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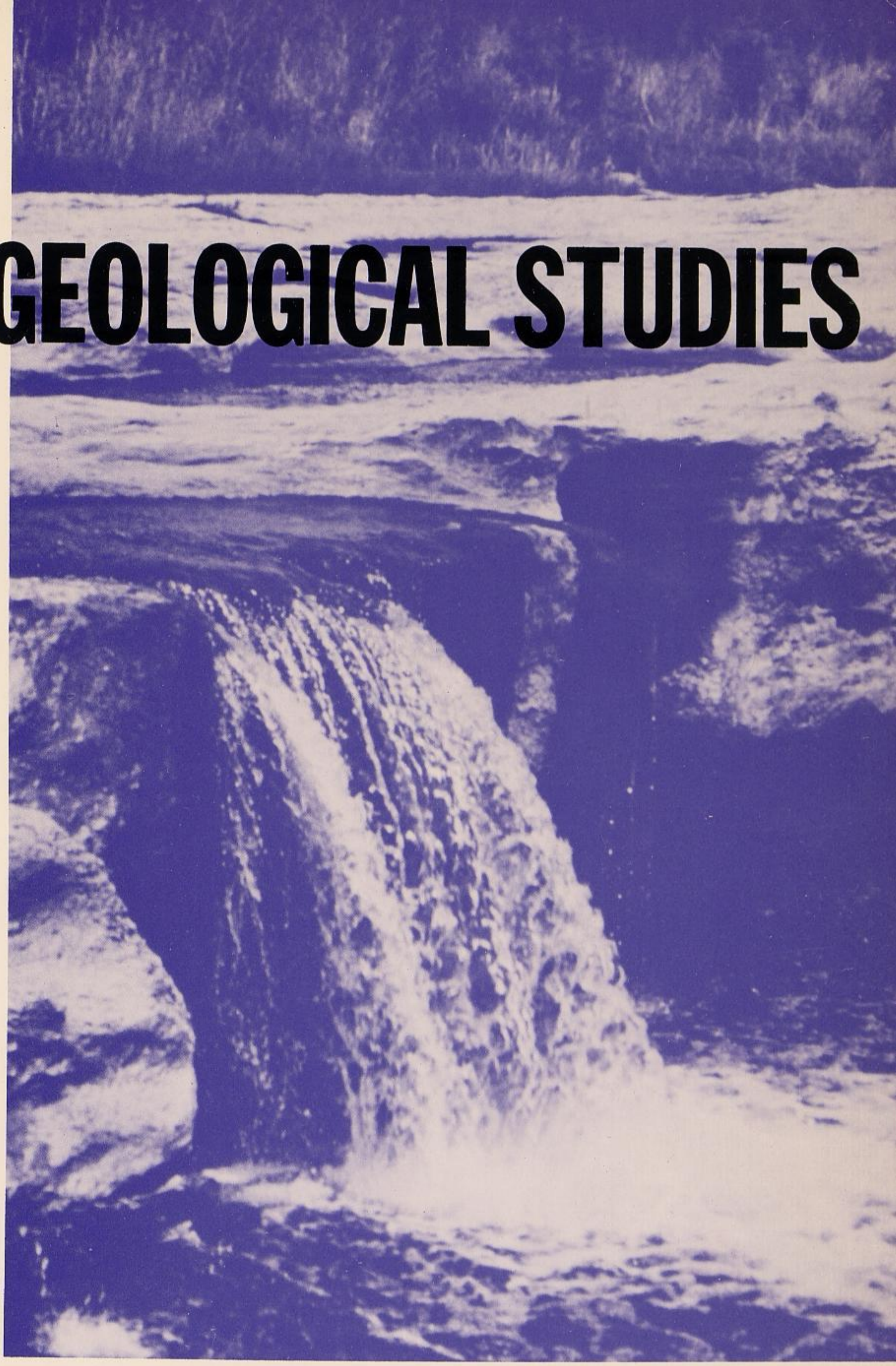

FALL 1986

Bulletin No. 44

The Petroleum Potential of "Serpentine Plugs" and Associated Rocks, Central and South Texas

TRUITT F. MATTHEWS

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

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

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

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Truitt F. Matthews

BAYLOR UNIVERSITY
Department of Geology
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CONTENTS

ILLUSTRATIONS

The Petroleum Potential of "Serpentine Plugs" and Associated Rocks, Central and South Texas

Truitt F. Matthews

ABSTRACT

During deposition of the Upper Cretaceous Austin Chalk and Taylor Marl, "serpentine plugs" were formed by submarine volcanic eruptions along major fault zones in the ancient Gulf of Mexico. The parent material was an alkaline-rich, silica-deficient basalt. After eruption, the mounds of pyroclastic material that accumulated around and over the volcanic centers underwent alteration by palagonitization, the hydration of basaltic glass. The topographic highs formed by the tuff mounds subsequently controlled localized deposition of shoal-water carbonates.

The "serpentine plugs" occur along an arcuate belt extending approximately 250 mi (400 km) from Milam County southwestward to Zavala County, Texas.

Hydrocarbon traps in and around these plugs have yielded approximately 54 million barrels of oil and significant quantities of natural gas from altered volcanic tuff and associated shoal-water carbonates. Shallower production occurs from overlying and marginal sedimentary rocks structurally influenced by the volcanic centers.

Entrapment of hydrocarbons occurs as: (1) stratigraphic traps within porous zones of volcanic tuff; (2) stratigraphic traps within porous, high energy carbonate units; (3) structural traps within overlying and marginal sands; and (4) traps related to fracturing of brittle carbonate units.

Analysis of known fields suggests that there are at least three distinctive groupings of "serpentine plugs": (1) a northern subprovince in which dominant hydrocarbon saturation is in the altered volcanic tuff; (2) a middle subprovince characterized by hydrocarbon-saturated biocalcarenite facies and fracture-related production in underlying units; and (3) a southern subprovince characterized by well-developed and productive overlying and marginal sands, which locally form domes by draping over the "serpentine plugs." Each of these subprovinces appears to reflect a somewhat different geologic history.

Exploration for "serpentine plugs" should be concentrated along existing fault zones related to extension. Modes of exploration include enhanced remote-sensing techniques, ground-level magnetics, and strategically placed seismic lines.

INTRODUCTION*

PURPOSE

Uniform deposition of the Upper Cretaceous (Coniacian/Campanian) Austin Chalk and Taylor Marl was interrupted by volcanic activity in the ancient Gulf of Mexico. As a product of eruption, tuff mounds, formed by the hydration of basaltic glass over eruption centers, controlled the localization of shoal-water carbonates on the topographic highs, which were formed by volcanic processes.

Although volcanic features are rarely sites for petroleum exploration, one of the most unusual and profitable hydrocarbon plays in central and south Texas coincides exactly with these volcanic features, each of which has the potential to produce from both volcanics and associated sediments. The belt of volcanic activity roughly parallels the ancient Ouachita structural belt and marks the southwestern margin of the East Texas basin and the northern margin of the Maverick basin. Since discovery in the subsurface in 1915, hydrocarbon traps in and around "serpentine plugs" have produced approximately 54 million barrels of oil and significant

*A thesis submitted in partial fulfillment of the requirements for the M.S. degree in Geology, Baylor University, 1985.

quantities of natural gas. Production is from isolated tuff mounds and associated shoal-water carbonates. Shallower production of oil and gas occurs from overlying sedimentary rocks structurally influenced by the volcanic "plugs." The occurrence of multiple reservoirs, the seemingly high success ratio found in association with these anomalies, and the overall cost-versus-return make the "serpentine plug" play an attractive venture.

Analysis of the plugs suggests that there are at least three distinctive groups: (1) a northern group in which the dominant hydrocarbon saturation is in the volcanics, (2) a middle group characterized by hydrocarbon-saturated biocalcarenite and reworked volcaniclastic facies, and (3) a southern group characterized by well-developed and productive overlying and marginal sands. Each of these groups appears to reflect a somewhat different geologic history. Therefore the purpose of this investigation is to describe the "serpentine plug" trend in its entirety, to interpret its history, to define those factors that control oil accumulation in the various definable subprovinces of the trend, and to recommend exploration procedures for the search for oil in this major trend.

LOCATION

The "serpentine plugs" are located within an arcuate belt extending 250 mi (400 km) from Milam County, southwestward to Maverick County, Texas (Figs. 1, 2). The area of study consists of 20 counties extending along this belt in central and south Texas (Fig. 2). Within this trend are approximately 225 surface and subsurface occurrences most of which are clustered in two defined subprovinces: (1) the Travis volcanic field near Austin, Texas, with approximately 70 plugs, and (2) the Uvalde volcanic field with approximately 150 plugs west of San Antonio, Texas. Another significant volcanic subprovince with from approximately three to five plugs has recently been discovered in Wilson County southeast of San Antonio.

The northern extent of the study area coincides with the southern limit of the East Texas basin; the western margin appears to follow the deeply buried western margin of the Ouachita thrust sheet of Paleozoic age; the southern margin is the Rio Grande embayment; the eastern border coincides with the Angelina-Caldwell flexure, the Cretaceous continental margin.

Structurally, the area lies entirely within the gently folded Gulf Coastal Plain. Compressional features dominate the Rio Grande embayment in the southern portion of the study area. Extensional features occur on the San Marcos platform and the remainder of the Gulf Coast region. The dominant structural features associated closely with these volcanic and intrusive bodies are four fault zones, which roughly coincide with the buried Ouachita thrust sheet: Balcones, Luling, Mexia, and Charlotte fault zones (Fig. 1).

Stratigraphically, the extrusive aspects of the "serpentine plugs" are confined to the Gulfian Upper Cretaceous (Santonian/Campanian) Austin and Taylor Formations (Fig. 3).

METHODS

The methods used in this investigation included limited field reconnaissance of known "serpentine plugs" in the study area; examination of available core and well-log control from selected fields in the three defined areas, a magnetic survey over a known producing plug; review of existing geologic literature; and analysis of oil and gas production histories of known fields.

Outcrop localities were examined for lithology, sedimentary structures, and stratigraphic relationships as clues to conditions at the time of deposition. On the basis of all available data, representative diagrammatic sections for different localities were generated as models to demonstrate regional changes throughout the study area. Cores and electric logs were used to produce a series of maps and cross-sections across existing fields to be used as actual examples for the trend. Available well cores were examined both in hand sample and thin section as an aid in interpretations of deposition and diagenesis. Scanning electron microscopy and microprobe were utilized to determine clay mineralogies and pore filling cement types. Cathode luminescence was used to substantiate the identification of cement types. These data aided in the recognition of regional geologic changes that occur along a northeast-southwest trend

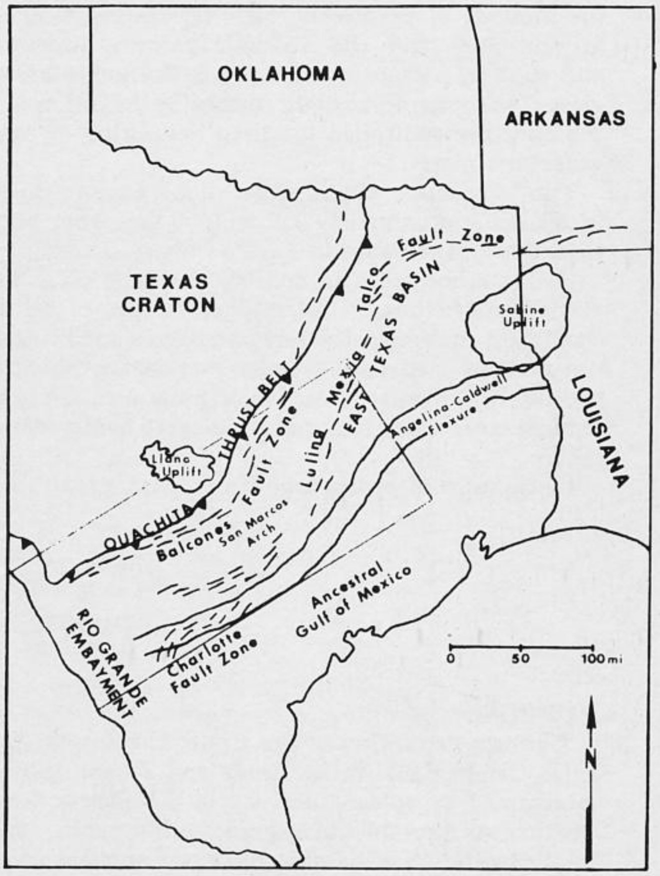

Fig. 1. Index map of study area (outlined) showing boundaries of the area under investigation and major structural elements that had an effect on the localization of the "serpentine plugs": (1) Ouachita thrust belt, (2) major fault zones, (3) San Marcos Arch, (4) Rio Grande embayment, (5) East Texas basin, and (6) the Angelina-Caldwell flexure (Fig. 2).

in the study area. The magnetic survey over a known producing "serpentine plug" produced at least one example of an actual magnetic signature, to guide in exploration of other "plugs." A comprehensive literature review dealt with: (1) works dealing with known "serpentine plugs" and their characteristics as seen in central and south Texas, (2) less specific works dealing with pyroclastic rocks in marine environments, (3) structural evolution of the area, and (4) environments of deposition.

PREVIOUS WORKS

Four categories of previous works are significant to this study: first, are those studies dealing specifically with known "serpentine plugs" in central and south Texas and the characteristics associated with these features in both the surface and subsurface; second, are those dealing with regional geology describing general or specific aspects of the distribution, stratigraphic setting, and origin of plugs and associated rocks; third, are less specific works dealing with structural evolution of the region, pyroclastic rocks in marine environments, and environments of marine deposition; and fourth, are works on techniques and approaches used in the exploration for "serpentine plugs."

Most previous works on the "serpentine plugs" describe individual "plugs" or a single grouping of "plugs" and contain limited reference to the entire trend. In order to obtain a more regional view, an extensive review of the literature of "serpentine plugs" was compiled. Some of the more important contributions are included in this paper.

The occurrence of igneous rocks intruding into the Cretaceous strata of south Texas was first reported by

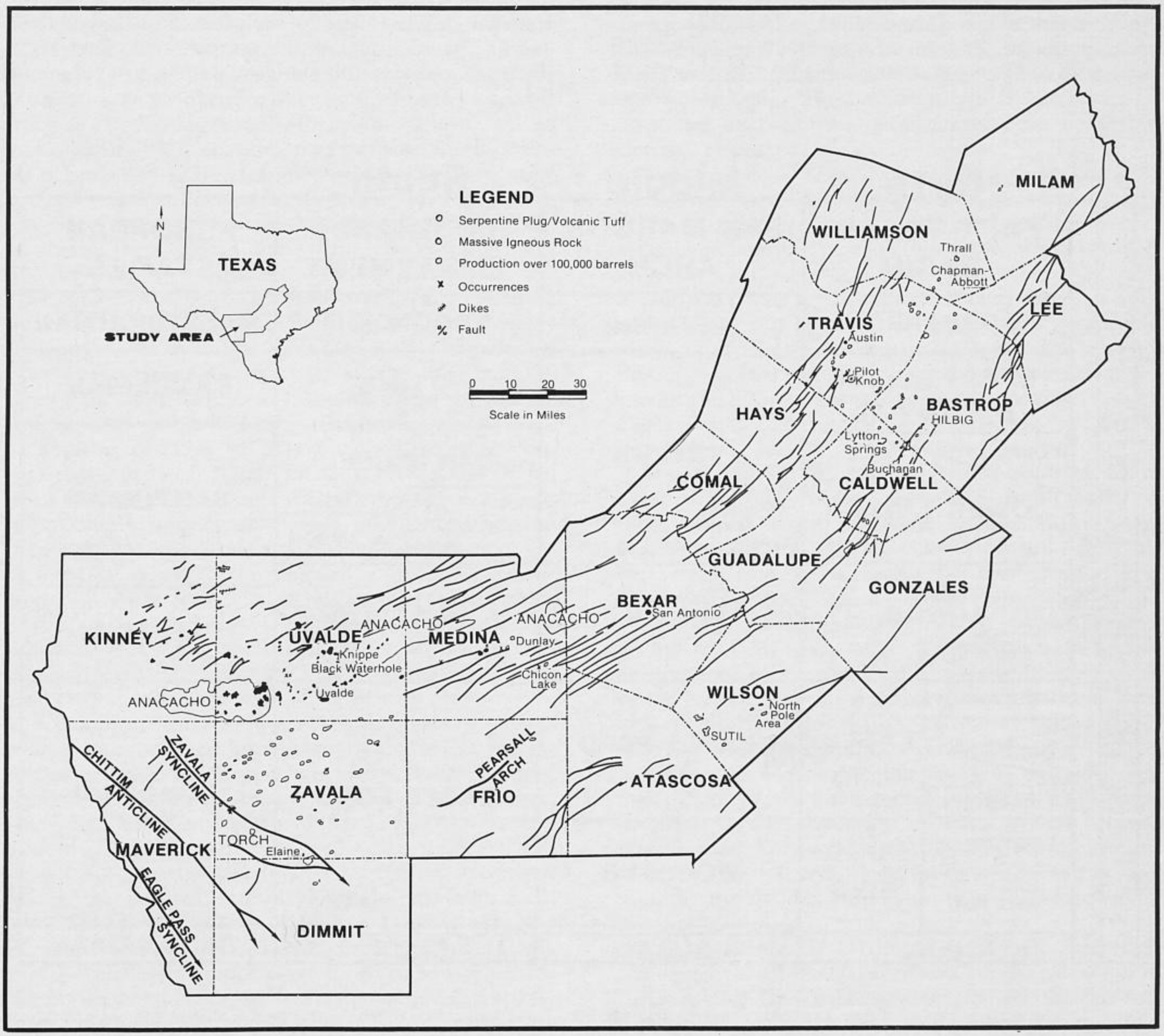

Fig. 2. Base map of study area. Adapted from Ewing and Caran, 1982.

