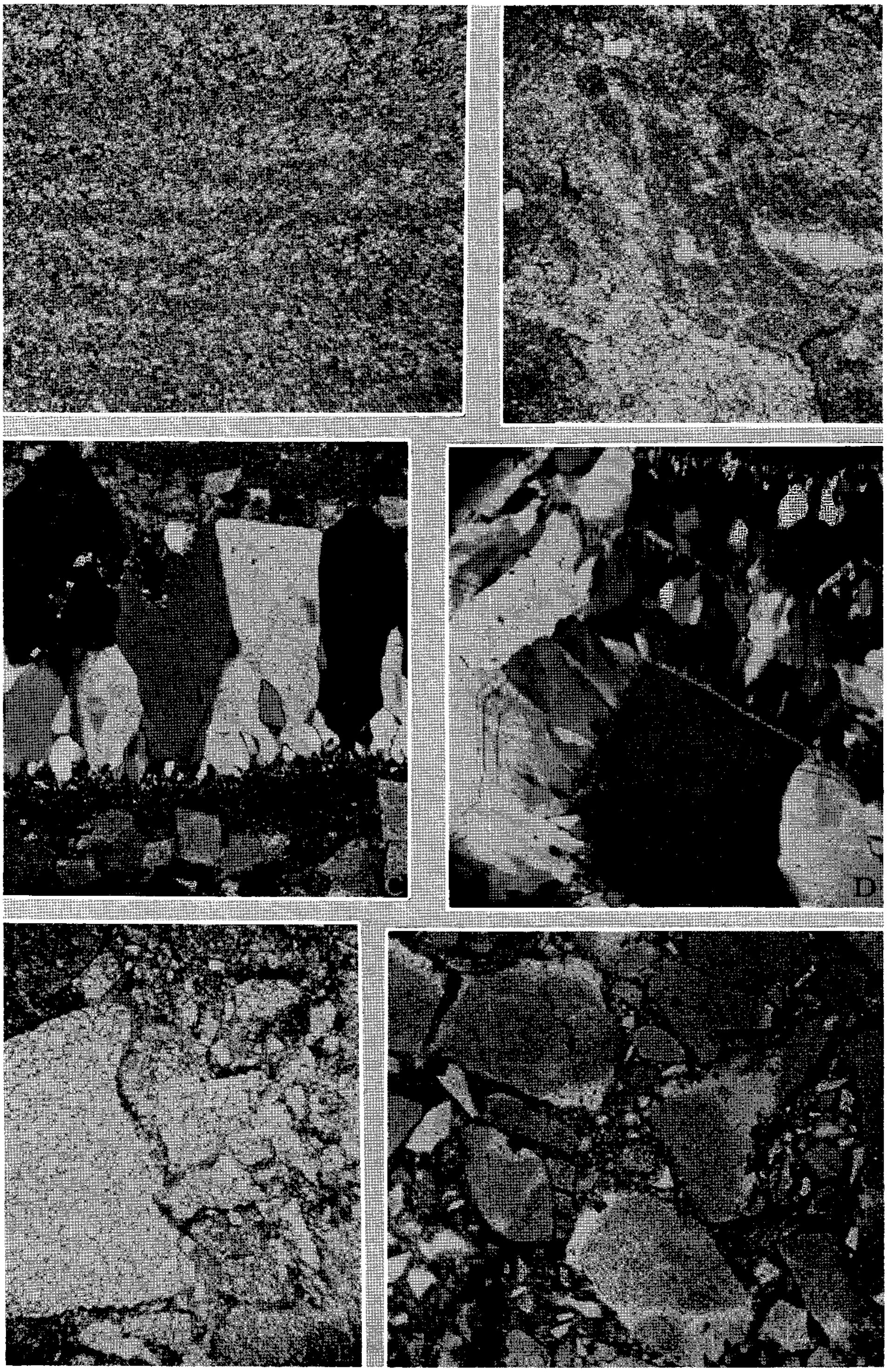
D

PLATE 52

Photomicrographs of Ellenburger rocks

A. This microcrystalline limestone (micrite) was partially dolomitized along certain laminae (light); these laminae were then broken apart (during slumping?) and the more plastic micrite squeezed into the openings (pp. 115, 771). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,112 feet. (x11)

B. Probable clastic dike, with rhythmic clayey bands, in dolomite. Both host rock and dike contain much quartz silt (pp. 115, 759). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,602 feet. (thin section B, x16)

C. Vein filled with clay and lined with large, clear dolomite crystals (pp. 115, 741). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 8,948 feet. (x11)

D. Clay-filled vein lined with clear dolomite crystals, which jut into the clay. Rounded fragments of finely crystalline dolomite are detached from the parent rock (pp. 115, 743). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,016 feet. (x11)

E. Clastic dike (?) in finely crystalline laminated dolomite. The dike is filled with clay and finely broken dolomite and is cut by a later tectonic joint filled with clear calcite (p. 115). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,301 feet. (x11)

F. Stylolites in medium crystalline dolomite, filled with black clayey material (p. 115). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 14,143 feet. (x16)

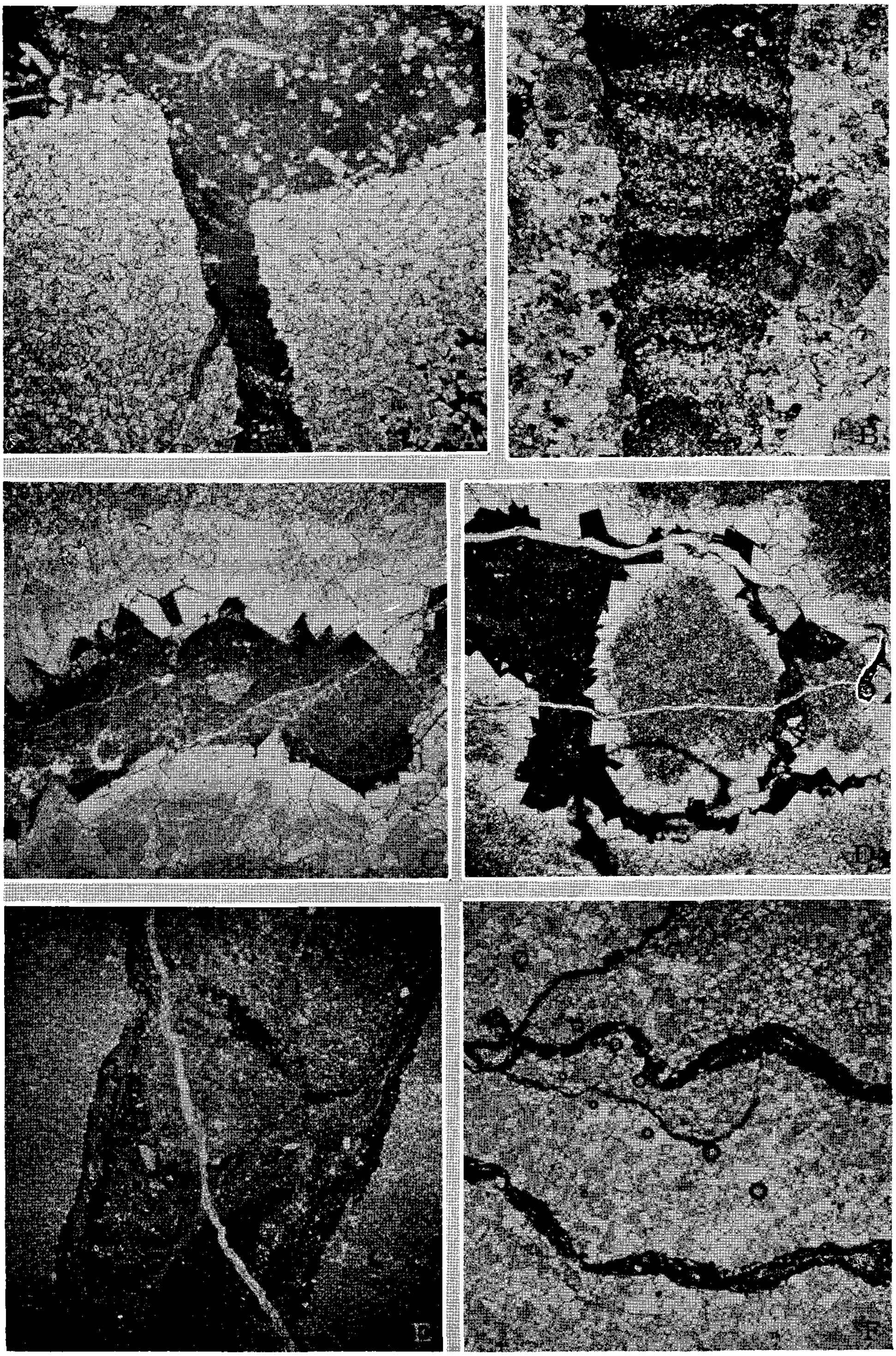

PLATE 53

Photomicrographs of Ellenburger and Arbuckle rocks

A. Stylolites and incipient stylolites in finely crystalline dolomite (p. 115). Phillips Petroleum Company No. 1 Glenna, Pecos County, Texas, 14,004 feet. (x42)

B. Detrital quartz grains sutured by solution along stylolites (p. 115). Wilshire Oil Company No. 14–130 McElroy, Upton County, Texas, 12,063 feet. (thin section C, x75)

C. Detrital quartz grains interpenetrating because of post-depositional solution (pp. 115, 778). Phillips Petroleum Company No. 1 Wilson, Val Verde County, Texas, 16,456 feet. (x40, crossed nicols)

D. Stylolite cutting indiscriminantly across detrital quartz grains and finely to very finely crystalline dolomite (p. 115). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,369 feet. (x42)

E. This rock apparently was originally a biomicrite consisting of fossils (curving strips) embedded in microcrystalline calcite ooze (dark areas). Parts of the micrite matrix were later dissolved out and refilled with sparry calcite (irregular clear areas) (pp. 116, 798). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,237 feet. (x28)

F. Porosity developed by solution of the microcrystalline ooze matrix of an intramicrite. Large, rounded objects are intraclasts (one intraclast consists of pelsparite). The irregular pores are now filled with sparry calcite and dolomite (clear) (pp. 116, 798). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,237 feet. (x28)

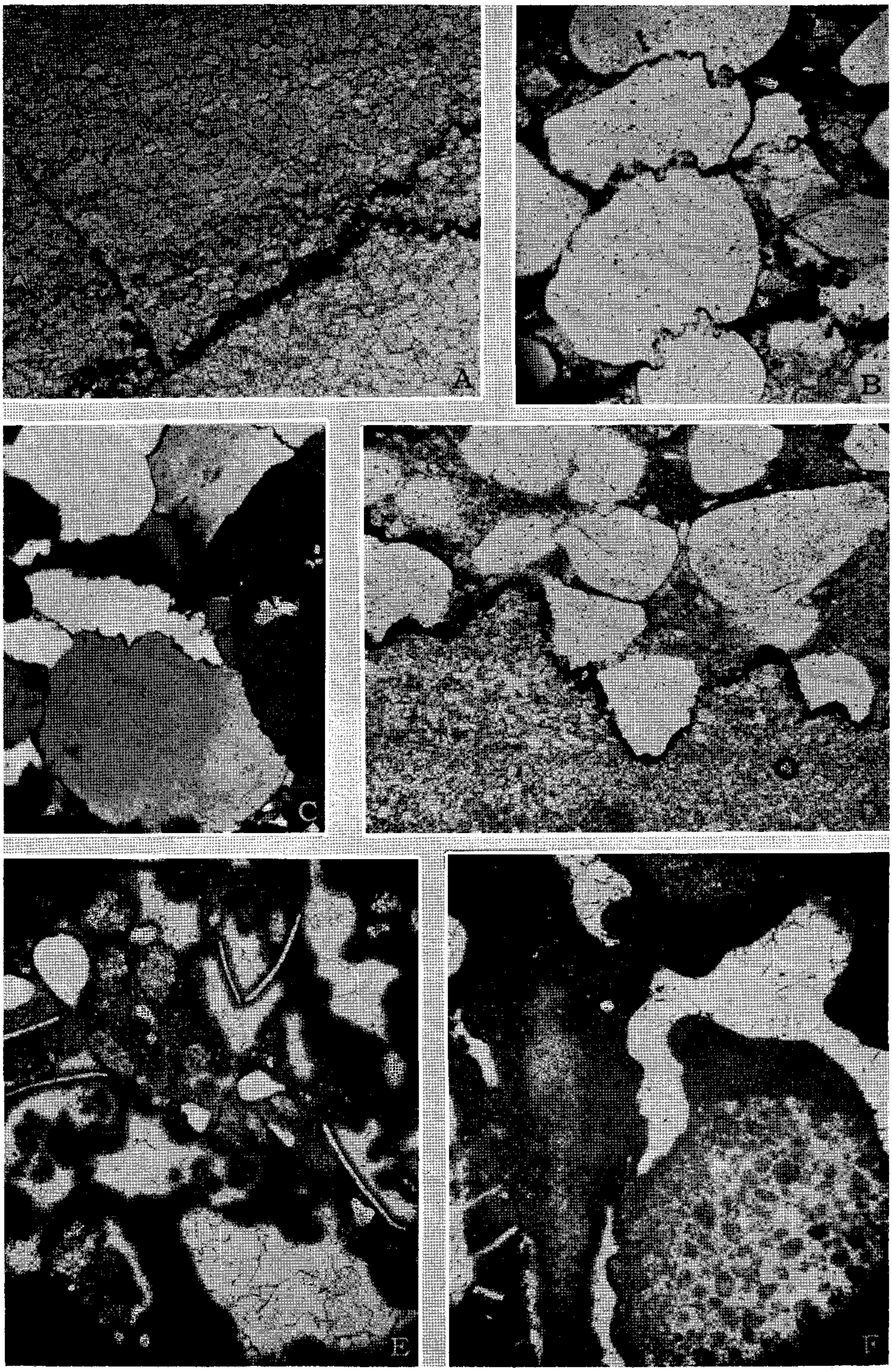
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PLATE 54

Photomicrographs of Ellenburger rocks

A. Pores developed in the center of oolite ghosts. This was formerly an oolitic limestone but has been completely replaced by medium crystalline dolomite (p. 116). Phillips Petroleum Company No. 1 Glenna, Pecos County, Texas, 14,201 feet. (x42)

B. Porosity developed by solution of oolites (possibly calcitic) in a dolomite matrix (p. 116). Richardson & Bass No. 1 Federal-Cobb, Eddy County, New Mexico, 16,090 feet. (x28)

C. Elongated cavities and filled cavities in medium crystalline dolomite, possibly representing a dolomitized algal reef. One of the cavities is filled with calcite, the other is empty (pp. 116, 790). The Superior Oil Company No. 1-27 University, Crockett County, Texas, 7,056 feet. (x16)

D. Intraclast ghosts(?) filled by dolomite (rhombic crystals), calcite, and occasionally anhydrite laths. These are all cavity fillings, not replacements (p. 116). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,829 feet. (thin section A, x11)

E. Irregular solution(?) cavities in dolomite filled with clearer, more coarsely crystalline dolomite (pp. 116, 747). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,167 feet. (x16)

F. Large pores in finely crystalline dolomite lined first by dead oil (black), then pore completely filled by clear, more coarsely crystalline dolomite (p. 116). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,312 feet. (x75)