Ferdinand Roemer (1852). Schott (1857) and Shumard (1886) recognized igneous rocks in present day Uvalde County while travelling westward across the state. The first solely geologic work was done by Owen (1889 in Spencer, 1965, p. 13) in Uvalde County, and it was followed by Tait (1889 in Spencer, 1965, p. 13) who also briefly touched on the igneous rocks. Hill (1889, p. 18-19) proposed the name Shumard Knobs in honor of the brothers G. G. and B. F. Shumard, the first state geologists of Texas, for the laccolithic and volcanic hills near Uvalde. Kemp (1890, p. 292-294) described the igneous rock at Pilot Knob in Travis County as nepheline basalt. Dumble and Hill (1890 in Spencer, 1965, p. 13) presented a brief account of the igneous rocks of central Texas. Hill (1890, p. 286-292) interpreted Pilot Knob as a marine volcano and noted "a soft amygdaloidal exfoliating material" derived from the weathering of igneous rock. Taff and Comstock (1892 in Spencer, 1965, p. 13) both recognized and commented on igneous rocks in Uvalde County. Osann (1893, p. 341-346) gave a petrographic description of a melilite nepheline-basalt and a nepheline basanite from Uvalde County, Texas, and briefly compared the descriptions with the basaltic rock from Pilot Knob, near Austin, Texas, in Travis County. Hill and Vaughn (1898 in Spencer, 1965, p. 13) observed that solid igneous masses occurred in Uvalde County, whereas buttes capped by igneous rock occurred in Kinney County.

Vaughn (1900 in Spencer, 1965, p. 13) referred to the weathering products of the igneous rock as "amygdaloidal basalt," but did not comment on the fact that they are in part sedimentary. Hill and Vaughn (1901 in Spencer, 1965, p. 13) did more detailed study of Pilot Knob. Udden (1907) presented a report and sketches of selected igneous rock sites in Kinney County.

With the discovery of the Thrall oil field in Williamson County, Texas, and the recognition that the reservoir was actually the erosional product and pyroclastic debris associated with an igneous mass, interest in "serpentine plugs" greatly increased. What had been an academic curiosity had suddenly become one of economic concern. Udden and Bybee (1916) investigated the Thrall oil field and the relationship of the igneous rocks and their weathering products to the stratigraphy, structure, and

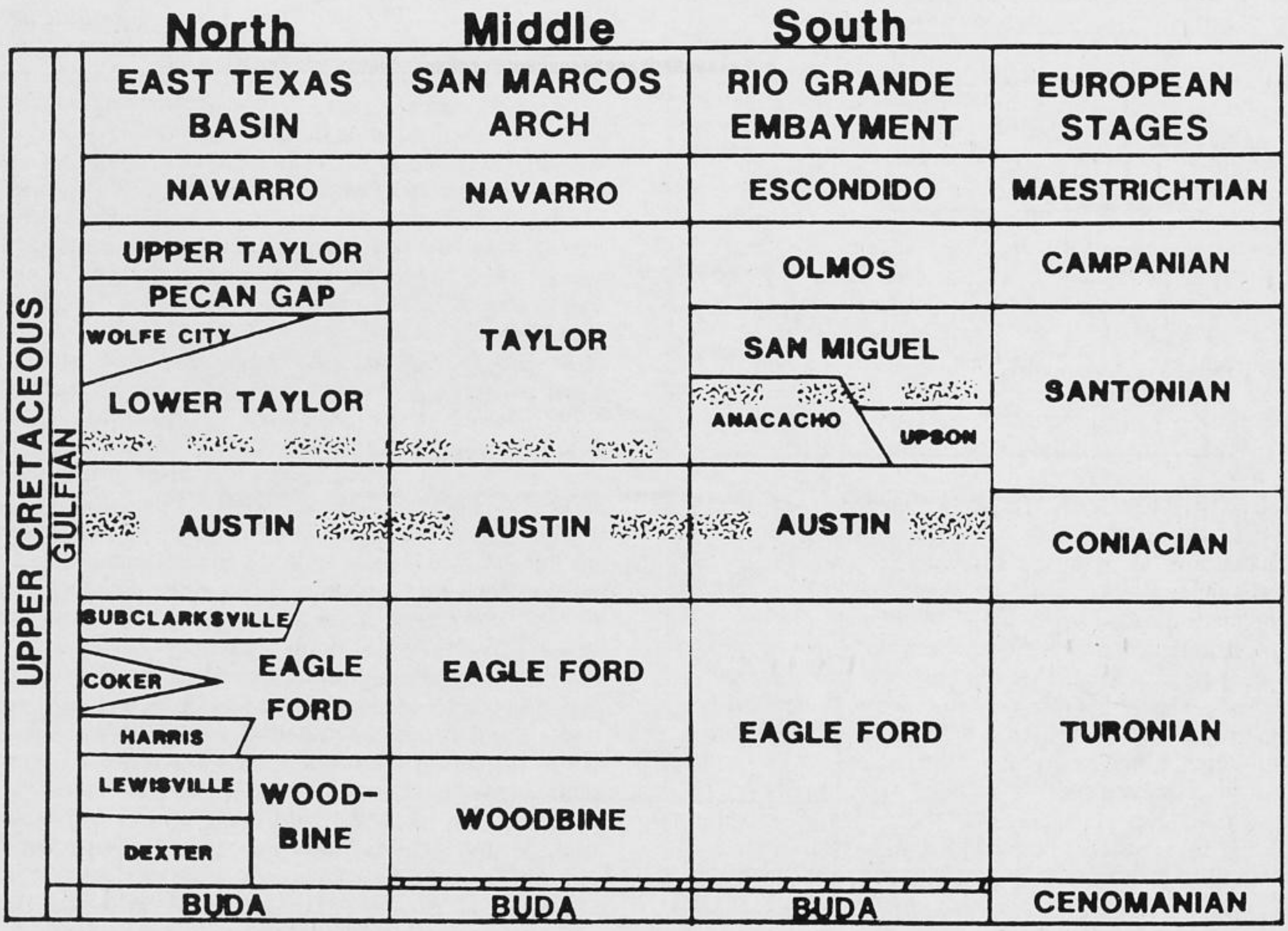

Fig. 3. Stratigraphic section of Upper Cretaceous rocks within the East Texas basin, Rio Grande embayment, and San Marcos arch areas of central and south Texas. Note the position of the Austin and Taylor Formations where the "serpentine plugs" occur. Note patterned bands showing stratigraphic positions of "plugs" in northern, middle and southern areas.

origin of the Thrall "plug" and to its relationship to petroleum occurrence. They believed the igneous body was extrusive and that it represented an irregular cone left by a small submarine eruption. They concluded that the rock was largely altered from its original state and for convenience gave the name "sepentine" to the characteristic green producing rock. Bybee recorded the production history of the Thrall oil field and postulated that the source of the oil was adjacent shales either above or below the volcanic rock (Bybee, 1921, p. 659).

Bybee and Short (1925) investigated the Lytton Springs oil field, the largest of the fields then producing from volcanic rock. They discussed in detail the structure, stratigraphy, origin, and petroleum occurrence within the field. Records from several wells indicated alternating layers of chalk and igneous rock; therefore, it was possible to compare this subsurface occurrence with alternating layers seen in surface exposures such as Pilot Knob (Bybee and Short, 1925, p. 13).

Collingwood and Rettger (1926) reviewed the short history of the Lytton Springs oil field in Caldwell County, focusing on the nature of the igneous body and its relation to production. They referred to the reservoir rock as a producing "sand" of igneous origin.

Lonsdale (1927) provided the first generalized review of original and altered igneous rocks of the "serpentine trend," and was the first to recognize that the igneous province was coincident with the Balcones fault zone, extending from Travis County in the northeast to Kinney County in the southwest. He suggested that the "serpentine" originated in three ways: (1) weathering residue of volcaniclastic detritus, (2) sedimentary redeposition of volcanic ejecta, and (3) alteration of massive volcanic flow rocks (Lonsdale, 1927, p. 139). He summarized earlier work and discussed most of the then known surface and subsurface occurrences.

Kirby et al. (1927, p. 621) described the occurrence of an igneous dike in Bandera County, Texas, and related it to the "serpentine trend." Considerable attention was given to the surface occurrence of dike-like igneous bodies as possible clues to petroleum occurrence.

Ross et al. (1928) investigated water-laid volcanic rocks of early Late Cretaceous age in southwestern Arkansas, southeastern Oklahoma, and northeastern Texas and related their occurrence to widespread volcanic activity during the Cretaceous period in south and central Texas, the zone of "serpentine plugs."

Collingwood and Rettger (1930, p. 1191) concluded that the use of magnetics in exploration for "serpentine plugs" should yield high magnetic anomalies over the igneous bodies of the "serpentine plugs." As an example, they cited a local anomaly over the Yoast field, Bastrop County, Texas.

A magnetometer investigation of igneous intrusions along the western end of the Balcones fault zone, exemplified by the Little Fry Pan area, Uvalde and Kinney Counties, Texas, was discussed by Liddle (1930, p. 509), and some "plugs" were found to be represented by positive anomalies, whereas others were marked by negative anomalies.

Adkins (1932) in an overview of Cretaceous stratigraphy of Texas, summarized briefly the then recognized occurrences of "serpentine plugs" and their structural and stratigraphic settings.

Sellards (1932) in a similar study also summarized briefly the known occurrences of "serpentine plugs" and their structural and stratigraphic settings.

McCallum (1933, p. 32) reported the occurrence of reworked igneous deposits peripheral to a "plug" that produced in the Darst Creek field, Guadalupe County, Texas.

Smiser and Winterman (1935, p. 206) discussed the character and possible origin of the producing rock in Hilbig oil field, Bastrop County, Texas. They concluded that it is a fragmental palagonite tuff and lapilli tuff. Blackburn, in a somewhat similar study, (1935, p. 1023) also described the structural setting, stratigraphic relations, and nature of the "serpentine" and its effect on hydrocarbon occurrence in Hilbig field.

Sayre (1936) mapped and reported locations of igneous bodies within Uvalde and Medina Counties, Texas, with emphasis on those exposed at the surface.

McKinlay (1940) and Moon (1942), in a discussion of Pilot Knob and associated volcanics, contributed to the understanding of the relationships and structure of associated igneous and sedimentary rocks of Travis County, Texas.

Weeks (1945, p. 1733) discussed the age of Balcones, Luling, and Mexia fault zones and related these systems to the geologic history of the Coastal Plain deposits. He did not, however, recognize the relationships between fault zones and volcanic occurrences.

Durham (1949, p. 102) described the tuffaceous beds and localized reef facies in his study of the stratigraphic relations of the Pilot Knob pyroclastics. He believed that the reef facies gave evidence of shallow-water, high-energy conditions, whereas the outlying areas of Austin Chalk were indicative of quiet-water accumulation below wave base.

Moody (1949) and Kidwell (1951) contrasted the exposed igneous rocks of central and south Texas to those of east Texas, Louisiana, and Arkansas, and concluded that the igneous activity was not limited to the ancient continental margin, but also occurred in a large sector of the northern Coastal Plain.

Romberg and Barnes (1954, p. 438) re-examined the geology of Pilot Knob and made gravity and magnetic observations so as to present a more complete picture of the feature, describing its relationship to the region, and its history of formation, as well as comparing it with subsurface "serpentine plugs" in the area.

Weiss and Clabaugh (1955, p. 136) described the mineralogy of the "serpentine" at Pilot Knob with emphasis on the alteration products of the original igneous rock. They concluded that the greenish material found at Pilot Knob is not "serpentine," but a clay mineral of the montmorillonite group known as nontronite.

Fowler (1956, p. 37-42) described the major structural features involved in the superficial crustal extension in the subsiding Gulf Coastal Plain and related these to the igneous activity that took place during Late Cretaceous, Austin and Taylor time. He believed that the igneous activity was contemporaneous with normal faulting in the northern San Marcos arch area.

Greenwood (1956) considered the possible occurrence of submarine volcanic mudflows in the Cretaceous age Grayson Formation of central Texas and suggested that igneous activity began in the Cretaceous as early as deposition of the lower Cenomanian Del Rio Formation and continued during deposition of the Maestrichtian Navarro Group

Lewis (1962, p. 257) described the structure, stratigraphy, reservoir characteristics, producing intervals, and regional significance of Torch field, Zavala County, Texas, and suggested that the structural entrapment of hydrocarbons was directly related to differential compaction of sediment over the "serpentine plug."

Flawn (1964) described the Ouachita structural belt in Texas and Oklahoma, with emphasis on the frontal zone of the belt, which corresponds roughly to the four major fault zones of central and south Texas: Balcones, Luling, Mexia, and Charlotte. While he did not discuss its relationship to igneous activity, he defined the zone of major interest to the present study.

Spencer (1965) compiled a summary of literature dealing with igneous rocks in the zone of "serpentine plugs." He also described the exposed alkalic igneous rocks of Uvalde County, Texas, which appear to be similar to but more diverse in composition than those found elsewhere in the trend.

Simmons (1967) described the "serpentine plug" trend on a regional scale focusing on the origin of the igneous bodies and their relationship to faulting and petroleum potential. He provided the first overview of the then known "serpentine plugs" since Lonsdale's report (1927).

Rives (1968) described the structural and stratigraphic entrapment of hydrocarbons in the vicinity of extrusive rocks in south-central Texas. He suggested that all the extrusive bodies located in south-central Texas occur on the downthrown side of the Balcones fault zone.

Spencer (1969) described the primary magmas from which all igneous rocks of the province were derived and presented detailed microscopic studies and chemical analyses to further substantiate the differentiation of magmas. He identified five major basaltic rock types that occur along the Balcones fault province: (1) olivine nephelinite, (2) melilite-olivine nephelinite, (3) analcite phonolite, (4) olivine basalt, and (5) nepheline basanite in order of decreasing abundance. He indicated that this variation was related to bulk chemical composition changes shown in the order of magma differentiation.

Bebout (1974) described the Early Cretaceous carbonate shelf margin in south Texas and the effect it had on the structural framework of south Texas during Late Cretaceous time. This was the area of major "plug" emplacement, and while he did not relate "plug" occurrence to the geology of the region, his description of depositional environments was of significant benefit.

Lewis (1977, p. 90) described the stratigraphy and entrapment of hydrocarbons in the San Miguel sands of southwest Texas. He presented evidence for both stratigraphic and structural entrapment and mentioned that the structural traps that occur over "serpentine plugs" are smaller, yet much more numerous, than the stratigraphic traps.

Luttrell (1977, p. 260) described and interpreted the depositional environments of five carbonate facies within the Anacacho Formation and related their distribution and fabric to the "serpentine plug" in Elaine Field, Dimmit County, Texas. He applied this information to petroleum occurrence.

Wilson (1977, p. 23-24) considered relict tectonism in south Texas and believed that injection of mantle material gave rise to "serpentine plugs." He believed that extrusion onto the Late Cretaceous sea floor was a result of renewed movement along pre-existing faults developed in late Paleozoic time.

Barker and Young (1979) described Pilot Knob as a submarine Cretaceous nepheline basanite volcano. They studied in detail the mineralogy and petrology of the massive igneous rocks and the pyroclastic debris that was ejected from the volcano and related this to a submarine volcanic history.