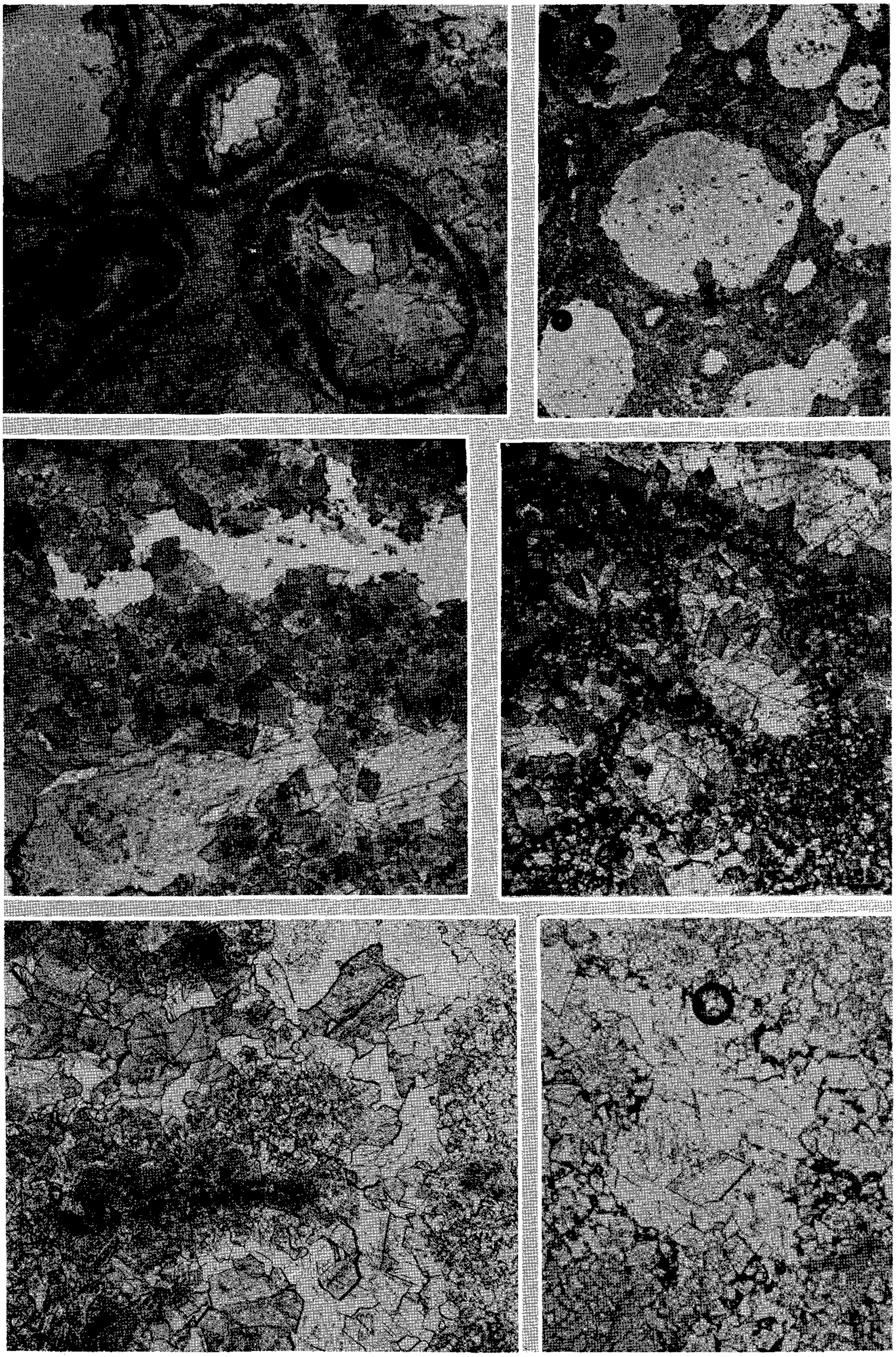

PLATE 55

Photomicrographs of Ellenburger and Arbuckle rocks

A. Dead oil (black) impregnating concentric bands in chalcedony spherulites. The bulk of the rock consists of chertified intraclasts (p. 116). Magnolia Petroleum Company No. 2-A Windham, Midland County, Texas, 12,906.5 feet. (x50)

B. Fractures in medium to finely crystalline dolomite filled with dead oil (black) (p. 116). Phillips Petroleum Company No. 1 Glenna, Pecos County, Texas, 14,489 feet. (x42)

C. Intrasparite, consisting of intraclasts cemented by medium crystalline sparry calcite. The intraclasts are themselves composed of finer grained pelsparite and intrasparite (pp. 123, 780). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,697 feet. (x28)

D. Oosparite, consisting of oolites cemented by sparry calcite (p. 123). Humble Oil & Refining Company No. 1-C Alma Cox, Crockett County, Texas, 8,417 feet. (x42)

E. Biomicrite, consisting of fossils embedded in microcrystalline calcite (pp. 124, 780). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,682 feet. (x42)

F. Biosparite, consisting of fossils cemented with sparry calcite. A few intraclasts and one oolite are also visible (p. 124). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas. 3,905.5 feet. (x42)

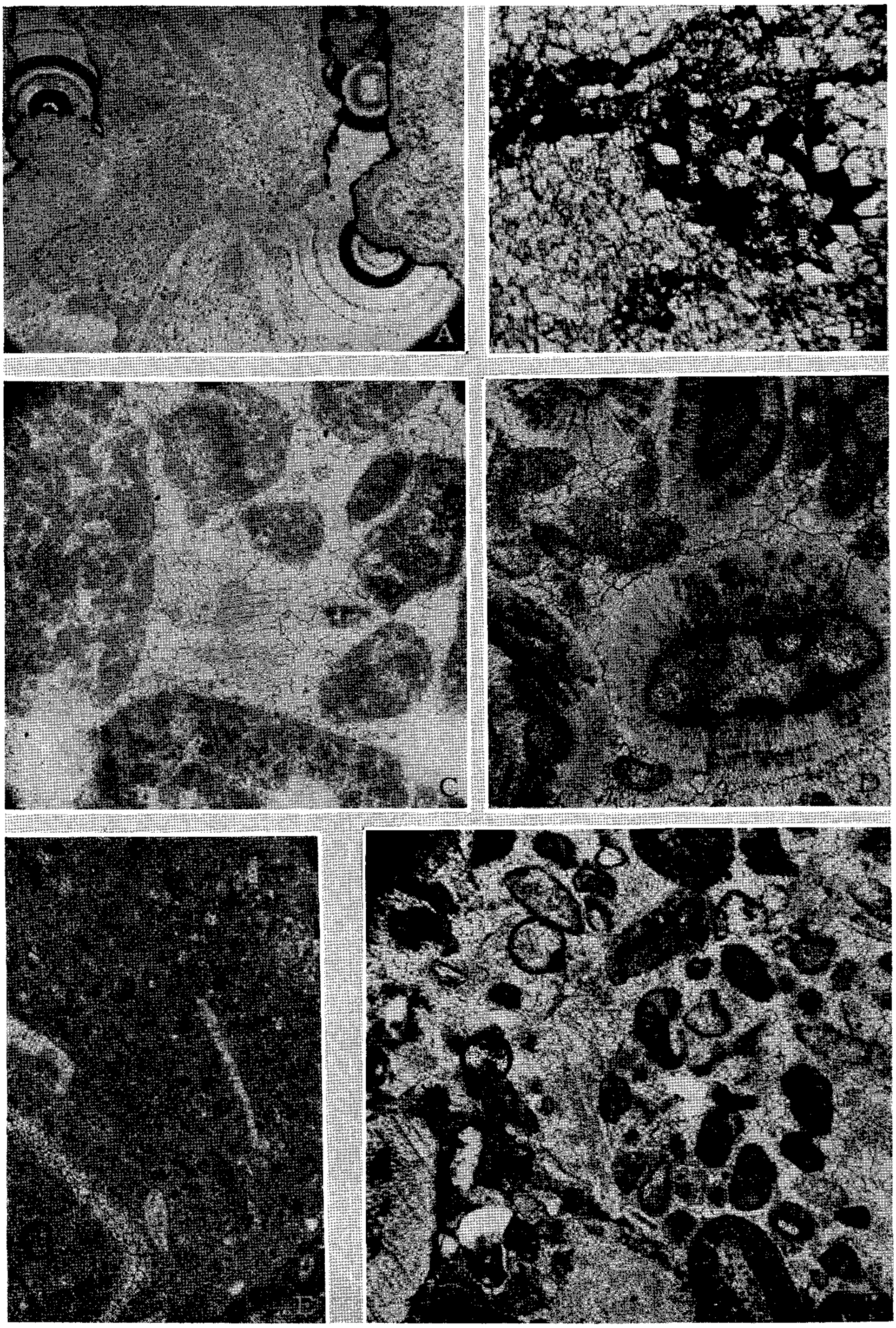
A
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PLATE 56

Photomicrographs of Ellenburger and Arbuckle rocks

A. Pelsparite, consisting of pellets cemented by sparry calcite (pp. 124, 781). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,718 feet. (x42)

B. Micrite, consisting of homogeneous microcrystalline calcite with a few thin and irregular clay seams (pp. 124, 781). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 10,233 feet. (x42)

C. Dismicrite, consisting of microcrystalline calcite ooze (dark) probably disturbed by boring organisms (pp. 124, 773). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,256.5 feet. (x42)

D. Idiomorphic dolomite in clay matrix; rhombs are notched at corners (p. 733). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,609 feet. (thin section A, x42)

E. Irregular quartz masses (clear) replacing twinned calcite at upper right and replacing dolomite rhombs (lower left). The quartz has borders convex against the carbonates and contains undigested carbonate inclusions which are in optical continuity with the adjoining crystals. Black is hematite (p. 736). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,829 feet. (thin section B, x75)

F. Same as "E." Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,829 feet. (thin section B, x60, crossed nicols)

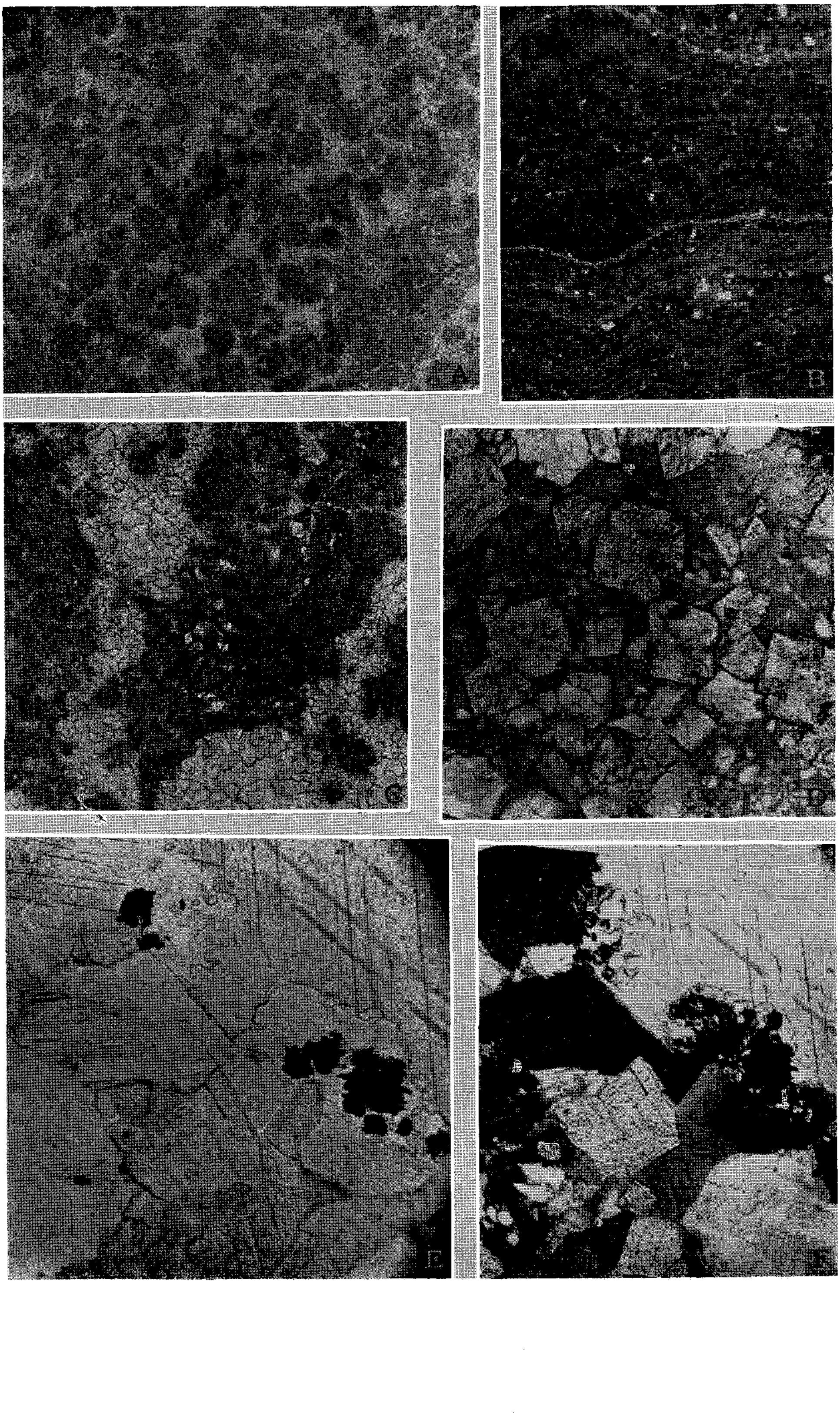


PLATE 57

Photomicrographs of Ellenburger rocks

A. Miniature mud volcano injecting laminated dolomite; laminae show plastic deformation (p. 737). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,853 feet. (x16)

B. Originally this rock consisted entirely of limestone. Certain limestone laminae were replaced by dolomite, then the remaining limestone was replaced by chert (clear), which failed to attack dolomite (p. 738). Gulf Oil Corporation No. 1 Mitchell Bros.—State, Presidio County, Texas, 15,893 feet. (x45)

C. Dolomite intraclasts in chert (clear) (p. 741). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 8,945 feet. (x75)

D. Dolomite rhombs replaced by flamboyant to chalcedonic quartz (p. 741). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 8,945 feet. (x60, crossed nicols)

E. Same as "D." Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 8,945 feet. (x75, ordinary light)

F. Pellet ghosts in medium crystalline dolomite (p. 743). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,005 feet. (x75)

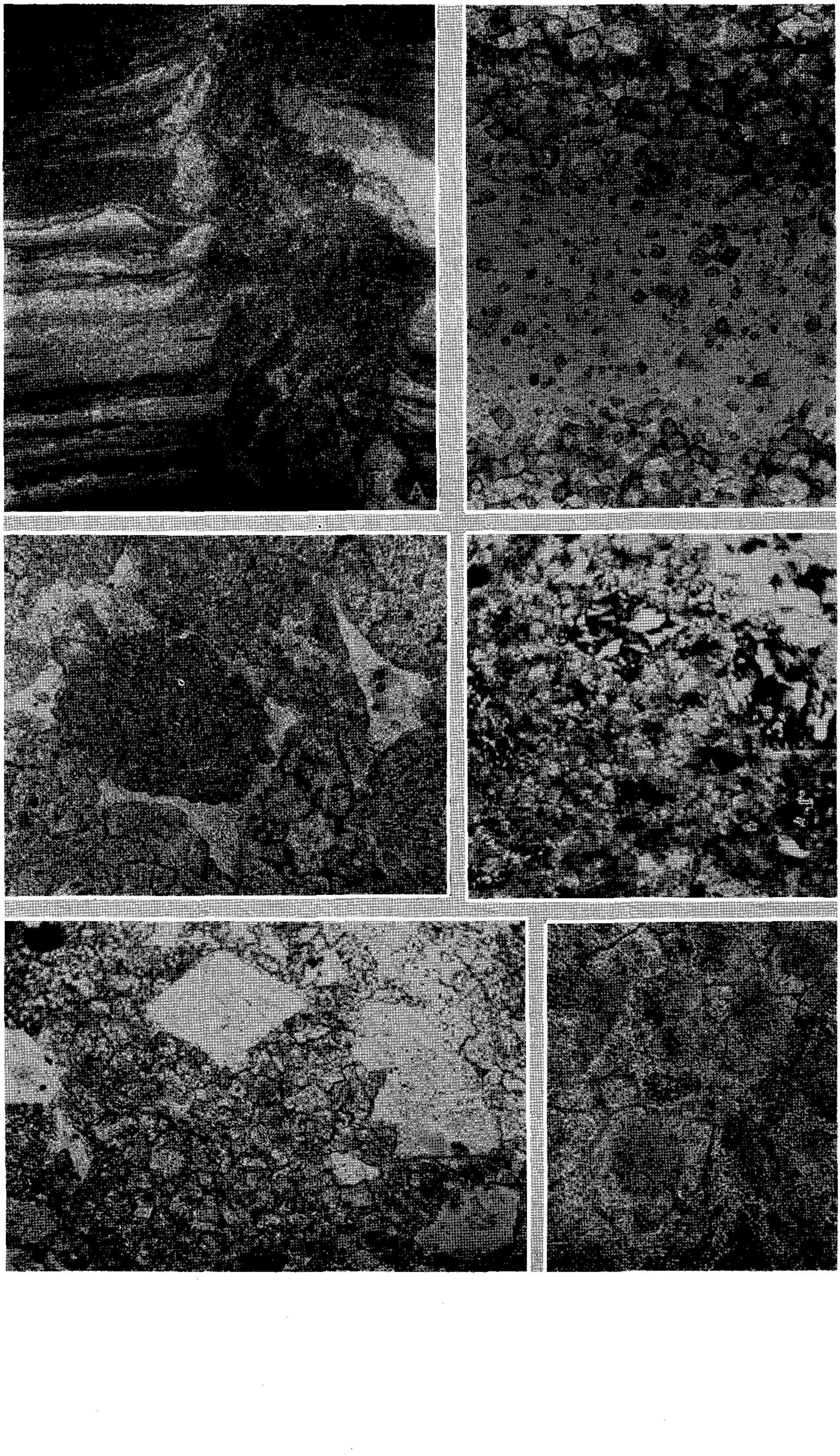


PLATE 58

Photomicrographs of Ellenburger rocks

A. Composite dolomite, showing peculiar internal structure (p. 745). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,084 feet. (x34, crossed nicols)

B. Coarsely crystalline composite dolomite with intraclast ghosts (p. 745). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,091 feet. (x42)

C. Same as "B." Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,091 feet. (x34, crossed nicols)

D. Composite dolomite showing ragged crystal margins (p. 745). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,091 feet. (x60, crossed nicols)

E. Probable oolite (or pellet) ghosts in coarsely crystalline, composite dolomite (p. 747). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,219 feet. (x42)

F. Dolomite rhomb containing pellet ghosts, embedded in relatively structureless clay shale (p. 748). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,235 feet. (thin section B, x75)