Hunter and Davies (1979, p. 147) discussed the distribution of volcanic sediments in the Gulf Coastal Province. They recognized two volcanic regions that were active during Late Cretaceous time, one in the Mississippi embayment and the second in the Rio Grande embayment. They indicated that volcanic detritus present in Upper Cretaceous rocks of the Gulf Coastal Plain has been shown to increase the potential for well damage during drilling and well stimulation.

Wilson (1981, p. 8), in a guide to the Anacacho Formation, described a high-energy carbonate bank associated with a surface exposure of a basaltic volcano. He recognized this as a surface parallel to subsurface occurrences.

Roy et al. (1981, p. 13) described a Late Cretaceous biocalcarenite beach complex associated with submarine volcanism and its relationship to hydrocarbon occurrence in selected fields in Wilson County.

Walker (1982, p. 52-57) examined a surface exposure of an igneous body that is being mined in Knippa, Texas. He described the exposure and presented a brief summary of the mineralogy, petrology, and areal extent of the intrusive and extrusive bodies.

Ewing and Caran (1982, p. 137) described Late Cretaceous volcanism on a regional scale in south and central Texas. They discussed the geologic history, the stratigraphic and structural entrapment of hydrocarbons in and around "serpentine plugs," the areal extent of the trend, and also the tools used for their exploration.

Clark (1982, p. 157) discussed the outline of the buried Ouachita orogenic belt in central Texas. He used geophysical measurements to define the "zone of weakness" that resulted in marginal rifting and igneous activity from Arkansas to south Texas. Subsequent rifting of this zone may have been related to the continued opening of the Gulf of Mexico.

Martinez (1982) examined the regional subsurface geology of the Austin Chalk in south Texas. She discussed the structure and stratigraphy of the Gulf Coastal Plain of south Texas and presented data showing that production for all Austin Chalk fields was from fractures caused either by volcanic bodies or structural flexures (Martinez, 1982, p. 49).

Young, Caran, and Ewing (1982) in a field guide to Cretaceous volcanism in the Austin area described exposures of pyroclastic and volcaniclastic material and the associated shoal-water carbonates that formed on the flanks of the Pilot Knob volcano of Travis County.

Lewis (1983, p. 19) reported on the use of strategically placed seismic lines as an exploration tool for "serpentine plugs" within the Maverick Basin of southwest Texas, and cited methods for recognition of "serpentine plugs" within the basin.

Wilson (1983, p. 22) described the stratigraphic relations of the Anacacho Formation of south Texas, which "grew" as patchy biostromes on igneous-related bathymetric highs. He indicated that the paleoenvironmental conditions in the northern Gulf Coastal Plain were significantly influenced during Late Cretaceous time by such features.

Fisher and Schmincke (1984) gave a detailed review of the origin of magmas and pyroclastic rocks. Of greatest interest to the current study was the emphasis on submarine volcanism, in which they discussed the alteration of basaltic glass, by palagonitization, and the resulting mineralogical and textural changes.

Sandlin (1984, p. 27-31) briefly reviewed the "serpentine plug" trend, discussed the origin of the igneous rocks, described hydrocarbon production, and related methods of exploration used in the Balcones fault zone.

ACKNOWLEDGMENTS

Appreciation is extended first to the many workers cited above who provided the principal foundation for this study.

Personal thanks are rendered to all of those who aided more directly in the completion of this study: O. T. Hayward, Department of Geology, Baylor University, for outlining procedures, supervising, and critical review of the manuscript; Robert C. Grayson, Jr., Department of Geology, Baylor University, and Lucille Brigham, Department of Mathematics, Baylor University, who provided constructive criticism of the manuscript.

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Gratitude is also extended to Brian Guillette and Rick Gibson of Baylor University, for assistance in reproduction of the manuscript and in field work; to Mrs. Viola Shivers for her dedication to the students as departmental secretary; and to the many friends whose moral support kept the lights burning during the sweet and sour spots of this study.

Lastly, the author would like to give special thanks to his parents, Floyd and Carolyn Matthews, and sister Tricia for their constant love and encouragement, which allowed the opportunity and privilege of attending Baylor University.

REGIONAL SETTING OF "SERPENTINE PLUGS"

Igneous rocks of Cretaceous age (Coniacian/Campanian) extend along a 250 mi (≈ 400 km) arcuate belt in central and south Texas. The regional geologic setting of these igneous rocks, commonly called "serpentine plugs," is best explained in geographic relationship to the Ouachita thrust sheet (and the four major fault zones that roughly coincide with the thrust sheet), the East Texas basin, and the Rio Grande embayment (Fig. 1).

The Ouachita structural belt of late Paleozoic age appears as an elongate, narrow feature with maximum width of approximately 80 mi (≈ 130 km) (Flawn, 1964, p. 273). The outline of this buried orogenic belt follows the ancient continental boundary that has apparently been involved in plate interaction since late Precambrian time. The Ouachita orogenic belt contains two tectonic provinces, a frontal zone with a series of overthrusts bordering the craton to the west and a strongly deformed interior zone marking the eastern margin. Following initial compression in late Paleozoic time, later relaxation apparently during the Late Permian to early Tertiary age resulted in formation of a rift zone parallel to the ancient continental edge and a sharp structural steepening along the outside edge of the interior zone (Clark, 1982, p. 157).

In this little understood and complex structural setting, intrusive and volcanic bodies of Late Cretaceous age appear to be aligned along, or adjacent to, four major fault zones that roughly bound the Ouachita structural belt: (1) Balcones, (2) Luling, (3) Mexia, and (4) Charlotte fault zones (Fig. 1). These are belts of normal faults that strike northeast and appear to be related to Cretaceous and Tertiary extension in the subsiding Gulf Coast Basin.

The Balcones fault zone extends from near Dallas, southward to Uvalde County west of San Antonio, and into northern Mexico. It occurs as a narrow discontinuous band of down-to-the-southeast faults, although in the western portion of the study area it becomes fan shaped and contains a great number of tiny fault blocks

(Fowler, 1956, p. 37) (Fig. 2).

The Luling fault zone lies coastward from the Balcones fault zone and consists of a belt of faults downthrown to the northwest, extending from Bastrop County on the north, southwestward to Guadalupe County on the south. Faults of this zone have the greatest displacement, reaching a maximum of 1500 ft (≈ 460m) (Weeks, 1945, p. 1734). The northern limit of the Luling fault zone appears to lie in Bastrop County, and the southwestern limit lies in Medina County where its identity is lost within the Balcones system.

The Charlotte fault zone is within Wilson, Atascosa, and Frio Counties, where it is a complex graben-like system of faults with southern landward-dipping faults and northern coastward-dipping faults. In the graben areas between there are numerous faults both landward and coastward dipping (Fowler, 1956, p. 37). The Mexia fault zone and the Charlotte belt are mirror images of one another being north and south respectively of the San Marcos arch. This arch was a broad structural promontory of the Llano Uplift; it plunged southeast and was seldom a truly positive area, but subsided at a substantially slower rate than the basins it divided (Luttrell, 1977, p. 261). The Mexia fault zone contains both down-to-the-east and up-to-the-east faults, and it extends north of Milam County into the East Texas basin, the northern limit of the study area.

The "serpentine plugs" of this investigation are associated principally with down-to-the-northwest faulting associated with the Luling and Charlotte fault zones, which, from direction of throw and magnitude, appear to be basement related (Fig. 2).

In the southwestern portion of the study area the Rio Grande embayment is a region of compressional faulting and folding. The Maverick basin is a subprovince of that embayment, which occurs in Maverick, Dimmit, and Zavala Counties (Fig. 2). The Rio Grande embayment was a gentle subsiding feature throughout Cretaceous and into early Tertiary time (Bebout and Loucks, 1974, p. 14). Later, during the Laramide orogeny the embayment was compressed to form the broad Chittim anticline and the Eagle Pass and Zavala synclines (Martinez, 1982, p. 10). Only minor faulting was associated with the deformation of this basin.

A transitional zone lies between the compressional structures of the Rio Grande embayment to the southwest and the extensional structures of the northeast. The structures of Medina, NE Uvalde, NE Zavala, and Frio Counties appear to be of compressional origin as is suggested by the southwest-plunging Pearsall anticline (Fig. 2). To the northwest and southeast the occurrence of normal faults and the position of the Pearsall anticline fold-axis transverse, with respect to the fold axes of the Rio Grande embayment, suggest the net effect of crustal extension (Fowler, 1956, p. 38).

The Rio Grande embayment, Pearsall anticline, Angelina-Caldwell flexure, and the San Marcos platform together comprise elements of a broad, subsiding continental shelf, which existed during Mesozoic time prior to the deposition of the Austin Chalk. The intrusive and volcanic activity that occurred along the margins of the ancient Gulf of Mexico preceded earliest recorded folding in the Rio Grande embayment and was contemporaneous with the normal faulting in the northern San Marcos arch area (Fowler, 1956, p. 41). Thus, it is probable that the igneous bodies on the southwestern edge of the arch were also contemporaneous with faulting.

Stratigraphically, the "serpentine plugs" throughout central and south Texas are confined to Gulfian age, Late Cretaceous (Coniacian/Campanian) Austin and Taylor Formations. They were extruded onto the paleo-seafloor during a period of igneous activity associated with extension, and the net effect on stratigraphy is reflected in formations ranging in age from the Cenomanian Buda Limestone to the Maestrichtian Escondido sand (Fig. 3).

DESCRIPTIVE GEOLOGY OF "SERPENTINE PLUGS"

The approximately 225 surface and subsurface occurrences of "serpentine plugs" within the "serpentine plug" trend are naturally divided into three subprovinces based on production histories and associated facies. These subprovinces include (1) a northern group in which the dominant hydrocarbon saturation is in the altered volcanics, (2) a middle group characterized by hydrocarbon saturated biocalcarenite, and (3) a southern group that has provided structure for well developed and productive overlying and marginal sands. Each of these three subprovinces is discussed in the sections that follow.

Use of the term "serpentine plug" to describe these unique features has come under much criticism. Initially, the altered igneous bodies were thought to be intrusive in origin; thus, the "plug" designation was appropriate. Further work on surface and subsurface examples revealed that the rocks were neither serpentine nor intrusive. They were, instead, recognized as a complex assemblage of hydrated magnesium silicates derived from the alteration of extrusive basaltic rocks. Texturally, they were indicative of pyroclastics resulting from extrusive volcanic activity in a submarine environment. Therefore, the name most widely used to denote these features is an error so thoroughly ingrained in geologic literature and so permanently entrenched by usage that it will almost certainly continue to be part of the Late Cretaceous nomenclature of central and south Texas.

NORTHERN SUBPROVINCE

Within the northern subprovince approximately 70 "serpentine plugs" have been described in surface and subsurface occurrences. These are confined to Williamson, Travis, Bastrop, Hays, Comal, Caldwell, and Guadalupe Counties (Ewing and Caran, 1982, p. 141) (Fig. 2).

Stratigraphically, the "serpentine plugs" of the northern subprovinces lie within the Upper Cretaceous (Santonian/Campanian) Austin and Taylor Formations (Fig. 3).

The volcanic and intrusive centers roughly parallel the Balcones and Luling fault zones, oriented on an axis trending approximately N 30° E. The largest grouping of "serpentine plugs" in the northern subprovince appears to extend from southwest Bastrop County, through central Caldwell County, into northern Guadalupe County (Fig. 2). This concentration of volcanic centers coincides directly with the down-to-the-north-northwest faults of the Luling fault zone where displacements of up to 1500 ft (≈ 460 m) occur (Weeks, 1945, p. 1734). There may be a relationship between the down-to-the-northwest faults, which (from direction of throw and magnitude) appear to be basement related, and the higher concentration of plug occurrences in this trend. Faults are directly and clearly related to several of the volcanic centers such as Lytton Springs and Yoast, whereas other fields such as the Buchanan field were discovered by wells located to test surface faults not recognized as "plug-related" (Sellards, 1932, p. 758). Major movement along the Luling fault zone occurred in Miocene time, but earlier movement occurred during Late Cretaceous time (Weeks, 1945, p. 1736). The alignment of "serpentine plugs" along the Luling fault zone and the orientation of faults in the various fields suggets that Luling faulting was active in central Texas during Austin/Taylor time.

The surfaces of larger volcanic mounds are relatively flattened ovate shapes, whereas smaller mounds may tend to rise to peaks. The volcanic mounds rose from approximately 150 to 300 ft (≈ 46-90 m) above the Austin sea floor, and present dips in adjacent and overlying beds are generally less than 5° (Ewing and Caran, 1982, p. 137).

Approximately 41 oil fields have been discovered in the northern subprovince in Williamson, Travis, Bastrop, Caldwell, and Guadalupe Counties (Fig. 2). All occur within the Austin and Taylor Formations. In most of the fields the extrusive rocks rest on Austin Chalk and are overlain by Taylor Marl. In other fields as much as 10 ft (≈ 3 m) of Taylor Marl have been found between the "serpentine" and the Austin Chalk (Sellards, 1932, p. 746). In the Lytton Springs field (Bybee and Short, 1925, p. 13) the drill passed from igneous rock into chalk and back into igneous rock, thus demonstrating the stratification of the volcanics and the sedimentary rocks.

The dominant producing rock of the northern subprovince is an alteration product of an alkaline-rich, silica-deficient basalt. The massive igneous rock in the northern subprovince is dark gray and porphyritic, with an aphanitic groundmass. The main rock constituents are olivine, clinopyroxene, and plagioclase with a groundmass composed of magnetite, clinopyroxene, apatite, and partly devitrified glass (Barker and Young, 1979, p. 9). On this basis the name "nepheline basanite" was given to the unaltered igneous rocks of the northern subprovince (ibid., p. 1). Basanites and nephelinites are more silica undersaturated and contain more alkali and volatiles than do alkali basalts. Basanites and nephelinites are generally much less abundant than alkali basalts, and they most often occur as products of intraplate volcanoes on continental rift zones (Fisher and Schmincke, 1984, p. 20). Of the rocks known from the northern subprovince none show more differentiation than is indicated by nepheline basanite (Ewing and Caran, 1982, p. 140). The parent magma is considered to have been an olivine nephelinite variety (Spencer, 1969, p. 272).

Around the eruption center ash and lapilli accumulated, mostly or entirely submarine, forming domal tuff accumulations that filled and buried the craters of the volcanoes after an explosive eruption. The tuff mounds were composed mainly of lapilli tuff and ash (Barker and Young, 1979, p. 19). The lapilli tuff and ash near Austin, Texas, consist of angular and subrounded fragments of completely altered and devitrified scoria, still preserving outlines of vesicles and of crystals of olivine, clinopyroxene, and plagioclase (Barker and Young, 1979, p. 19). Much of the glass and nearly all crystalline phases have been altered to clay minerals of the smectite group, chiefly of the Fe-Mg rich nontronite and saponite series (Weiss and Clabaugh, 1955, p. 146).

The glassy shards created by explosions became hydrated in the submarine environment and underwent alteration by palagonitization, the formation of a mineraloid formed by the alteration of basaltic glass (Fisher and Schmincke, 1984, p. 314-327).

A caprock of limestone overlies the "serpentine" in a few fields such as Thrall, Chapman Abbott, and the Buchanan oil fields (Fig. 2). The limestone occurs principally on the north, northeast, and northwest sides of the volcanic centers suggesting a regional pattern of predominantly northeast winds and ocean currents. The limestones consist largely of porous shell breccia composed of oyster-algal grainstones. These shoal-water carbonates (McKown and Dale Limestones) are localized facies of Austin age associated only with the volcanic centers. In a few fields the upper Austin Formation and portions of the lower Taylor Formation have been truncated by erosion, and younger Taylor sediments overlie the "serpentine plugs." These limestones lose their shoal-water characteristics farther from the volcanic centers where they consist of clay, marl, and chalky limestone. Some of the fields developed over volcanic centers; notably the Lytton Springs and Yoast fields have little or no documented carbonate development.

Locally, doming of overlying sedimentary rocks over igneous "plugs" has been described in a few fields, such as Lytton Springs, Thrall, and Chapman Abbott. This slight doming may have been caused by (1) sedimentary draping over a volcanic core, or (2) intrusive igneous activity following deposition of overlying sedimentary rocks. It is doubtful that this doming continues above the Taylor Formation, having been concealed by Taylor deposition (Sellards, 1932, p. 751). Faulting within known fields apparently occurred after the placement of volcanic centers and was caused either by collapse of the crater walls or by slumping along the outer flanks of the "serpentine plug" (Simmons, 1967, p. 129).