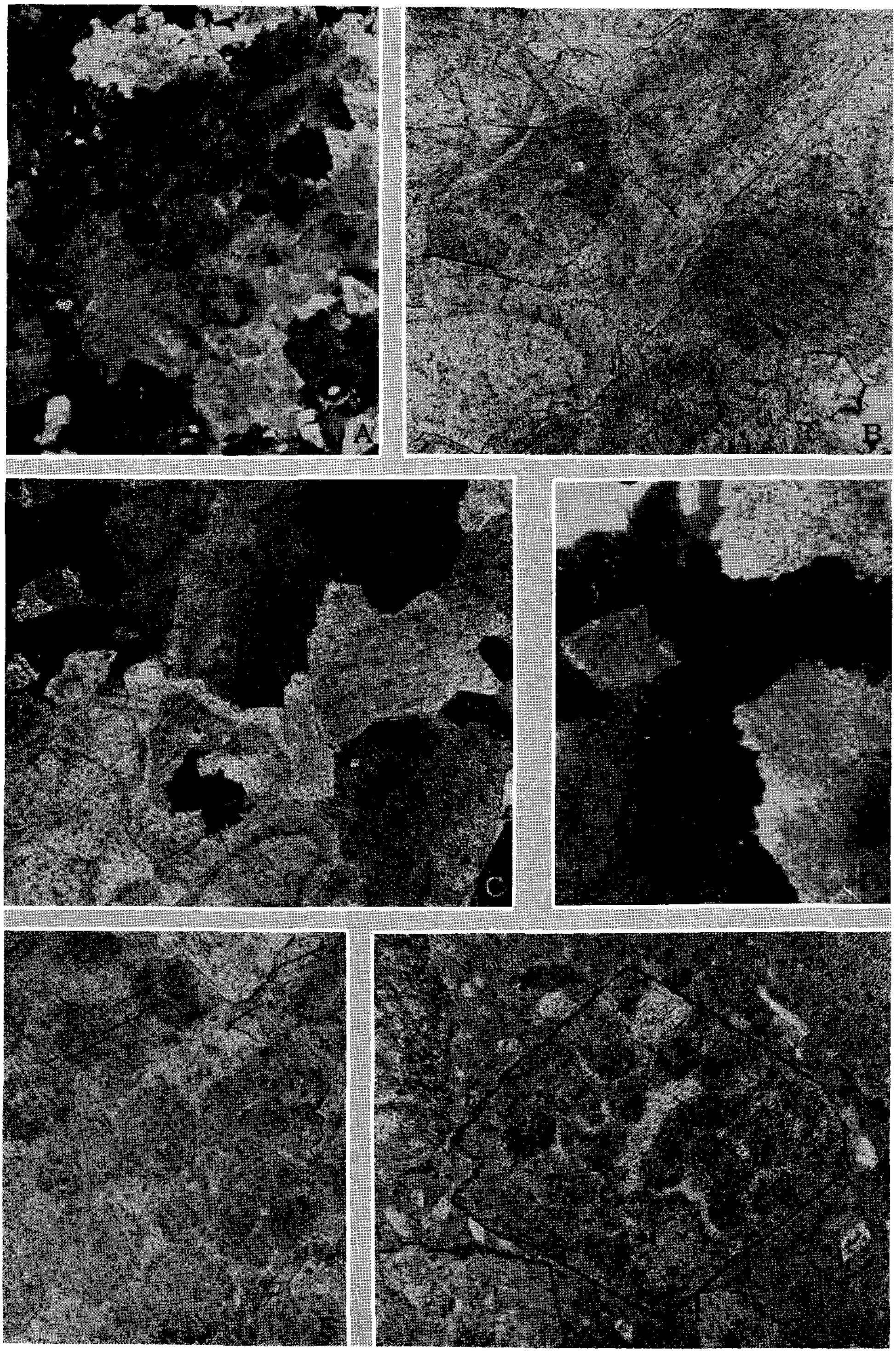

A
B
C

PLATE 59

Photomicrographs of Ellenburger rocks

A. Originally this rock consisted of limestone pellets or intraclasts (now visible only as dark, rounded ghosts). The rock was apparently replaced partially by dolomite rhombs; later, the remaining limestone was partially replaced by chert, and some chert formed as a cavity filling. The cavity-filling chert encrusts the surfaces of dolomite rhombs; the remaining pore space was filled by megaquartz (clear). The pellet or intraclast ghosts pass from dolomite through the replacement chert (p. 750). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,297 feet. (x75)

B. Same as "A." Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,297 feet. (x60, crossed nicols)

C. "Porphyritic" dolomite; the larger crystals are zoned (p. 750). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,313 feet. (x42)

D. Chert containing abundant pseudomorphs after dolomite (p. 751). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,316 feet. (x75)

E. Same as "D." Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,316 feet. (x60, crossed nicols)

F. Chert with rounded quartz sand and chalcedonic pseudomorphs after some unknown mineral (p. 752). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,391 feet. (x60, crossed nicols)

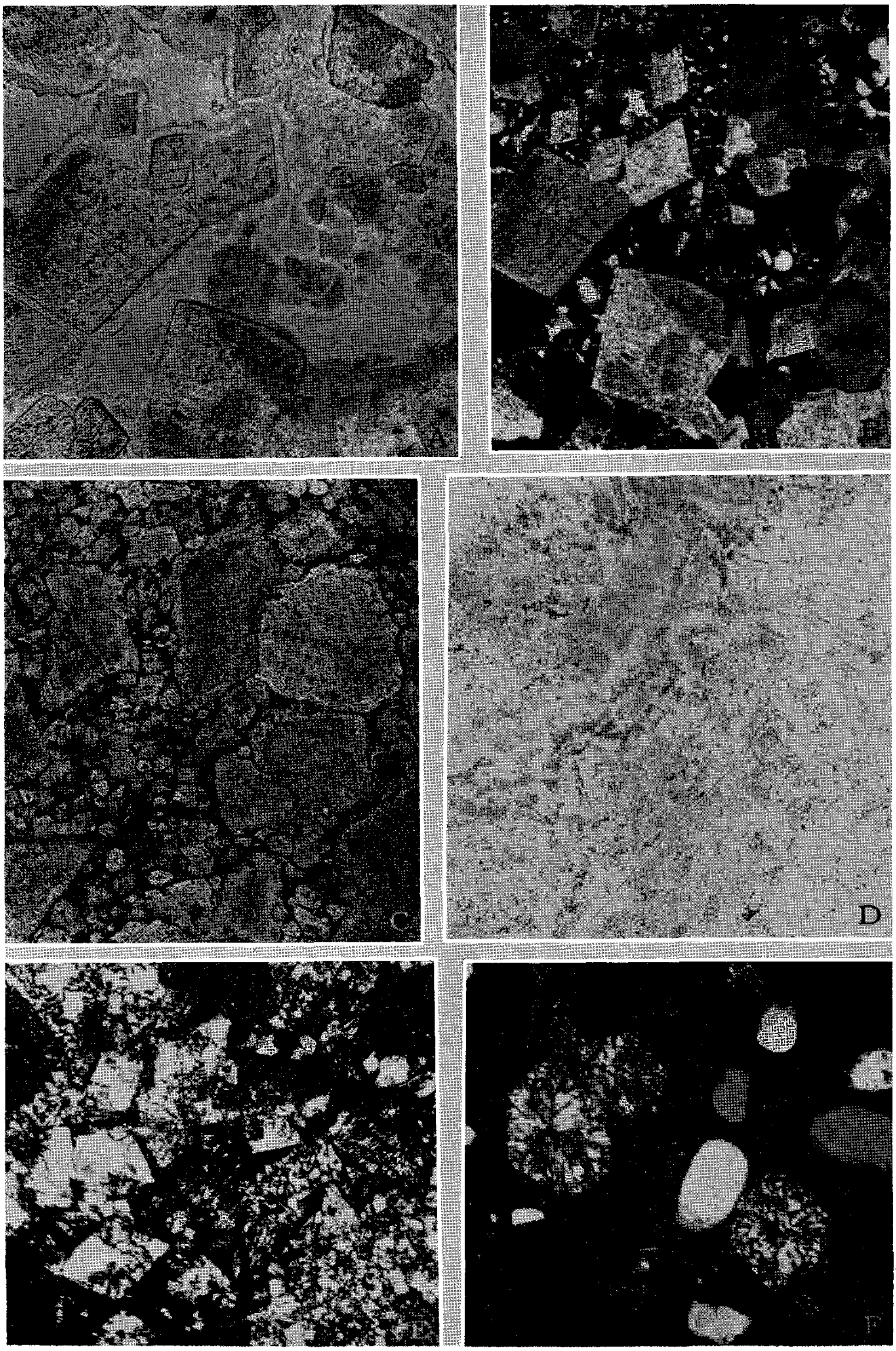

D

PLATE 60

Photomicrographs of Ellenburger rocks

A. Irregular knots of very finely crystalline calcite in chert (dark) (p. 753). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,415 feet. (x34, crossed nicols)

B. Intraclast ghosts in dolomite (p. 754). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,423 feet. (x42)

C. Edge of quartz spherulite replacing dolomite. The spherulite has a scalloped margin convex toward host. Fibrous structure in quartz may indicate that it is in part pseudomorphous after gypsum (p. 757). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,588 feet. (x42)

D. Immature arkosic sandstone. Grains are extremely angular, poorly sorted, and there is an abundant clay matrix (p. 759). Gulf Oil Corporation No. 108-E Keystone, Winkler County, Texas, 9,605 feet. (x34, crossed nicols)

E. Calcite masses in optical continuity (light) replacing chert (dark) selectively along certain bedding planes. Both the chert and the calcite contain tiny dolomite rhombs (p. 775). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,355 feet. (x34, crossed nicols)

F. Calcite with colloform structure. Despite this appearance, the entire area of calcite is in optical continuity with uniform extinction position. Apparently the calcite has replaced colloform chalcedonic quartz (p. 775). Magnolia Petroleum Company No. 1 Below, Kendall County, Texas, 4,355 feet. (x75)