Hilbig field, 10 mi (16 km) southwest of Bastrop, in Bastrop County (Fig. 4), covers an area of approximately 1.2 mi² (≈ 3 km²) The stratigraphic section within Hilbig field is best illustrated by the Humble Oil, Hilbig Oil Unit #17 well (Fig. 5). The "serpentine plug" lies largely within the Austin Chalk and is covered by Taylor Marl. In several wells from 5 to 50 ft (≈ 1.5-15 m) of Austin Chalk overlie the "serpentine" (Blackburn, 1935, p. 1025). In places the chalk is located only on the flanks of the structure due to truncation by erosion. Here portions of the basal Taylor Formation are absent over the crest of the plug where younger Taylor-age sediments are in contact with the plug (Figs. 6, 7).

The central igneous core is a dome-shaped body with minor lobes extruded to the east and west from a central vent (Fig. 4). The steep side of the volcano is to the east-northeast, and it becomes gentle to the north-northwest and southwest. The subsea depths to the top of the "serpentine" range from 1878 to 2331 ft (≈ 570-710 m). Based on limited well control, a maximum thickness is thought to be approximately 450 ft (≈ 137 m). The thicknesses of beds that overlie the volcanic center are relatively uniform with only neglible doming in the Taylor Formation. This unconformity shows the limited effect of the "serpentine plug" on later regional structure of the area (Fig. 6).

Cores taken from the Hilbig field were examined both in hand specimen and microscopically and are described in Appendix I.

In hand specimens the producing rock is dull to dark olive green in color and conglomeratic, containing various quantities of calcareous material throughout the matrix. There is a large variation in the size of rock fragments; the finer fraction ranging from 1 mm to 4 mm, a maximum for tuff, and the larger particles up to 3.5 cm with an average size of from 4 to 6 mm, characteristic for lapilli tuff. The rock is a poorly to moderately sorted, subangular-subrounded, lapilli litharenite to lithrudite with sparry calcite as the matrix. Calcite or calcareous material is most abundant in samples consisting of larger rock fragments (Figs. 8a, 8b). The samples show definite graded bedding of coarse- to fine-grained particles.

The areal limit of pyroclastic rocks that form the tuff mound at Hilbig field is defined by the zero isopach of tuff, which surrounds the volcanic center, an area of approximately 0.68 mi² (≈ 1.8 km²) (Young et al., 1982, p. 57).

Porosity in the altered pyroclastic rock is both original and secondary. Porosity is commonly reduced with the occurrence of diagnetic filling or coating of grains and fractures. The controls on these diagenetic events are not well understood. The occurrence of calcite in the matrix and as fracture fill shows both original incorporation from marine deposition and later infiltration (Smiser and Winterman, 1935, p. 219). Portions of the pyroclastic section display porosity whereas others do not. The average porosity found within the producing interval of porous "serpentine" was 22% (Blackburn, 1935, p. 1036). In some examples a non-porous section overlies a porous section. This is given as evidence that alteration occurred from within (Blackburn, 1935, p. 1036). Portions of the core show altered pyroclastic rock in contact with Austin Chalk, and the contact is not noticeably altered.

The source for oil in Hilbig field is not known, but the overlying Taylor Formation is a suggested parent, as are the Austin Chalk and the Eagle Ford Group.

Pilot Knob is an excellent exposure of a mound of igneous material and associated rocks, located in east-central Travis County approximately 7 mi (≈ 11 km) southeast of Austin, Texas (Fig. 2). At Pilot Knob at least eight plug-like feeders of igneous rocks form the Knob (Ewing and Caran, 1982, p. 137). Linear trends

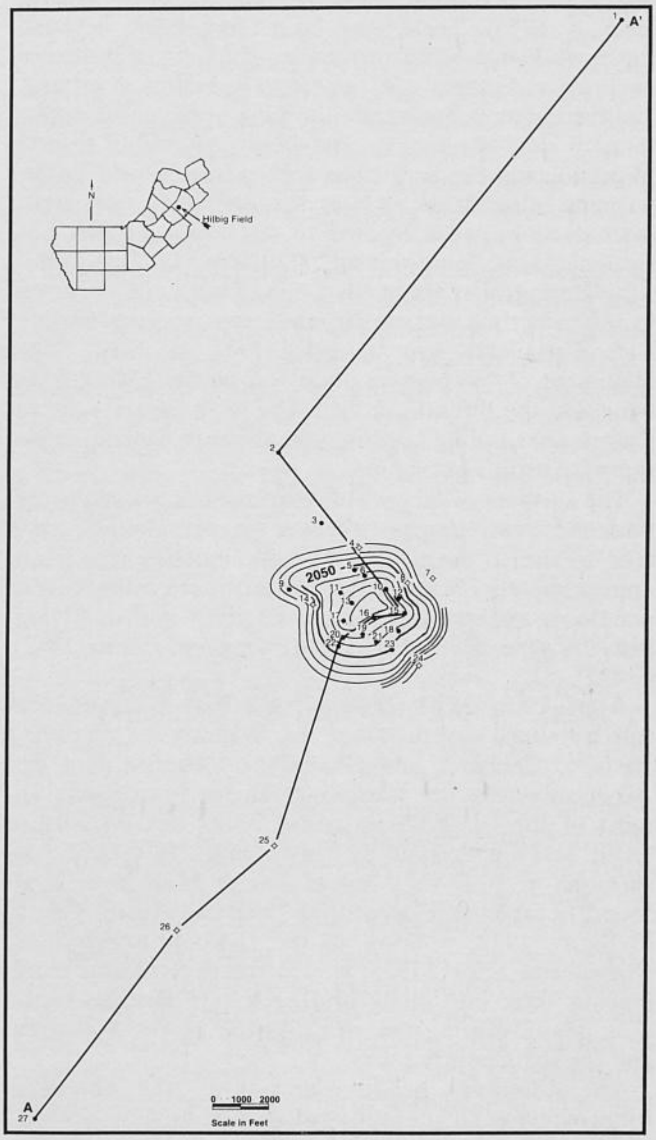


Fig. 4. Structure map, top of volcanics, Hilbig field, Bastrop County. *Modified* after Blackburn, 1935.

of distribution of igneous rocks in central and south Texas suggest that these features are dikes (Young et al., 1982, p. 52).

The vent at Pilot Knob supplied approximately 0.62 mi³ (≈ 2.6 km³) of ejecta to the surrounding area (Barker and Young, 1979, p. 5). Volcaniclastic rocks of both fine-grained ash and coarse-grained lapilli tuff accumulated mostly if not entirely underwater. The volcaniclastic rocks are stratified and in places exhibit crossbedding. Within the volcaniclastic facies, rock fragments ranging from pebble to boulder size (approximately 24 in (≈ 60 cm) are found. They are thought to be of Austin age, but possibly some Eagle Ford and Del Rio clasts are also included. The volcaniclastic rocks occur in close proximity to a volcanic center and occur sporadically filling shallow explosion craters, thus forming a cone. A dark greenish brown clayey ash occurs on the north, northeast, and northwest sides of the volcano, overlain by shoal-water carbonates consisting mainly of shell breccia. Flow rocks and volcaniclastic rocks interfinger with, and are overlain by carbonates, known locally as the McKown and Dale limestones (Fig. 9). The flow rocks and volcaniclastic deposits reach 820 ft (≈ 250 m) in thickness and thin distally as they interfinger with surrounding sedimentary rocks (Barker and Young, 1979, p. 6) (Fig. 10). Periods of erosion are indicated by truncation of volcaniclastic rocks at contacts with the overlying sedimentry rocks. Pilot Knob appears to be representative of the "plugs" in the northern group.

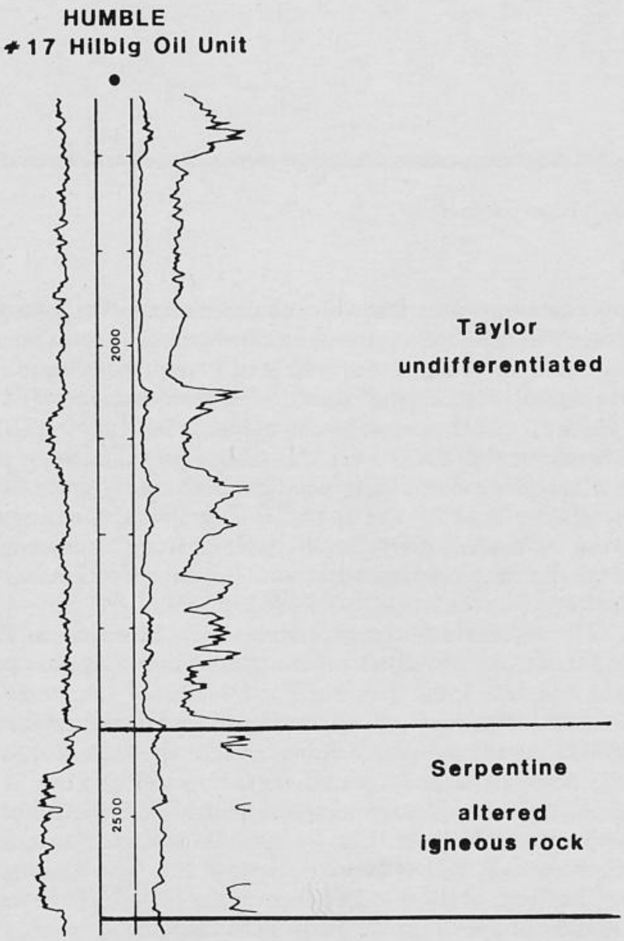


Fig. 5. Representative electric log from the Hilbig field, Bastrop County, showing signatures of the section of interest. Note the serrated SP signature of the "serpentine," which is overlain by Taylor age sediments. Saturation in altered igneous rock.

MIDDLE SUBPROVINCE

The middle subprovince has seven known fields associated with three to five volcanic centers (Fig. 2). The subprovince to date is confined to Wilson County, but with exploration portions of Guadalupe, Gonzales, Bexar, and Atascosa Counties may soon be included.

Stratigraphically, the "serpentine plugs" of the middle province appear to be older than those in the northern subprovince; in this middle province normal Austin shelf facies overlie the volcanic centers.

The total stratigraphic section involved ranges from the (Cenomanian) Buda Formation to the (Campanian) Taylor Formation. The "serpentine plugs" are Coniacian/Santonian Age, but their eruption affected older strata, as evidenced by loss of section from the Eagle Ford and Buda Formations in the immediate area of a volcanic center (Roy et al., 1981, p. 174).

The known volcanic centers are concentrated in the south-central portion of Wilson County (Fig. 2), where the area of "serpentine plugs" roughly coincides with down-to-the-northwest faulting of the Luling and Charlotte fault zones and lies within the graben area associated with these major faults. No faults within individual fields are known at this time.

No surface exposures of volcanic rocks exist in the middle area; thus, description relies largely on limited subsurface data, which allow for only broad generalizations.

The only published description of a volcanic center and its associated facies within the middle subprovince is of the North Poth area located in south-central Wilson County (Fig. 2). The regional dip of the Austin Formation is interrupted by a northeast-southwest trending anticlinal structure, which apparently owes its existence to the compaction of sediments over the volcanic complex. The volcanic center lies toward the northeastern end of an anticline, with associated pyroclastics and reworked volcanics accumulated to the southwest on the gently sloping side (Roy et al., 1981, p. 175). The gentle slope is due to the gradual thinning of the volcanics, which form a ramp to the southwest; a more rapid thinning occurs to the northeast forming a steeper slope. The average thickness of the Austin Formation within south-central Wilson County is between 250 and 300 ft (76-91 m); however, in the North Poth volcanic complex it thins to approximately 20 ft (6 m) over the volcanic center (ibid., 1981, p. 175).

A thin bioclastic reef or biocalcarenite facies, which forms a barchanoid beach deposit west of the volcano, overlies the slope of reworked volcanics and pyroclastic debris on the southwestern side of the volcanic center (ibid., 1981, p. 176). This beach deposit has a maximum thickness of 35 ft (11 m) and thins gradually to the west where it is less than 10 ft (3 m) thick 3 mi (5 km) from

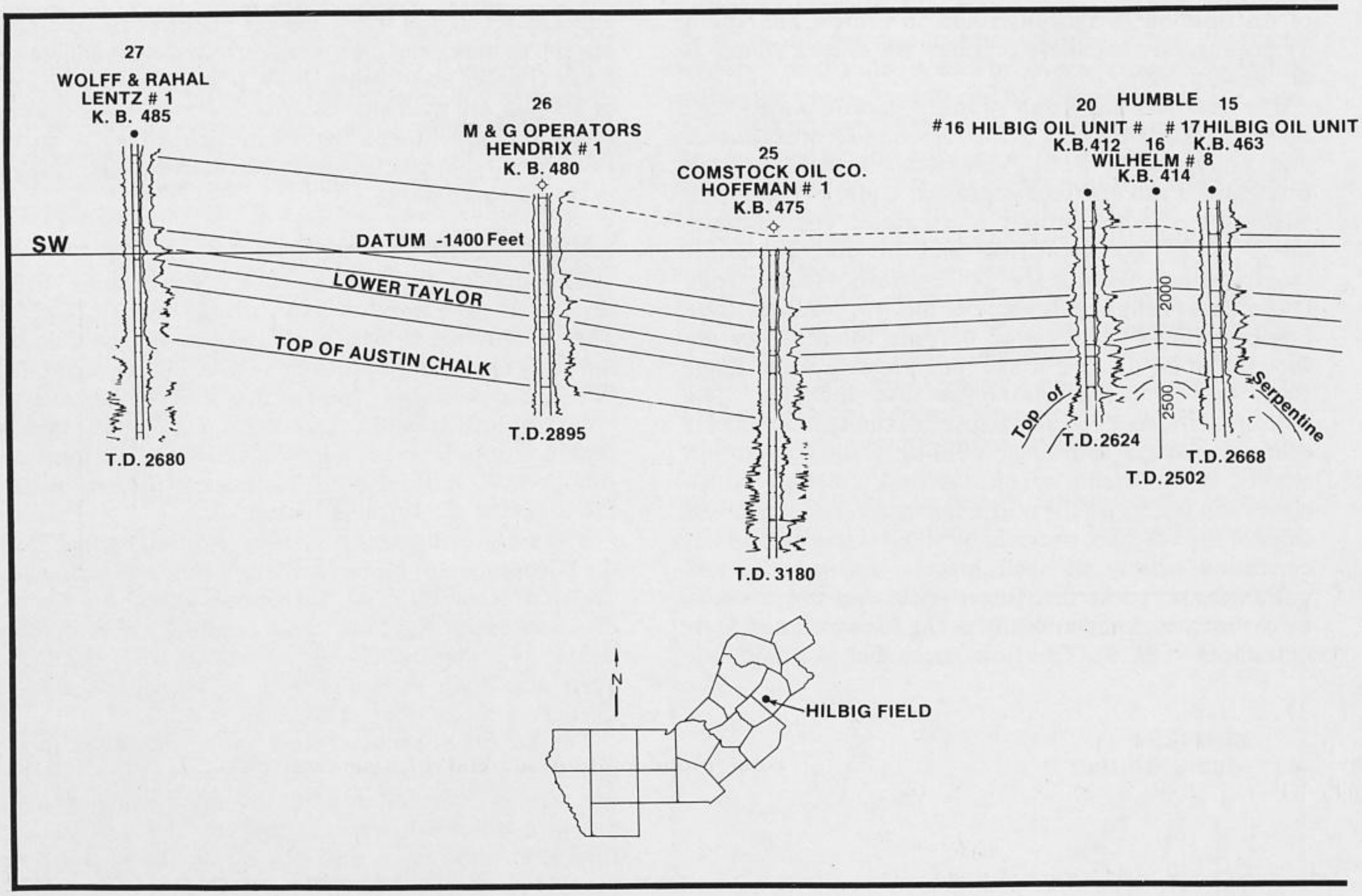


Fig. 6. Structure cross-section A-A', Hilbig field, Bastrop County. Datum 1400 ft below sea level.