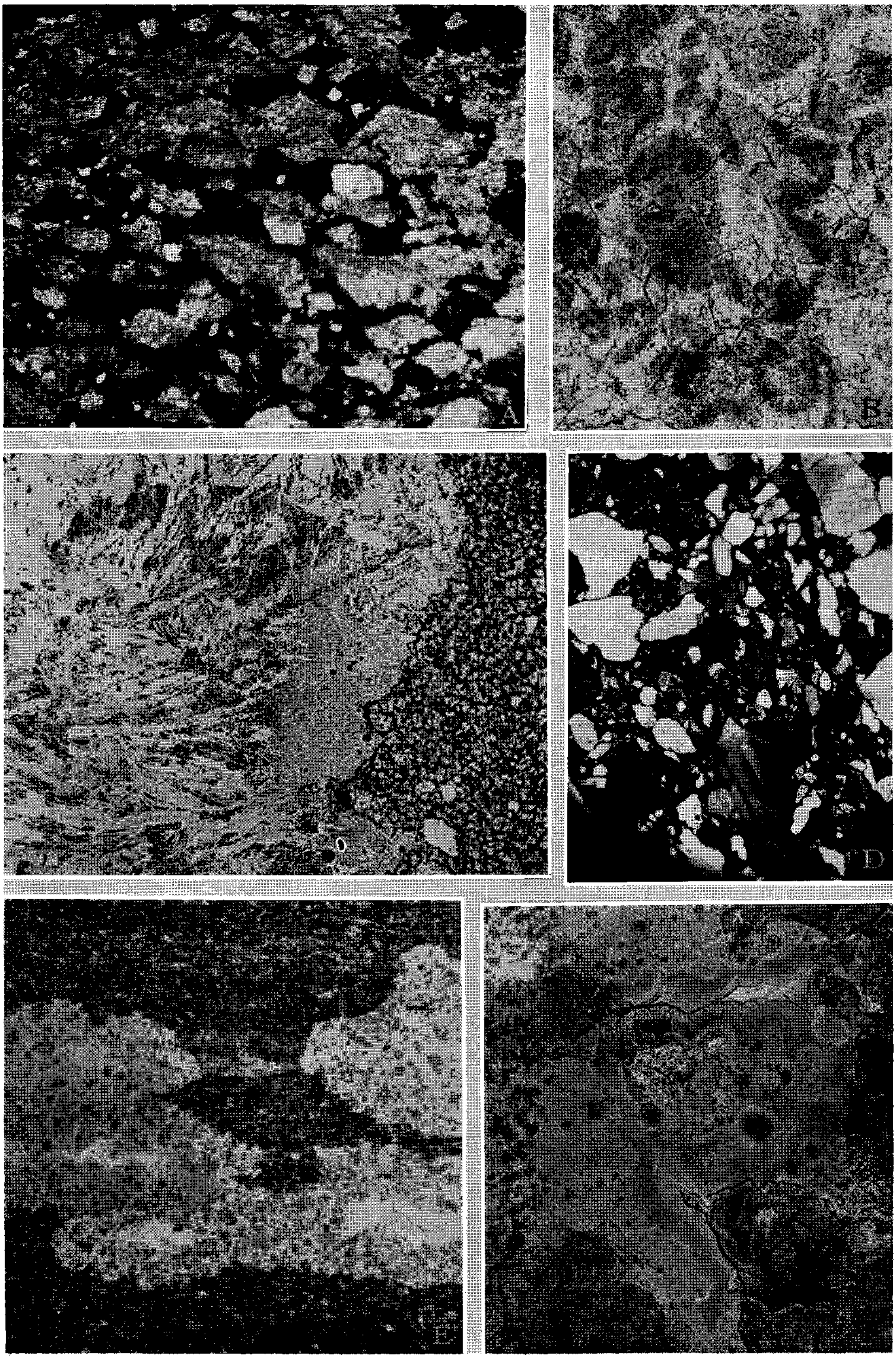

A
B
D

PLATE 61

Photomicrographs of Ellenburger and Arbuckle rocks

A. Dismicrite, the result of microcrystalline calcite being bored by organisms to produce sharply bounded, irregular areas of medium to coarsely crystalline sparry calcite (p. 781). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 9,821 feet. (x16)

B. Dismicrite, consisting of vague areas of microcrystalline ooze and pellets with irregular patches of sparry calcite (p. 784). Humble Oil & Refining Company No. 1 Miller, Collin County, Texas, 11,283 feet. (x45)

C. Intensely "pleochroic" dolomite replacing chert (clear) (p. 788). Gulf Oil Corporation No. 1 Texas "000," Andrews County, Texas, 12,664 feet. (thin section B, x45)

D. Same as "C," stage rotated 90 degrees. Corresponding portions of dolomite masses have changed color. Intensely "pleochroic" dolomite results when that mineral replaces chert and is due to the presence of a great quantity of very tiny undigested chert inclusions. Gulf Oil Corporation No. 1 Texas "000," Andrews County, Texas, 12,664 feet. (thin section B, x45)

E. Chert with fibrous internal structure, perhaps resulting from replacement of gypsum (pp. 110, 111). Humble Oil & Refining Company No. 6 "V" N.M. State, Lea County, New Mexico, 7,678 feet. (x45)

F. Same as "E." Humble Oil & Refining Company No. 6 "V" N.M. State, Lea County, New Mexico, 7,678 feet. (x34, crossed nicols)

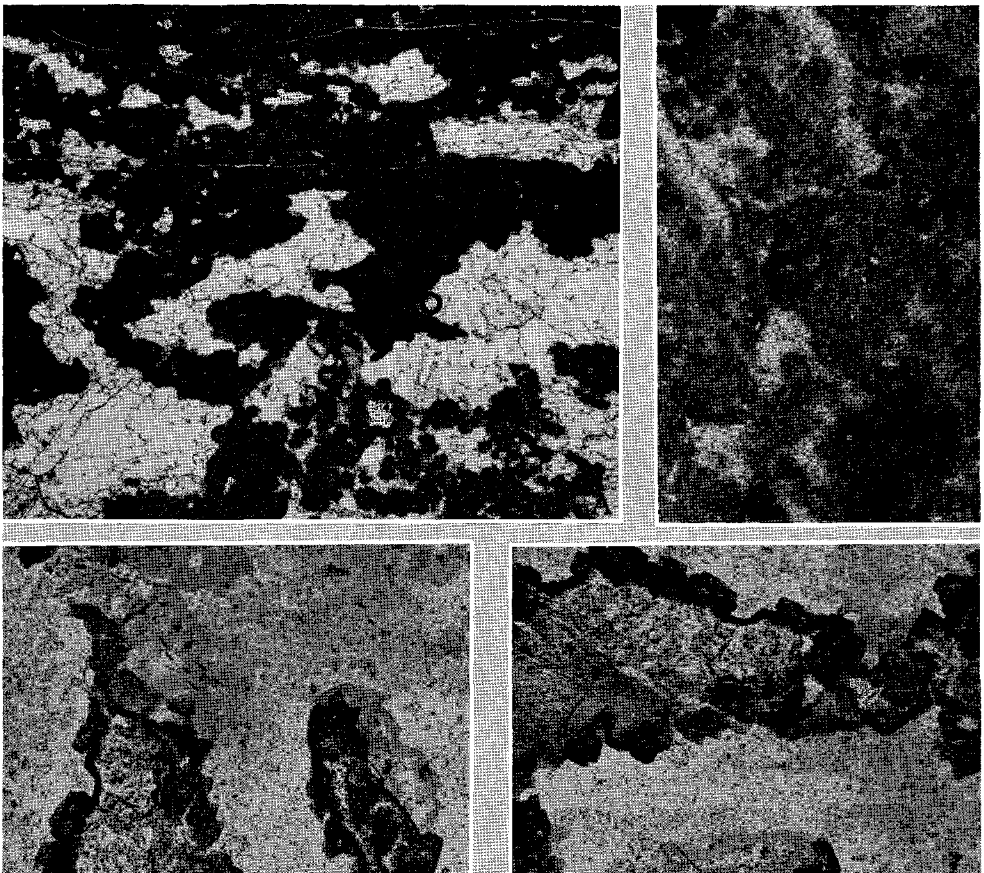

C
E

PLATE 62

Photomicrographs of Ellenburger rocks

A. "Swiss-cheese" overgrowths on rounded detrital quartz grains which are embedded in chert (dark) (p. 787). Gulf Oil Corporation No. 1 McElroy-State, Upton County, Texas, 12,145 feet. (x60, crossed nicols)

B. Chert possibly pseudomorphous after gypsum (pp. 110, 111). Humble Oil & Refining Company No. 1-M University, Reagan County, Texas, 10,917 feet. (x45)

C. A peculiar intrasparite in which the intraclasts become more coarsely crystalline upward. No simple explanation can be advanced unless it be that the intraclasts have been partially dissolved and later were refilled by sparry calcite (p. 799). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,246 feet. (x30)

D. Clear, idiomorphic dolomite lining a clay- and dolomite-filled fracture. Dolomite in the parent rock is cloudy (p. 799). Phillips Petroleum Company No. 1-C Puckett, Pecos County, Texas, 13,246 feet. (x16)

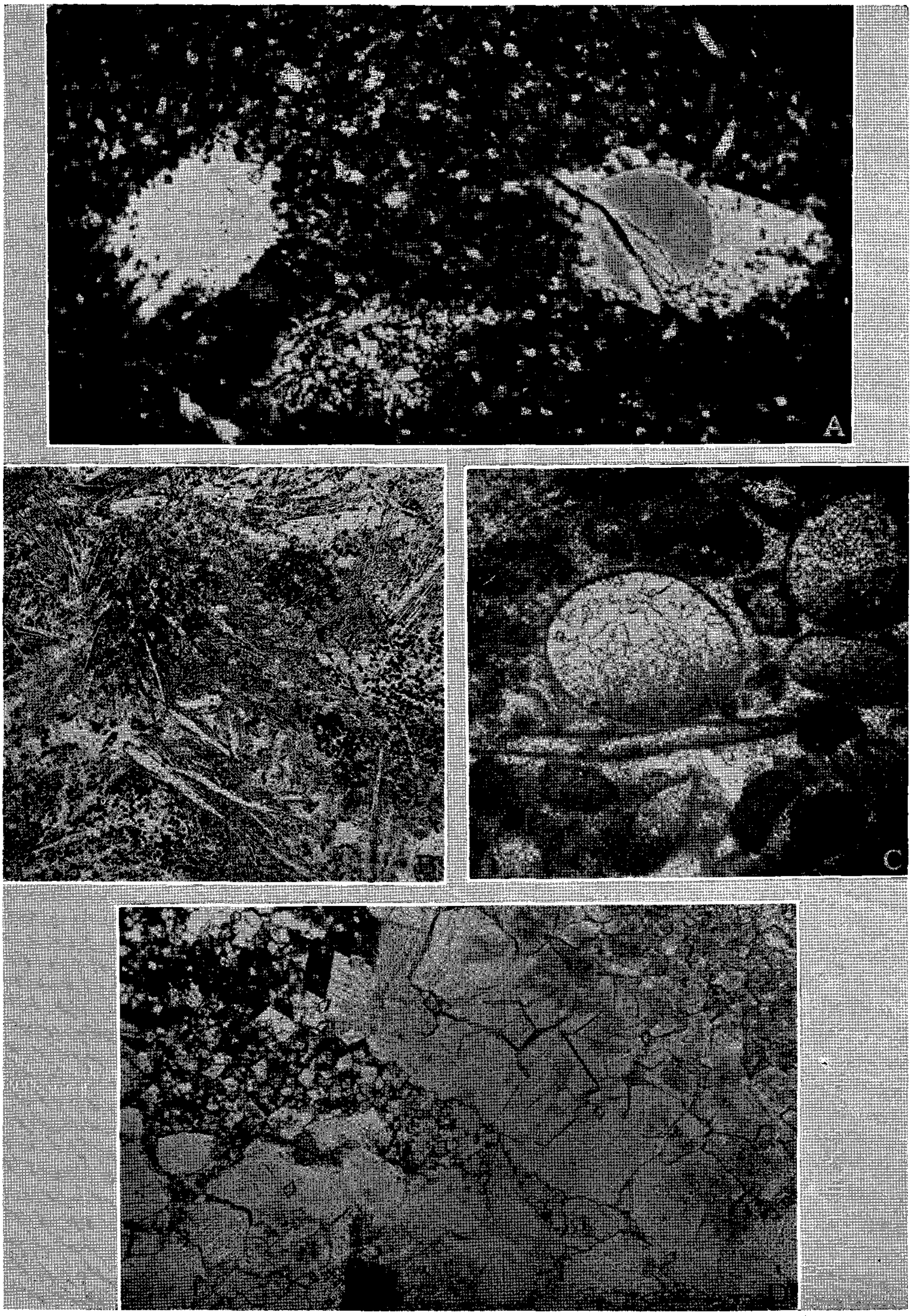

A
C

PLATE 63

Photomicrographs of Ellenburger rocks

A. Chert pseudomorphs after an unknown mineral (p. 801). Shell Oil Company No. 5 State, Lea County, New Mexico, 7,874 feet. (x30)

B. Same as "A." Shell Oil Company No. 5 State, Lea County, New Mexico, 7,874 feet. (x23, crossed nicols)

C. Peculiar irregular knots of calcite (dark) in chert (p. 791). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,092 feet. (thin section A, x45)

D. Poorly developed dolomite crystals with ragged edges, embedded in chert (p. 791). The Superior Oil Company No. 1–27 University, Crockett County, Texas, 7,092 feet. (thin section B, x75)

E. Oolites replaced first by chert (dark), later by dolomite (light). Near the center of the photograph two chert oolites have been replaced by one dolomite crystal unit (light gray), which completely replaces one oolite and spills across into the second oolite. Dolomite replaces only the oolites, not the matrix; the spaces between oolites are filled with chalcedonic quartz and megaquartz (p. 793). Wilshire Oil Company No. 23–118 Windham, Upton County, Texas, 12,416 feet. (x34, crossed nicols)

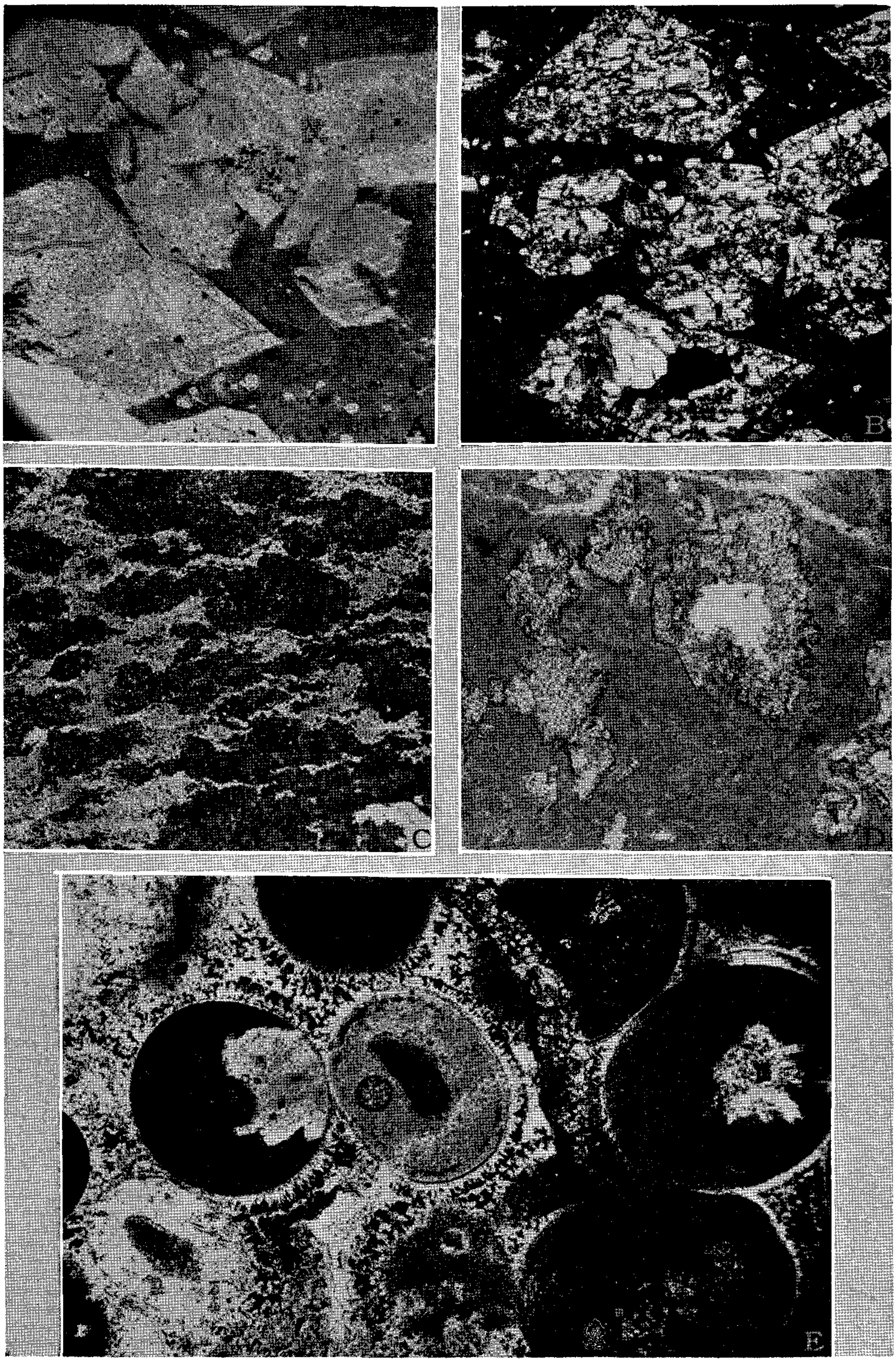

B
C
E

PLATE 64

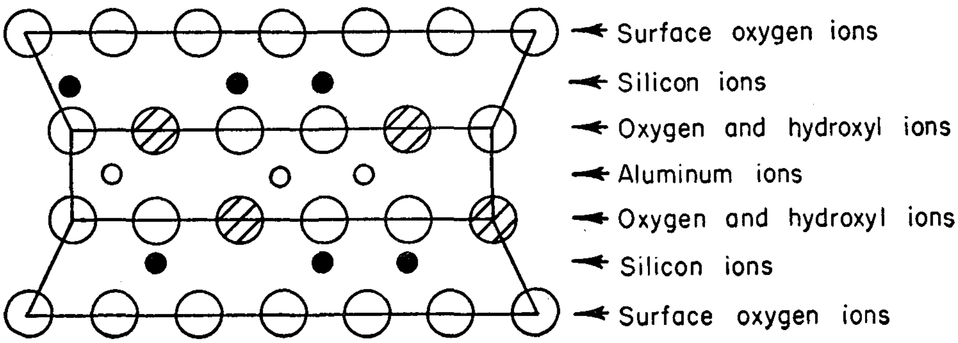
Sterograms of part of a layer silicate unit showing positions of oxygen ions (large black balls), hydroxyl ions (large white balls), and octahedral cations (small balls). The tetrahedral cations are very small and not visible in any of the views.