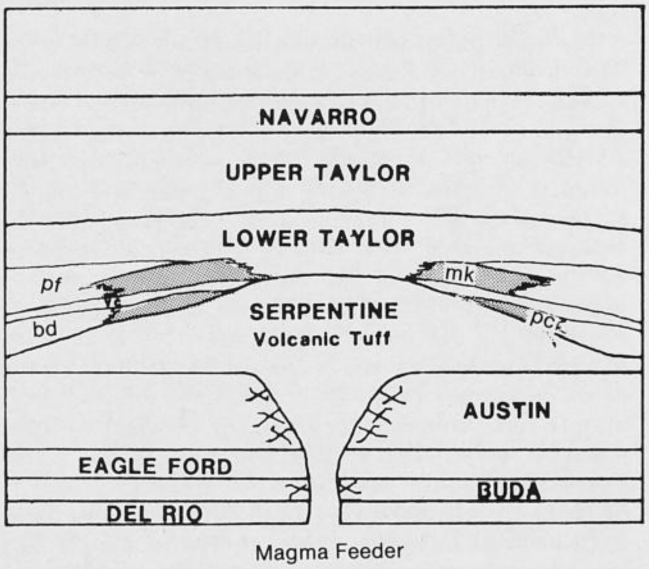


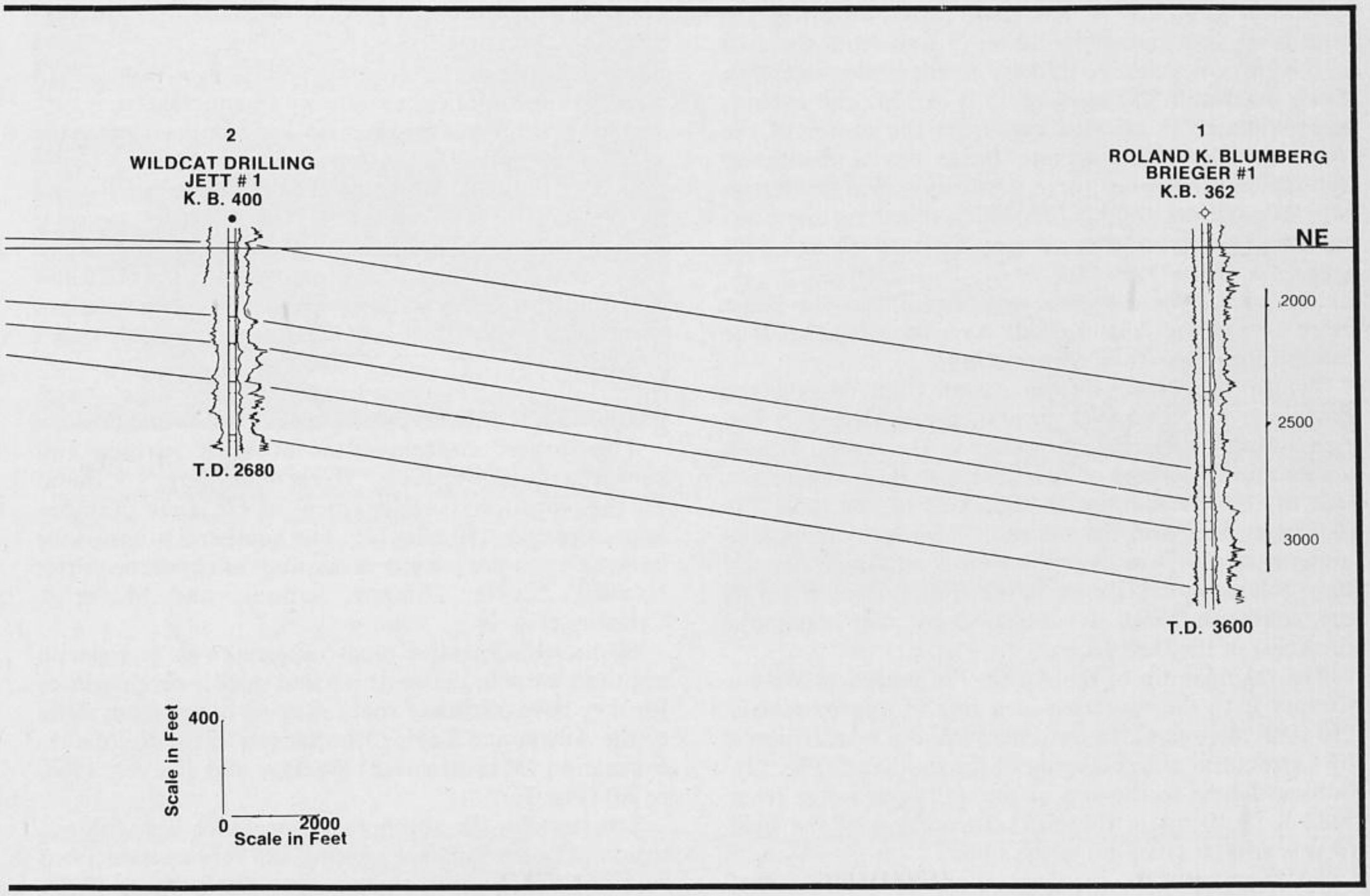
Fig. 7. Representative diagrammatic section of the "serpentine plugs" and their associated facies in the northern subprovince. Note the volcanic tuff filling the explosion crater, the reworked pyroclastic and volcaniclastic facies, the truncation of the McKown Formation, and the typical Austin shelf facies on the flanks of the volcanic center. Production shown as shaded is generally associated with the McKown Formation, pyroclastic facies, and various porous intervals of the volcanic tuff mound. (mk=McKown, pf=Pflugerville, vc=volcaniclastic, pc=pyroclastic, bd=Burditt).

the volcanic center. The volcanics around the "serpentine plugs" of the middle subprovince have much greater areal extent than those in the northern group, possibly due to origin in shallower water with resultant ramp-like beaches to the southwest (ibid., 1981, p. 176). Biocalcarenite zones over the ramp-like talus slope to the southwest indicate shallower water. Normally bioclastic beaches are found facing the predominant wind or current direction, but during Late Cretaceous time the predominant wind and current direction were from the northeast (Wilson, 1983, p. 27).

The occurrence of relatively thin biocalcarenites indicates that the conditions under which they formed did not last long. Normal shelf facies of the Austin Formation are deposited over the entire volcanic center, indicating the continued subsidence of the Gulf Coastal Plain and perhaps increased water depth (Fig. 11).

Sutil field is located in south-central Wilson County approximately 3 mi (5 km) from the Wilson and Atascosa County line, and it is here used as the type example of the fields of the middle subprovince (Fig. 2). It covers an area of approximately 6 mi^2 (15 km^2).

The stratigraphic section in Sutil field is best illustrated by the Barker Exploration Company, Bienck #1 well (Fig. 12). The Eagle Ford and Buda Formations were domed in the development of the mound, as is suggested by erosional removal of portions of both formations



around the volcanic center. Complete sections of Buda and Eagle Ford Formations are present in other wells northeast and southwest of the volcano.

The volcanic center lies largely within the Austin Formation. In some wells the lower Austin is absent, apparently removed by erosion before the extrusion of volcanic material (Fig. 13). The middle Austin is characterized by reworked, fine-to-coarse-grained pyroclastic material and altered volcanic material mixed with ejecta brought from greater depths in the lower Austin. Included within the upper Austin Formation is a porous biocalcarenite facies. The total thickness of the Austin Formation ranges from 180 to 300 ft (55-91 m).

The maximum thickness of total volcanic material encountered to date is in the M.D. McGregor, Doege #1 well where a total of 277 ft (84 m) of igneous rock was penetrated. This thickness includes both volcanic and pyroclastic material as well as ejecta from lower formations. The finer grained pyroclastic material is represented by low resistivity below the resistive biocalcarenite zone and above the resistive ejecta (Fig. 12). The low resistivity is believed to be indicative of a clay-rich zone saturated with interstitial waters. The isopach of the finer grained pyroclastic material shows rapid thinning to the east-northeast and gradual less pronounced thinning to the west-southwest (Fig. 14). The rapid thinning and stratigraphic relations of the volcanic material indicate that the northeastern side of the volcano is much steeper than the southwestern side.

It is probable that the volcanic material is predominantly ash and lapilli with compositions similar to that of the igneous material described for the northern subprovince. The parent magma is likely alkaline-rich, silica-deficient basalt. The green to gray fine-grained volcanic material immediately underlying the biocalcarenite has been altered principally to nontronite and saponite, Fe-Mg rich clay minerals of the smectite group (Appendix I). A more advanced stage of palagonitization is indicated by the occurrence of phillipsite, a zeolite that occurs as an alteration of volcanic glass (Hurlbut and Klein, 1977, p. 438). Phillipsite is also present as pore lining associated with the recrystallized calcite within the biocalcarenite facies (Fig. 15). Crystallization of phillipsite occurs in a closed marine system (geochemically) where no ion interaction occurs from an outside source (Fisher and Schmincke, 1984, p. 317).

Overlying the slope of the reworked volcanic talus to the southwest and sporadically to the east-northeast is a thin tan to gray bioclastic algal packstone-to-grainstone (Fig. 11; Appendix I). The occurrence of the red algae *Goniolithon* within the biocalcarenite facies is indicative of a high energy environment (Fig. 16). This unit reaches a maximum thickness of 30 ft (9 m) and thins gradually to less than 15 ft (4.5 m) to the southwest approximately 3.2 mi (5 km) from the area of thickest volcanics. To the east-northeast this limestone has a maximum thickness of 15 ft (4.5 m) and extends approximately 1 mi (1.6 km) from the center of the volcano. The biocalcarenite facies has a distinctive spontaneous potential curve, easily identified on electric logs. It possesses good permeability, reflecting intercrystalline primary porosity ranging between 12 and 18% (Figs. 12, 15).

The source for the oil is not certain, but the Eagle Ford Group and Austin Chalk have been suggested, as has the overlying Taylor Formation.

Typical shelf facies of the Austin Chalk overlie the biocalcarenite facies over the entire volcanic center. The non-volcanic calcareous lithology of the Austin attains a maximum thickness of 78 ft (24 m) on the southeastern side of the volcanic center and thins to less than 3 ft (0.9 m) directly over the volcano. This readily mappable uppermost unit was deposited on a relatively flat sea floor following subsidence of the Gulf Coastal Plain to the south-southeast as indicated by the maximum thickness of the shelf facies.

The regional dip of the Austin Formation in Wilson County is to the southeast at a rate of approximately 250 ft/mi (47 m/km). In Sutil field this dip is interrupted by a structural nose plunging to the southeast (Fig. 17). Subsea depths to the top of the volcanics range from 5282 ft (1610 m) in the northern portion of the field to near 6500 ft (1981 m) in the south.

To show original sea-floor topography a residual structure map was constructed, which shows an elongate, northeast-southwest asymmetrical cone, with the steeper side on the northeast (Fig. 18).

A southwest-northeast structural cross-section through the Sutil field also shows an anticlinal structure resulting from compaction of sediments around the volcanic complex (Fig. 13). Again, as in the case of the North Poth area, the biocalcarenite facies overlies the gentle slope to the southwest. The structural reversal shown on the cross-section provides evidence that tilting of the anticline occurred after extrusion of the volcanics and during the deposition of the Austin Formation, probably as a result of subsidence into the Gulf Coast Basin.

SOUTHERN SUBPROVINCE

The largest concentration of both surface and subsurface occurrences of "serpentine plugs" is found in the southern subprovince where they number approximately 150 (Fig. 2). The southern subprovince is a seven-county area consisting of Medina, Frio, Uvalde, Zavala, Dimmit, Kinney, and Maverick Counties (Fig. 2).

Here the "serpentine plugs" appear to be younger in age than those in the northern and middle subprovinces for they have disturbed rocks ranging in age from those of the Austin and Taylor Formations to the Escondido Formation (Maestrichtian) (Welder and Reeves, 1964, p. 20) (Fig. 3).

Structurally, the southern subprovince lies within a region of compressional faulting and folding associated with the Rio Grande embayment. The northern flank of the Rio Grande embayment, where a predominantly

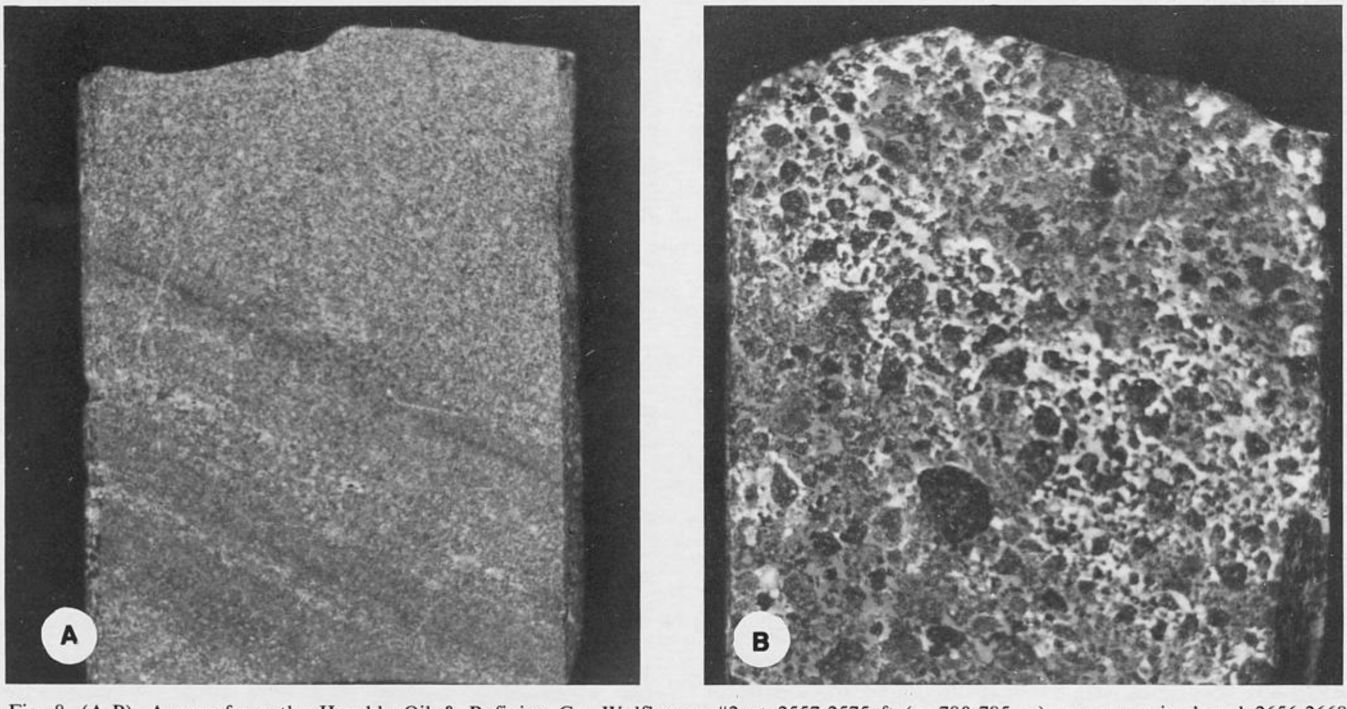


Fig. 8. (A-B). A core from the Humble Oil & Refining Co. Wolfbarger #2 at 2557-2575 ft (≈ 780-785 m), coarse grained and 2656-2668 ft (≈ 809-813 m), fine grained. The predominantly fine-grained sample shows crude bedding of fine and coarser grained fragments and faint cross-bedding. The coarse-grained sample shows the rounded, poorly to moderately sorted, conglomeratic nature of the pyroclastic material. The calcareous material is light colored and is visible as cement and fracture fill. Typically saturation occurs in the porous, diagenetically altered volcanic tuff, both fine and coarse grained. (A) = 1½ in (3.8 cm) wide; (B) = 2 in (5 cm) wide.

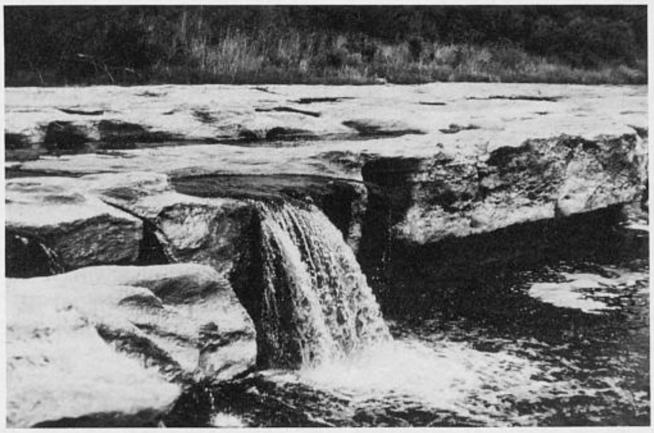


Fig. 9. McKown Formation exposed at McKinney Falls State Park. The McKown Formation is a shoal-water carbonate facies of the Austin Group, here underlain by fine-grained nontronitic clays. Just a few miles away from this locality are normal shelf facies of the Austin Formation. This appears to be typical of "plugs" of the northern region.