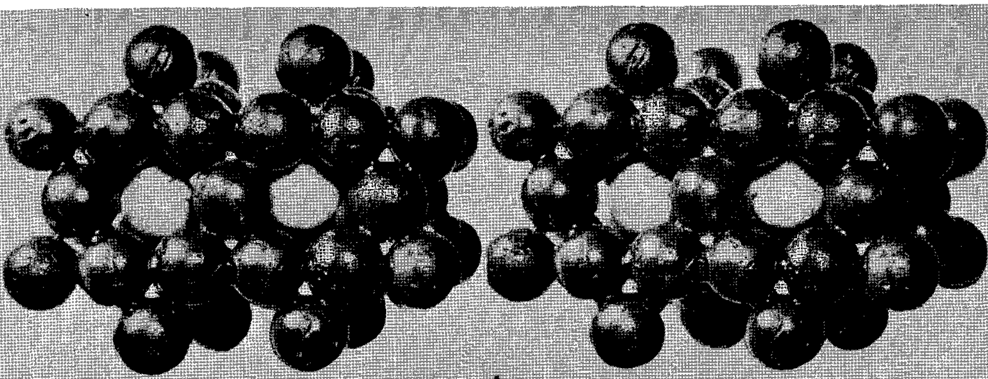
View A is perpendicular to the *ab*-crystallographic plane which is the cleavage direction of micaceous minerals.

View B is parallel to the *a*-crystallographic axis.

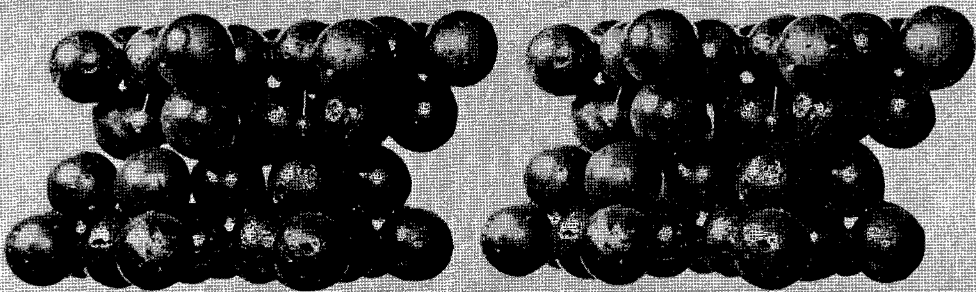
View C is parallel to the *b*-crystallographic axis. Views B and C show the end and side of the cleavage flake.

The following digram is a schematic representation of the arrangement similar to view B. This unit is extended in both the *a*- and *b*-crystallographic directions to form the sheets of micaceous minerals.

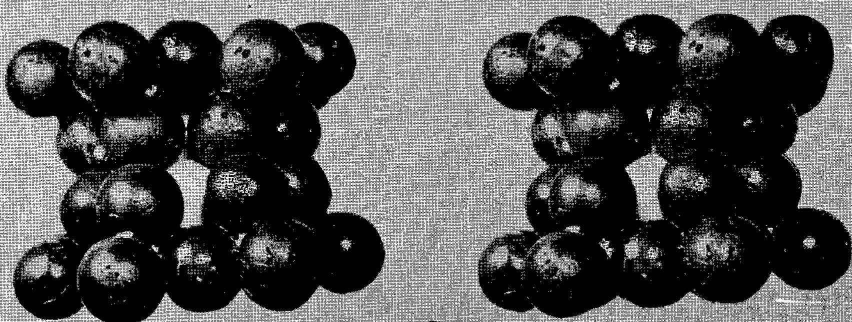




A



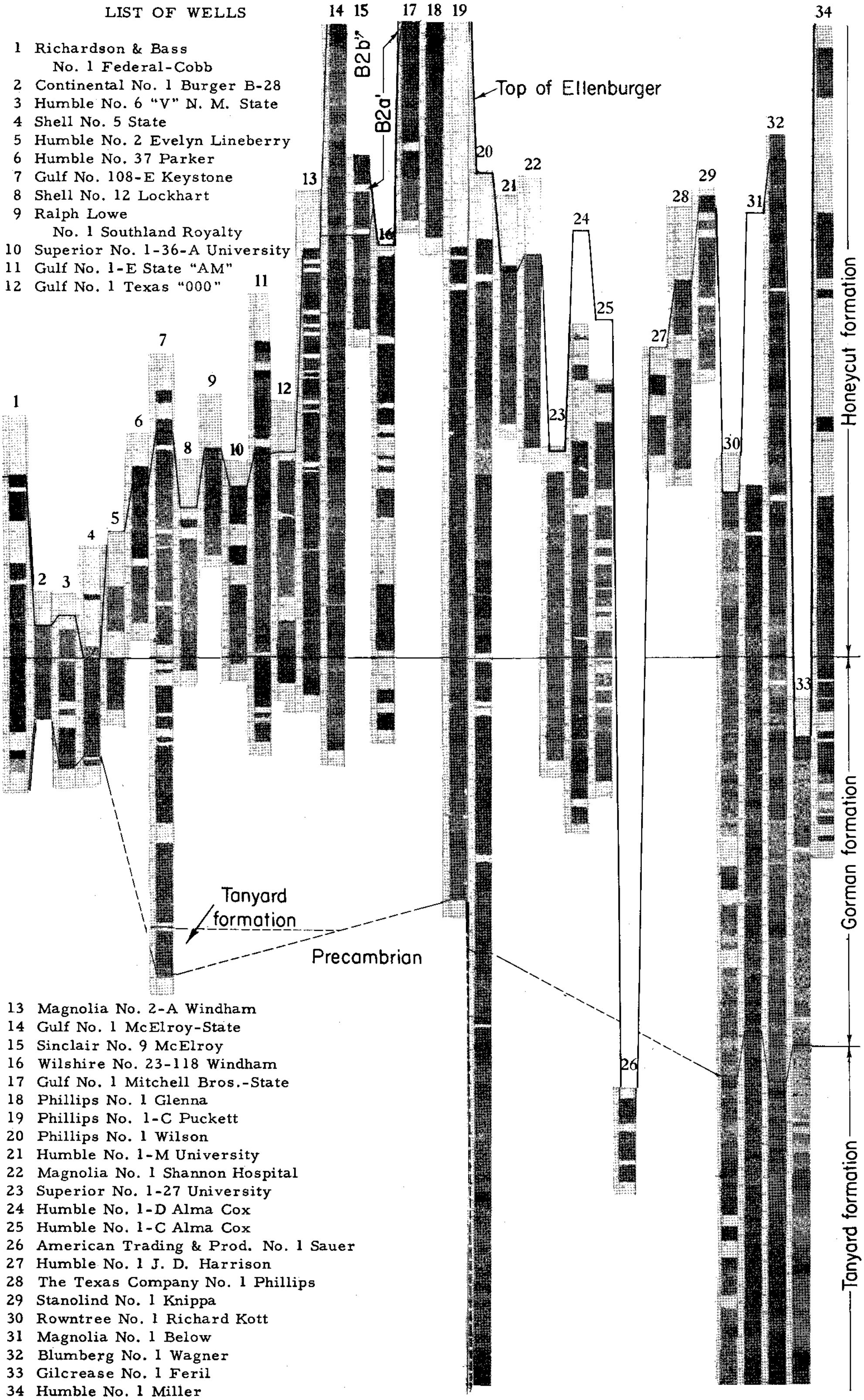
B



C

LIST OF WELLS

1 Richardson & Bass No. 1 Federal-Cobb
2 Continental No. 1 Burger B-28
3 Humble No. 6 "V" N. M. State
4 Shell No. 5 State
5 Humble No. 2 Evelyn Lineberry
6 Humble No. 37 Parker
7 Gulf No. 108-E Keystone
8 Shell No. 12 Lockhart
9 Ralph Lowe No. 1 Southland Royalty
10 Superior No. 1-36-A University
11 Gulf No. 1-E State "AM"
12 Gulf No. 1 Texas "000"



13 Magnolia No. 2-A Windham
14 Gulf No. 1 McElroy-State
15 Sinclair No. 9 McElroy
16 Wilshire No. 23-118 Windham
17 Gulf No. 1 Mitchell Bros.-State
18 Phillips No. 1 Glenna
19 Phillips No. 1-C Puckett
20 Phillips No. 1 Wilson
21 Humble No. 1-M University
22 Magnolia No. 1 Shannon Hospital
23 Superior No. 1-27 University
24 Humble No. 1-D Alma Cox
25 Humble No. 1-C Alma Cox
26 American Trading & Prod. No. 1 Sauer
27 Humble No. 1 J. D. Harrison
28 The Texas Company No. 1 Phillips
29 Stanolind No. 1 Knippa
30 Rowntree No. 1 Richard Kott
31 Magnolia No. 1 Below
32 Blumberg No. 1 Wagner
33 Gilcrease No. 1 Feril
34 Humble No. 1 Miller

Photograph of sample-mounted logs showing variation in color intensity of Ellenburger and Arbuckle rocks.

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