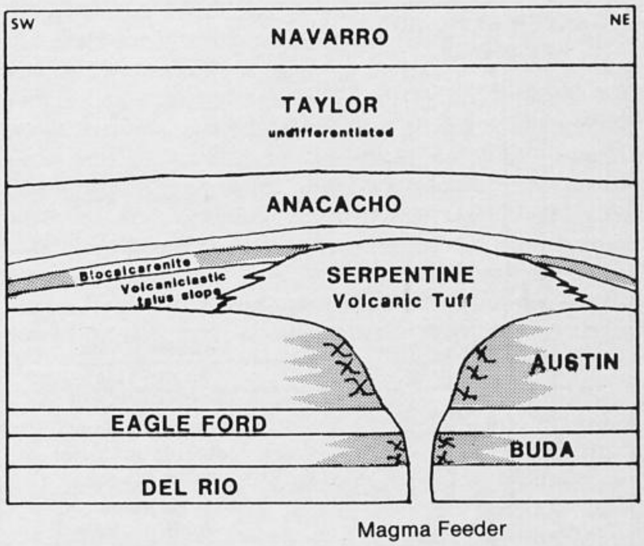


Fig. 11. Representative diagrammatic section of a "serpentine plug" and its associated facies in the middle subprovince.

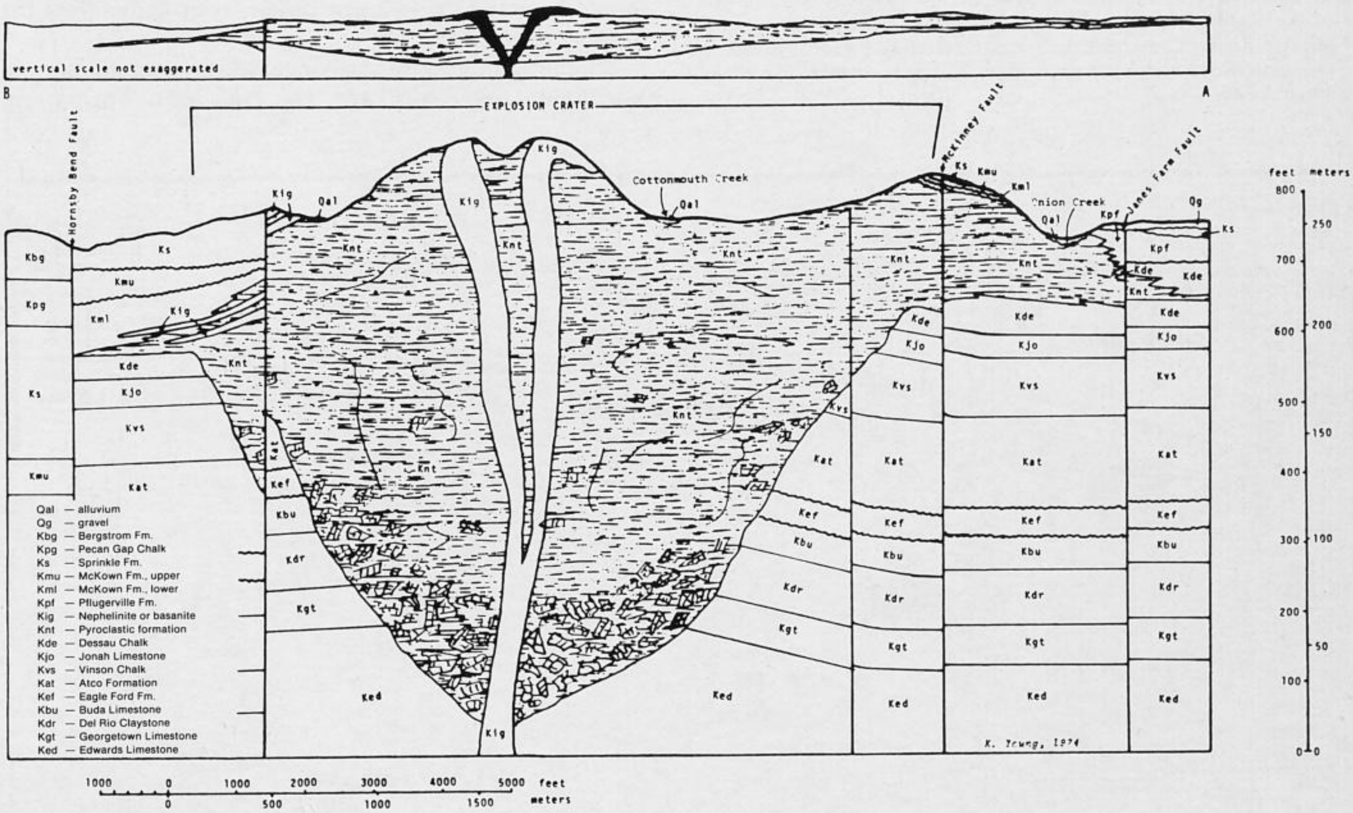


Fig. 10. East-west diagrammatic cross-section through Pilot Knob, Austin, Texas, showing the local interfingering of flow rocks, volcaniclastics, and carbonate units (*from* Young et al., 1982, p. 31). This interfingering of volcanics and carbonates occurs within the subsurface throughout the northern subprovince.

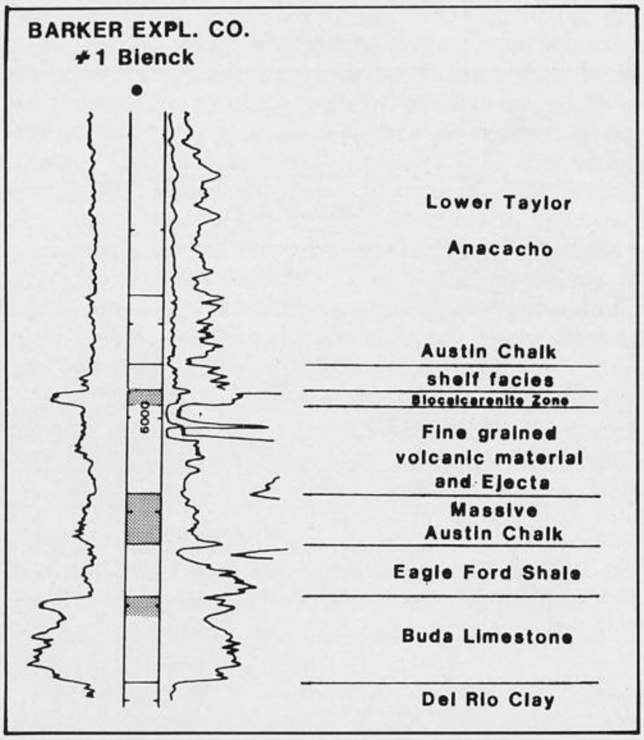


Fig. 12. Representative electric log from Sutil field, Wilson County, showing signatures of the entire section of interest. Note the distinctive SP signature of the biocalcarenite zone, the low resistivity characteristic of the fine-grained pyroclastic zone, and the contact between the massive Austin Chalk and the ejecta. Saturation (shaded) occurs in the upper Buda, lower Austin, and in the biocalcarenite zone of the upper Austin.

east-west strike changes to a north-south strike, was the major focus of volcanic activity. The southwestern boundary coincides roughly with the axis of the Rio Grande embayment, and the southeastern boundary with the Pearsall arch. No conspicuous alignment of "plug" groups is apparent within the southern subprovince, although there is some elongation of individual volcanic centers along the Balcones fault zone. Similar rough parallel alignment is shown along a line east of the northwest-southeast trending Chittim anticline and Zavala syncline to the west (Fig. 2). These lineaments formed during deformation of the basin, with which only minor faulting was associated.

Approximately 55 "serpentine plugs" occur in the subsurface of the southern subprovince in Medina, Frio, Zavala, and Dimmit Counties, south and southeast of the outcrop of the Anacacho Formation. The largest concentration occurs in Zavala County (Fig. 2).

Mineralogically, igneous rocks of the southern subprovince contain olivine, pyroxene, plagioclase, and nepheline. Mellilite occurs when plagioclase is absent (Spencer, 1965, p. 15). Accessory minerals include biotite, apatite, opaque minerals, analcite, and amphiboles, and zeolites. Chlorite occurs as an alteration product of the pyroclastic basaltic rocks (Spencer, 1969, p. 287).

Pyroclastic rocks such as ash and lapilli formed by explosive eruptions and accumulated to form a tuff mound around the volcanic center, eventually filling the initial crater.

In the southern subprovince widespread biohermal carbonates of Taylor age, the Anacacho Formation,

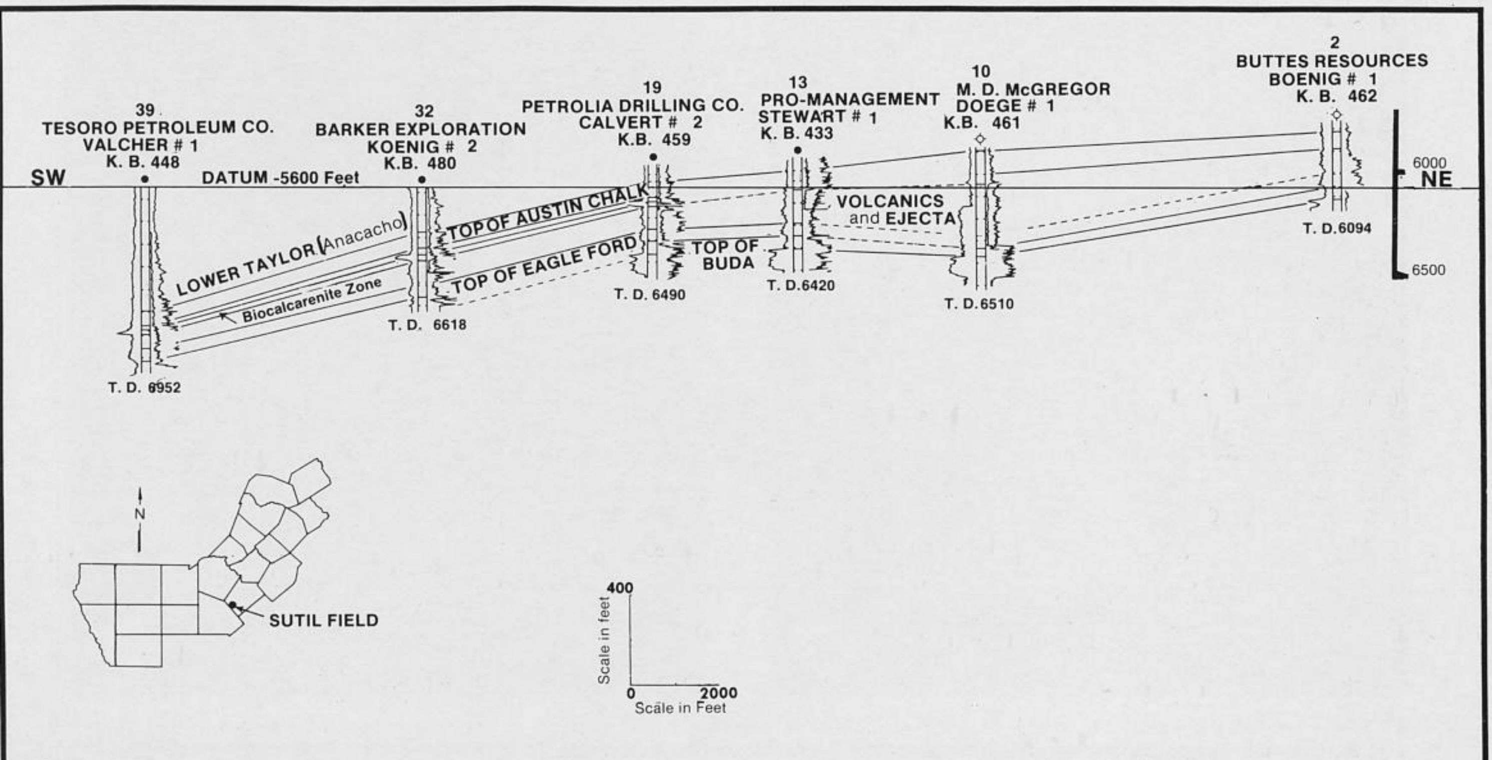


Fig. 13. SW-NE structure cross-section B-B', Sutil field, Wilson County. Datum 5600 ft (≈ 1700 m) below sea level.

overlie the volcanic centers. The best documented development of the Anachacho Formation is at Elaine field, north-central Dimmit County (Fig. 2). The depositional environments of five carbonate facies in the Elaine field were described and interpreted on the basis of allochem type and relative amount of micrite in the carbonate rocks. These represent open shelf, beach, lagoon, packstone halo, and reef environments (Luttrell, 1977, p. 262) (Fig. 19). The facies of the shoal complex with the greatest shell content was best developed on the northeastern side of the volcanic center (ibid., 1977, p. 263). This relationship is similar to that in the northern subprovince, where the development of the McKown and Dale limestones occurred on the northeast, north, and northwest sides of the volcanic centers, suggesting a regional pattern of prevailing northeasterly winds and ocean currents. Red algae occur in all environments but were most abundant in the shoal complex. Similar relationships exist in the shoal-water carbonates in the northern and middle subprovinces. Only local shell accumulations with little reworking have been described from the southwest side of the volcanic center at the Elaine field, but based upon the middle subprovince it is possible that more extensive carbonate reservoirs exist

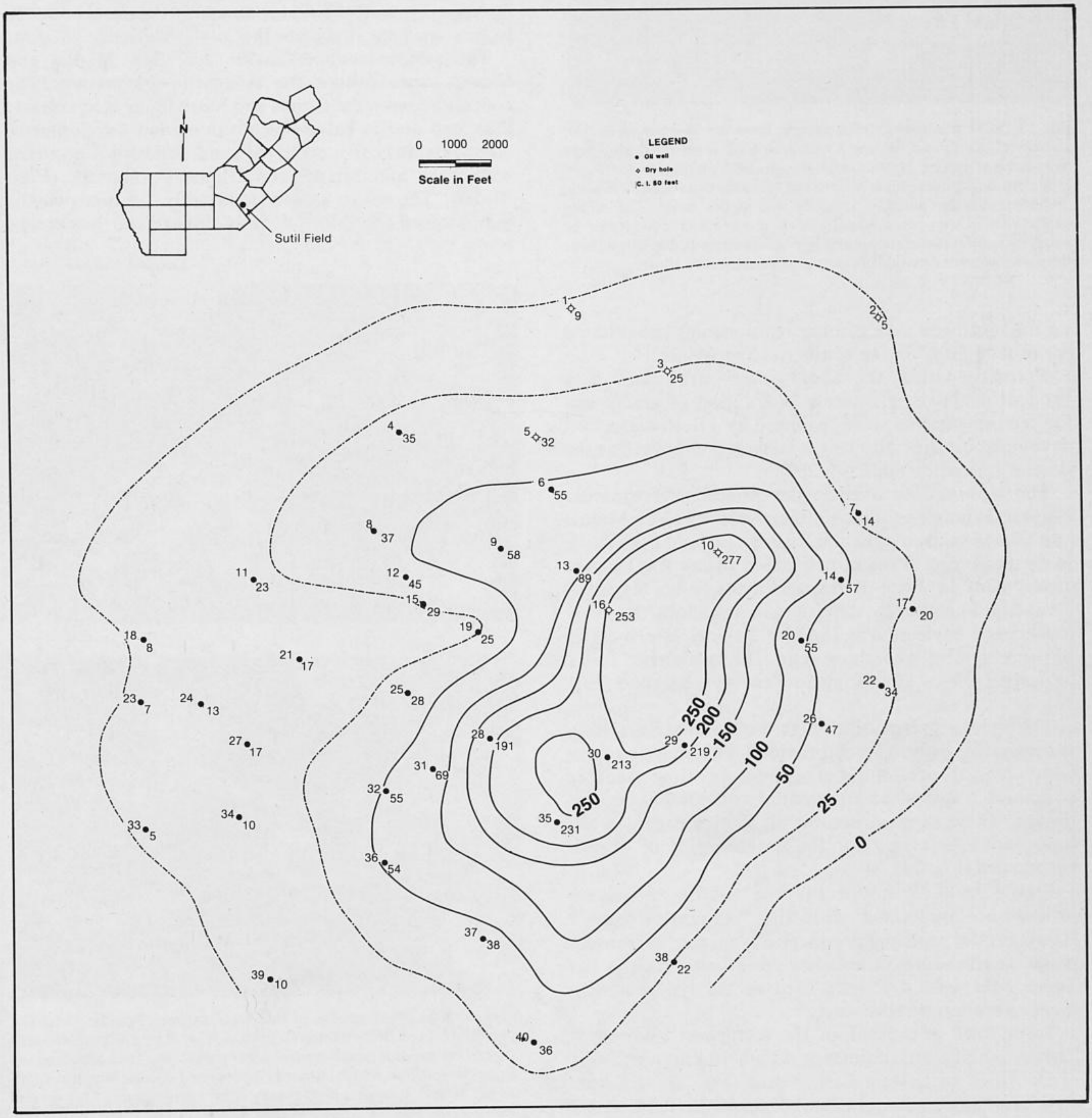


Fig. 14. Isopach map of fine-grained volcanics, Sutil field.

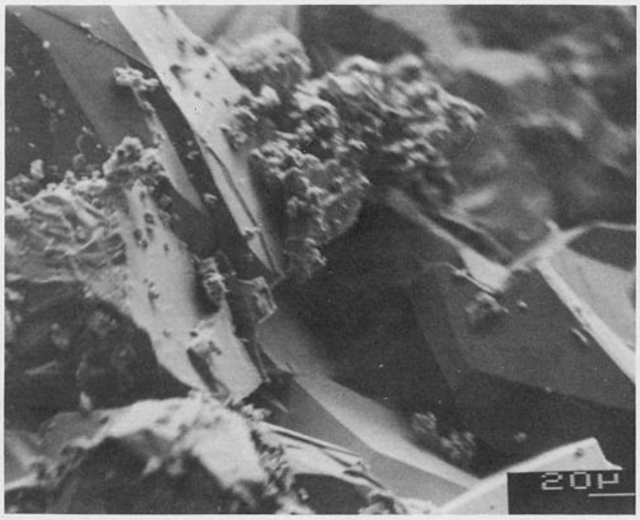


Fig. 15. SEM photograph of a sample from the Petrolia Drlg. Co. Calvert #2, Sutil field, Wilson County, at 6138 ft (≈ 1871 m). Large recrystallized calcite crystals with fine-grained phillipsite developed as a pore lining are evident within the biocalcarenite facies reducing the intercrystalline porosity normally seen in this facies. The zeolite phillipsite occurs as a result of a more advanced stage of palagonitization. Saturation normally occurs sporadically throughout this facies where favorable porosity and permeability allow.

on the southwest side. Similar relationships should hold for other "plugs" in the southern subprovince.

Porosity within the shoal-water carbonates is a product of diagenesis, where dissolution of grains and limited cementation were enhanced by a fresh-water lens developed in association with subaerial exposure at the time of formation (Ibid., p. 260).

The Upson Clay overlies the Anacacho Formation (Taylor) in portions of the southern area. The San Miguel and Olmos sands overlie the Upson Clay and are known to be developed in the northern end of the Rio Grande embayment in Frio, Dimmit, Zavala, and Maverick Counties. These sands, deposited in a shallow, relatively low-energy environment (middle Taylor), are a series of overlapping nearshore and fluvial-deltaic facies indicative of an advancing low-energy shoreline (Fig. 20).

The effect of "serpentine plugs" on regional deposition is neglegible. Locally, they provided bottom highs upon which sands accumulated. These in time became structural traps, when differential compaction created domes. These same structural highs also provided the topography necessary for the development of porous carbonates (Fig. 21).

Elaine field is noted for the major carbonate production associated with the "serpentine plug." However, the principal production from the "serpentine plugs" in the southern area occurs in fields such as the Torch field, and it is here used as the type example for the southern subprovince.

Torch field is located in the southwest quarter of Zavala County, approximately 12 mi (19 km) northwest of the town of Crystal City, Texas (Fig. 2). It covers an area of approximately 1 mi^2 (2.6 km^2).

The stratigraphic section in the Torch field is best illustrated by the Skelly Oil Company, Ware #2 well (Fig. 22). The "serpentine" lies within the Austin and Taylor Formations (Fig. 3). The top of massive igneous rock was penetrated in several wells, but no wells are known to have penetrated through a volcanic center. Cores of the igneous material show variable degrees of alteration. Unaltered basaltic rock was encountered in two wells, whereas highly altered fine-grained ash and lapilli, which formed the tuff mound, occurred in other wells (Lewis, 1962, p. 257).

Overlying the "serpentine" mainly on the flanks of the volcanic center is the Anacacho Formation of Taylor age. Comparison with electric logs from Sutil field shows the spontaneous potential character in the shoal complex to be somewhat similar to that of Torch field.

The middle-to-upper-Taylor age, San Miguel and Olmos sands overlie the Anacacho Formation. The contact between the Olmos and San Miguel is not clearly indicated and is based solely upon sand development. Approximately five cycles of sand deposition occurred within the San Miguel and Olmos Formations (Figs. 22, 23). The shales interbedded with the sands in the San Miguel are thinly bedded, black, and calcareous

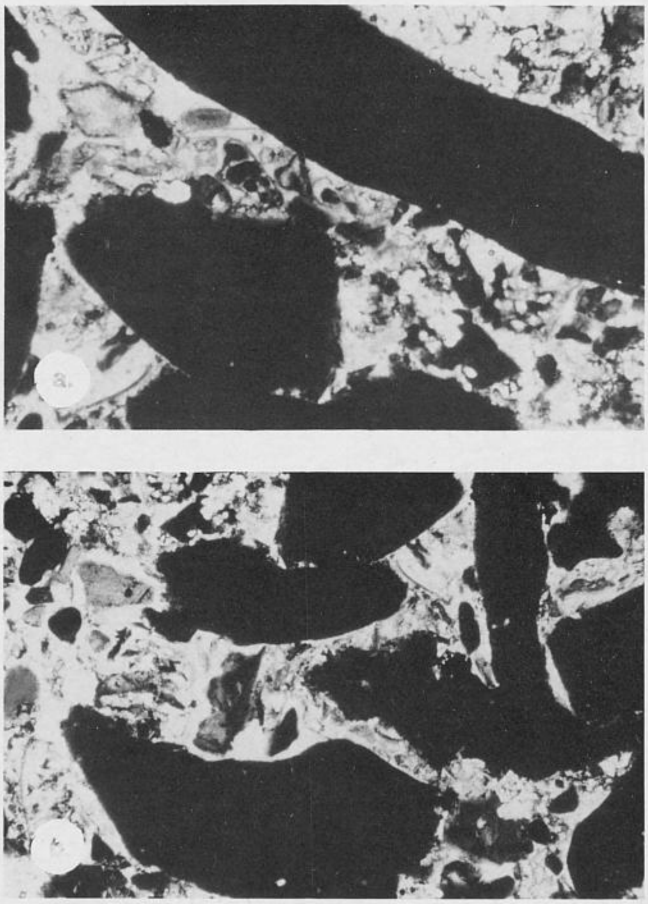


Fig. 16. (a-b). Photographs of thin sections from Petrolia Drlg. Co. Calvert #2, Sutil field, Wilson County, at 6141 ft (≈ 1872 m), showing slightly oil-stained, poorly sorted, algal packstone. The encrusting red algae *Goniolithon*, which shows well-preserved cellular structure (dark areas), is indicative of a high-energy shoal environment. Also present are gastropods, echinoid spines, foraminifers, and pelecypod fragments.

(Lewis, 1977, p. 93). The sands are usually fine-grained quartz sands with a clay matrix containing volcanic fragments. The occurrence of volcanic fragments within the sands indicates that the "serpentine plugs" were topographically high and subject to wave erosion. The sands exhibit intense burrowing.

The "serpentine plug" is a domal structure with minor elongation to the south-southwest (Fig. 24). A graben roughly divides the field into northwest and southeast halves with a small northeast-southwest syncline lying to the northwest of the field (Fig. 24). The fault lying to the northwest has a throw of approximately 110 ft (33.5 m), and the fault to the southeast has a throw of approximately 130 ft (40 m). Within a structural field, such as Torch field, rarely are faults found with displacement greater than 140 ft (43 m), most being less than 100 ft (30 m) (ibid., p. 91). The faulting appears to die out on top of the "serpentine plug." There is very little effect of the faulting associated with the "serpentine plug" above the Cretaceous section (Fig. 23). The cause of the faulting within Torch field, and other structural fields of this type, is uncertain but believed to be due to the collapse of serpentine within the crater as overburden increased (Simmons, 1967, p. 129).

Due to the small size of the structure, the map contoured on the San Miguel "King" sand (the major producing sand in the field) shows only limited regional expression (Fig. 24). The faults apparently die out to the northeast, but the fault to the northwest may extend for some distance to the southwest as is indicated by

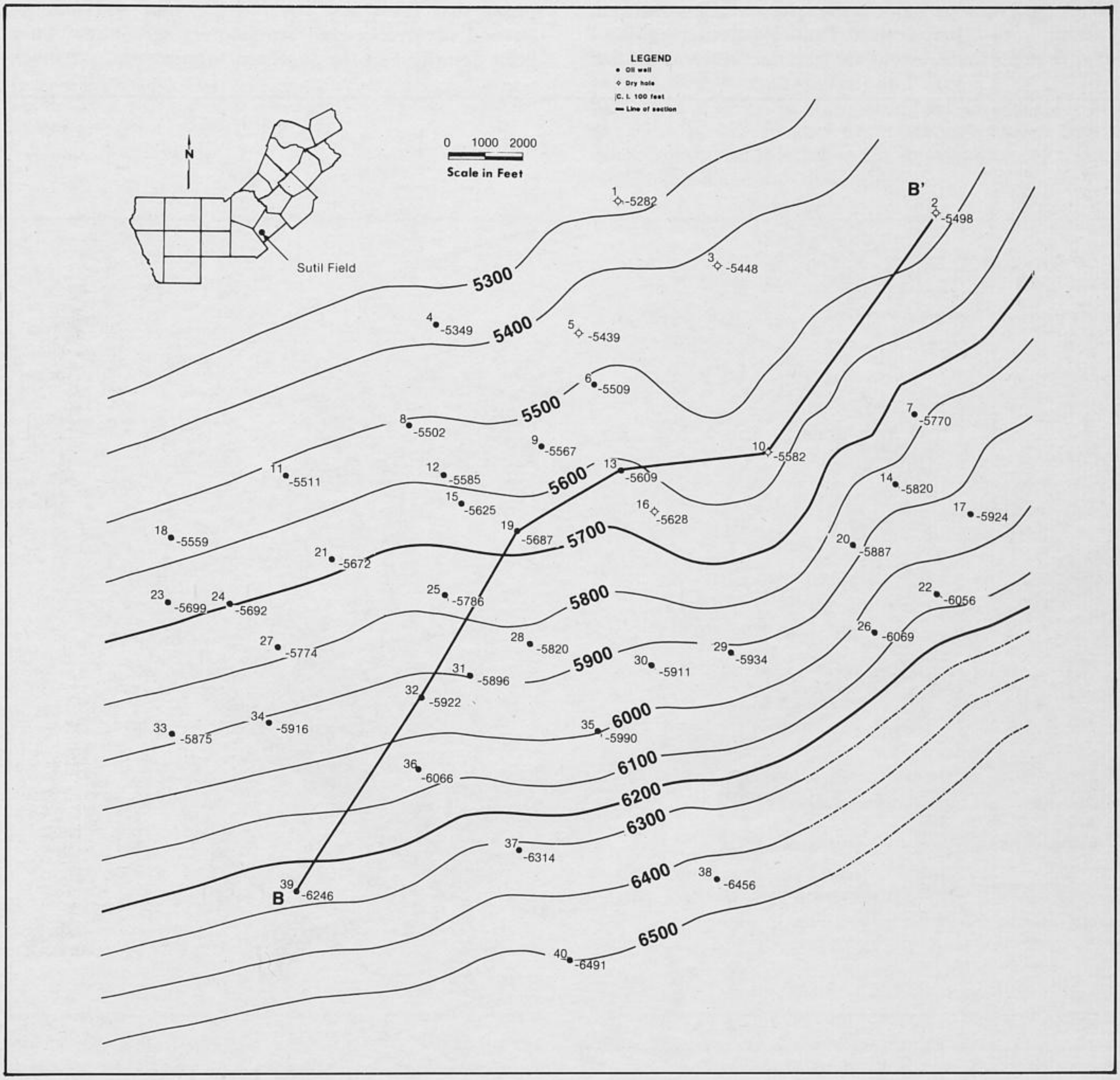


Fig. 17. Structure map, top of volcanics, Sutil field, Wilson County.

well #31, structurally low to the wells to the northwest. Both San Miguel and Olmos sands thin over the top of the structure, with perhaps some thinning evident in the Escondido sand of Navarro age (Fig. 23).

The producing sands of Torch field have an average porosity of 24% and an average permeability of 75 millidarcies (Lewis, 1977, p. 95). The source for the oil in Torch field is not known, but the shales in the alternating sands and shales of the Taylor Formation are suggested parents.

The massive igneous rocks of the southern subprovince are more abundant and more variable than in the northern and middle groups. Five major basaltic rock types are exposed in the south Texas area: (1) olivine nephelinite, (2) mellilite olivine, (3) analcite phonolite, (4) alkalic olivine basalt, and (5) nepheline basanite (Walker, 1982, p. 53). These alkalic, silica-deficient basaltic rock types, derived from a parent magma of olivine nephelinite, occur as sills, laccoliths, plug-like bodies, small volcanoes and a few dikes. All were either extruded onto the Late Cretaceous sea floor or were hypabyssal.

A quarry in Knippa, approximately 73 mi (117 km) west of San Antonio, has exposed a porphyritic, holocrystalline, mellilite-olivine nephelinite mass, with olivine, and pyroxene phenocrysts set in a groundmass of euhedral nepheline (ibid., p. 54) (Fig. 2).

The Black Waterhole locality, approximately 6 mi (10 km) east-northeast of Uvalde, exposes a smaller plug-like mass lying between two fragmental tuffs. Thus it is an example of a highly altered, unfragmented material filling in and overlying a tuff ring (Ewing and Caran, 1982, p. 139) (Fig. 2), probably indicating that initial violent eruptions with abundant pyroclastics eventually ceased as the mound rose, to be followed by a flow phase that filled and covered the vent and mound. Several occurrences of "sedimentary serpentine" have been described in the southern subprovince. At Black

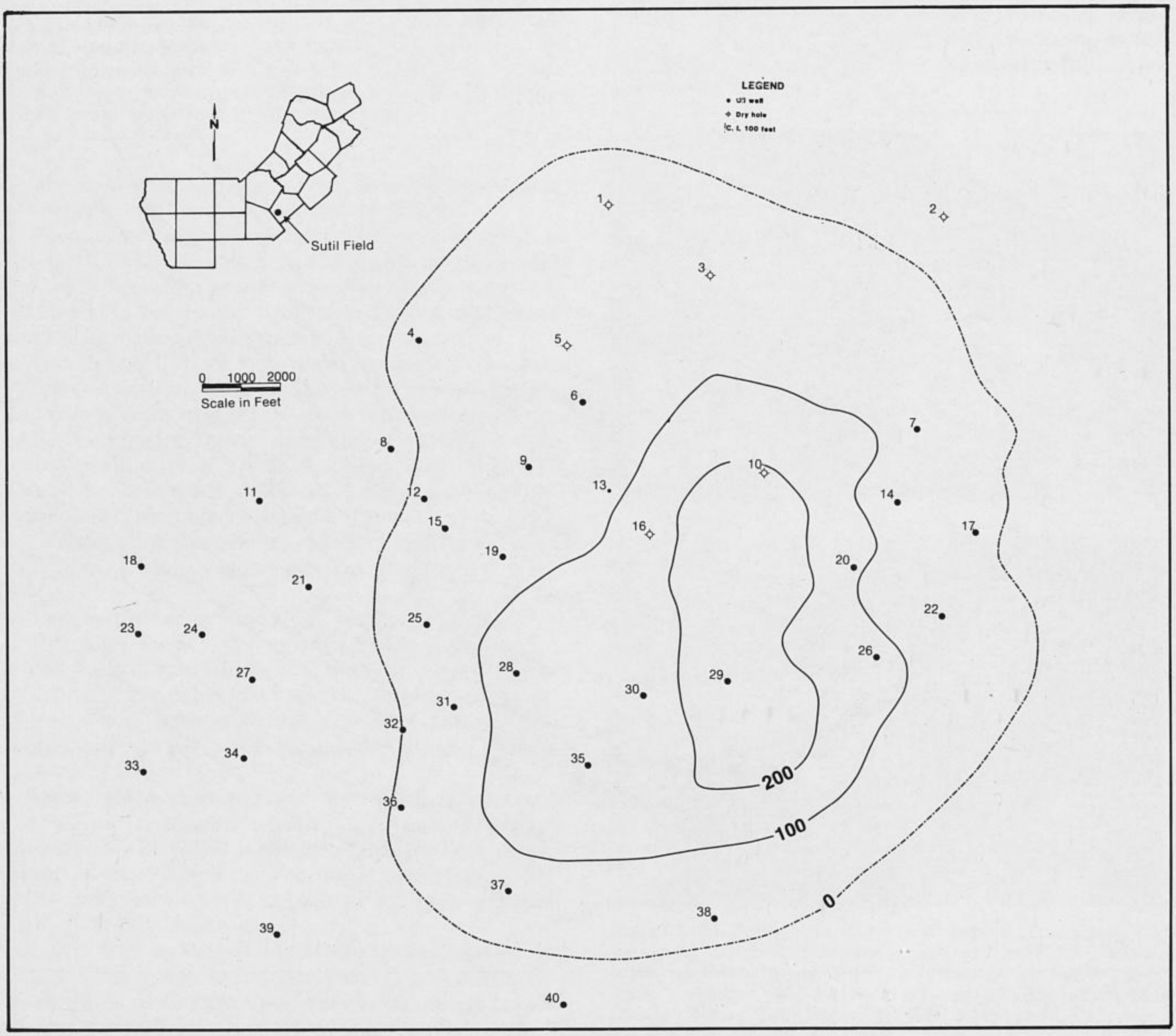
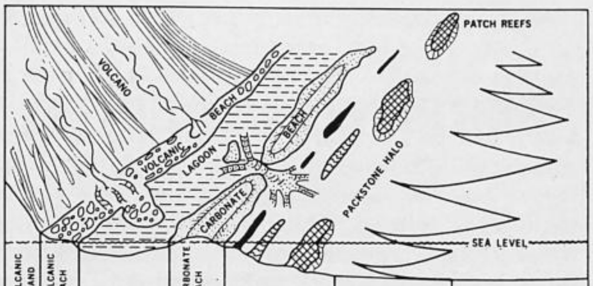


Fig. 18. Original sea floor topography of volcanics, Sutil field, Wilson County.



ENVIRONMENT	VOLCANIC ISLAND	VOLCANIC BEACH	LAGOON	CARBONATE BEACH	SHOREFACE	TRANSITION ZONE	OPEN SHELF
DOMINANT FEATURES		POOR SORTING	VOLCANIC DEBRIS, BEACH ALLOCHEMS	ALGAL BORING, ROUNDING, SORTING	RED ALGAL RIDGES, RUDIST REEFS, PACKSTONE HALO	STREAKY BEDDING, REEF DEBRIS	STREAKY BEDDING, LAMINATIONS, ARGILLACEOUS
PHYSICAL PROCESSES	EROSION	REWORKING	BURROWING, RIPPLES	CROSS-BEDDING, STORM DEPOSITS	CROSS-BEDDING, STORM DEPOSITS	BURROWING, STORM DEPOSITS	BURROWING, SLOW DEPOSITION, STORM DEPOSITS
TEXTURE			PACKSTONE GRAINSTONE WACKESTONE	GRAINSTONE BOUNDSTONE PACKSTONE	PACKSTONE WACKESTONE • BOUNDSTONE	WACKESTONE	MUDSTONE WACKESTONE

Fig. 19. Schematic model of the facies associated with the Elaine field volcanic complex, Dimmit County. The carbonate facies represent beach, lagoon, algal packstone halo, high-energy reef, and open-shelf environments (*from* Luttrell, 1977, p. 273).

Waterhole the "serpentine" occurs in distinct beds composed of fine- to coarse-grained, poorly to well-sorted pyroclastic material interbedded with thin calcareous layers (Lonsdale, 1927, p. 125). Calcite seams and the alteration of original igneous materials to clays (predominantly to chlorite) show much similarity to equivalent deposits in tuff mounds in the northern and middle subprovinces.

Surface exposures of the Anacacho Formation east and west of Uvalde consist predominantly of fine- to coarse-grained bryozoan-algal limestone, with alternating clay interbeds and some coquinoidal limestone (Fig. 2). Intense magmatism domed the Uvalde area during Austin and Taylor time leading to local subaerial erosion and deposition of shoal-water carbonates (Ewing and Caran, 1982, p. 142).

Outcrops within the Anacacho Mountains suggest that a patchy carbonate facies occurred over volcanic centers in Uvalde County. Later skeletal debris shed from the bank facies was reworked and transported to the southwest in the form of migrating sand waves (Wilson, D., 1983, p. 22). Further accumulation of shell debris to the southwest resulted in the development of a later bank sequence in that direction.

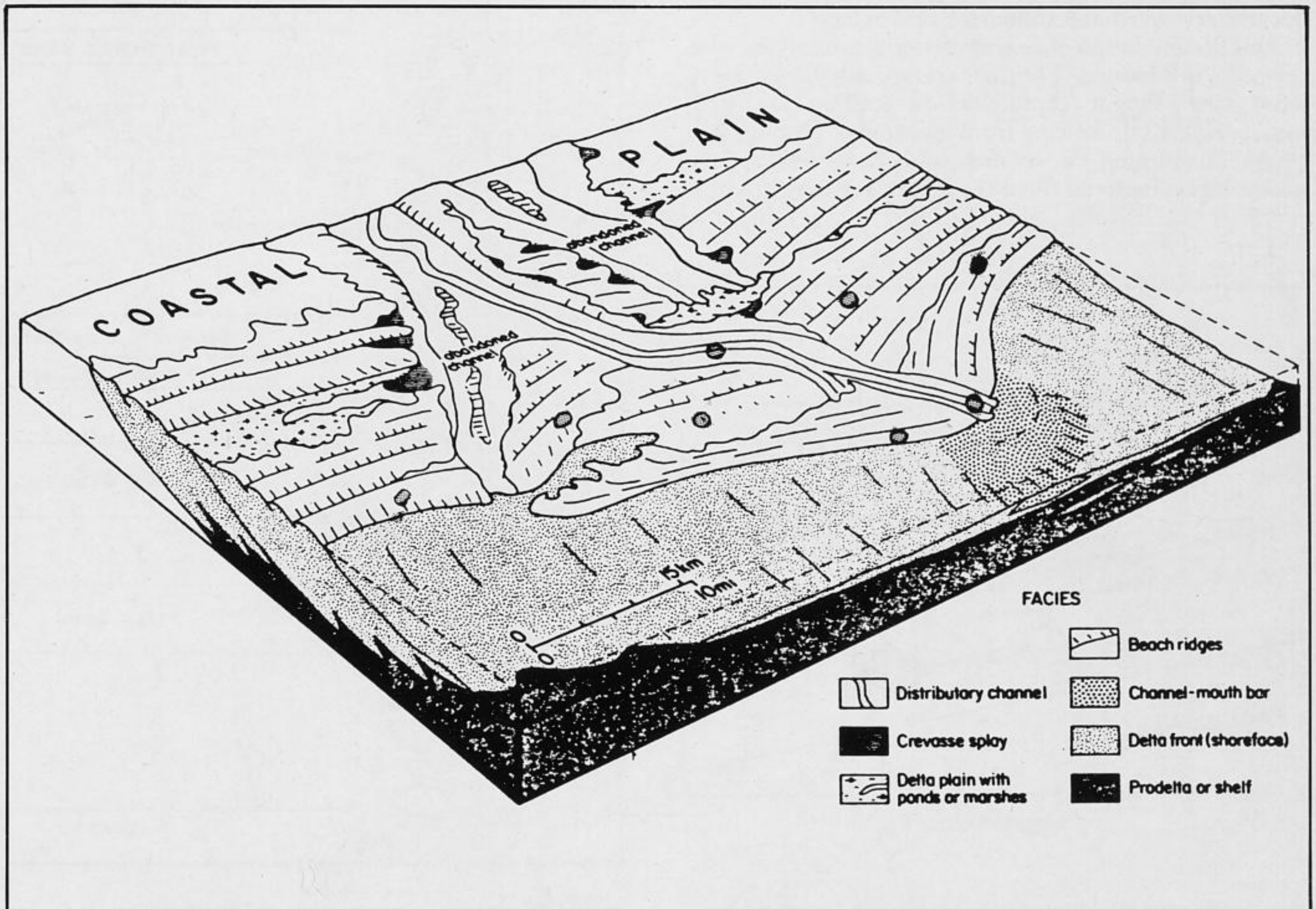


Fig. 20. Schematic depositional model of the San Miguel and Olmos sand reservoirs. The sands were deposited as a series of overlapping, nearshore and fluvial-deltaic facies indicative of an advancing shoreline. The principal reservoir facies are beach-ridge and delta-front deposits (*from* Weise, 1980, p. 20). The location of "serpentine plugs" is shaded. Note that these plugs caused localized sand deposition, but more importantly caused development of domes, which later became reservoirs.

ORIGIN AND HISTORY OF "SERPENTINE PLUGS"

It is not known if all the "serpentine plugs" originated in the same manner, though numerous similarities exist.

Throughout the area of this investigation the late Austin-early Taylor sea was relatively shallow, ranging between 100 and 300 ft (30-91 m) in depth (Martinez, 1982, p. 35). Volcanic activity began as intrusions into this marine section. Initially, each volcanic center consisted of one or more closely spaced dikes, or plug-like magma feeders, which extended along fractures to the surface. Upon breaching the sea floor, or encountering aquifers below the sea floor, the ascending magma exploded into a phreatomagmatic eruption (Fig. 25). These explosions, at or below sea level, created craters in the underlying sedimentary strata (Young et al., 1982, p. 53) from which ash and lapilli were blasted skyward in a fluidized steam jet. Much of the ejected material fell back into the crater to be again expelled, while larger more consolidated material fell back into the crater and became reworked and rounded by turbulence.

This accumulation of coarser material around the vent formed a tuff mound. The finer grained ash drifted away from the volcanic center before settling in finely laminated beds downwind from the mound. During later stages of eruption the explosions became less violent and volcanic material filled the crater, forming a gently sloping tuff-mound, which in some cases reached the water surface. Around some "plugs" cinder and lava flows may have formed in later eruptions (Young et al., 1982, p. 54), leading to variety in "plug" architecture. During and after formation tuff mounds were subjected to intense submarine diagenesis, altering much of the glass and crystalline phases to clay.

Unaltered basalt has been encountered in several wells within tuff mounds (Simmons, 1967, p. 127). This basalt suggests that after eruption had ceased and the tuff mound had settled and compacted sufficiently to prevent

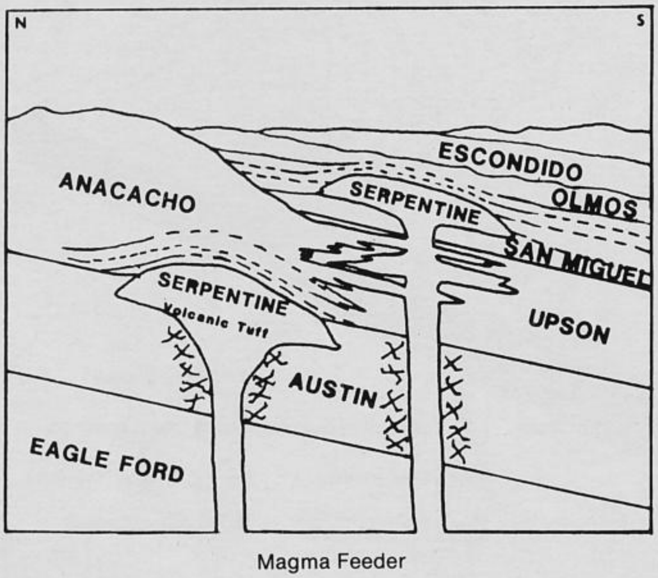


Fig. 21. Representative diagrammatic section of a "serpentine plug" and its associated facies in the southern subprovince. The north-south section shows the high-energy Anacacho Formation on the topographic highs formed by the "serpentine plugs." The San Miguel and Olmos sands form a compactional drape over the "plug" and thin over the crest. The Escondido sand shows minor draping (*after* Luttrell, 1977, p. 262). Saturated zones are shown in Fig. 22.

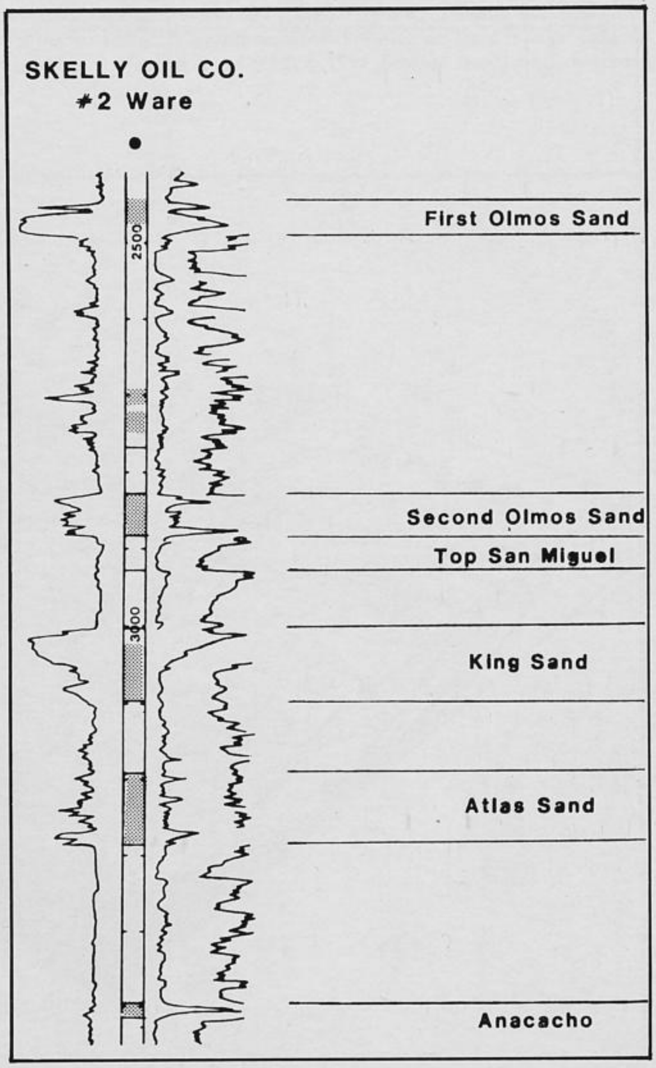


Fig. 22. Representative electric log from Torch field, Zavala County, showing the signatures of the section affected by the "serpentine plug." Note the characteristic SP signature of the San Miguel "King sand," the dominant producing unit in Torch field. Producing zones are shown as shaded and include the overlapping and marginal sands, the Anacacho, "serpentine," and possibly fractured reservoirs at greater depths.

the percolation of sea water, renewed volcanic activity led to the late intrusion of magma (ibid.).

The mounds of ash and tuff were subject to erosion almost from the moment of formation, resulting in repeated reworking of volcanic material by waves and currents. Three facies of subaqueously deposited volcanics were generated: (1) near source facies consisting of lava flows and pyroclastic debris; (2) intermediate source facies characterized by pyroclastic flows, lava flows and their reworked products (as distance from source increases non-volcanic clastic material is mixed with volcanic debris); and (3) distant facies represented by generally thin-bedded, fine-grained ash deposits downwind and down current from the mound (Fisher and Schmincke, 1984, p. 358-359). All facies were rich in feldspars and igneous rock fragments and highly susceptible to alteration by diagenesis (Hunter and Davies, 1979, p. 147).

The primary magmas were silica-deficient alkalic basalts and rarer basanite and olivine nephelinite magmas, apparently derived from partial melting of mantle rocks from 80 to 150 km deep (Fisher and Schmincke, 1984, p. 17-18). This indicates that major faulting penetrated the crust and allowed magma to ascend. It was this deep faulting that explains the general alignment of the "plug" trend with the major fault systems and the Ouachita system.

During and after the igneous phases the tuff mound provided the necessary topography for shallow-water carbonate build-up, producing facies quite different from normal Austin and Taylor rocks. In the northern subprovince the Dale and McKown limestones are of Austin age. These oyster-algal grainstone facies are overlain by open-shelf facies of the Austin Formation, or by fine-grained clastics of the Taylor Formation where truncation of the Austin has taken place. The thin-bedded bioclastic algal packstone and grainstone facies of the middle subprovince are of Austin age, overlain by the upper Austin shelf facies, suggesting that this environment was shortlived. The Anacacho Limestone occurred as an extensive shallow water, high-energy shelf carbonate within the southern subprovince. It is of early Taylor age, overlain conformably to the south by the Upson Clay, and unconformably to the north by the Escondido sand (Navarro). The San Miguel and Olmos sands (Taylor) and the Escondido sand (Navarro) were products of progradation, but locally were influenced by the topographic mounds within the southern

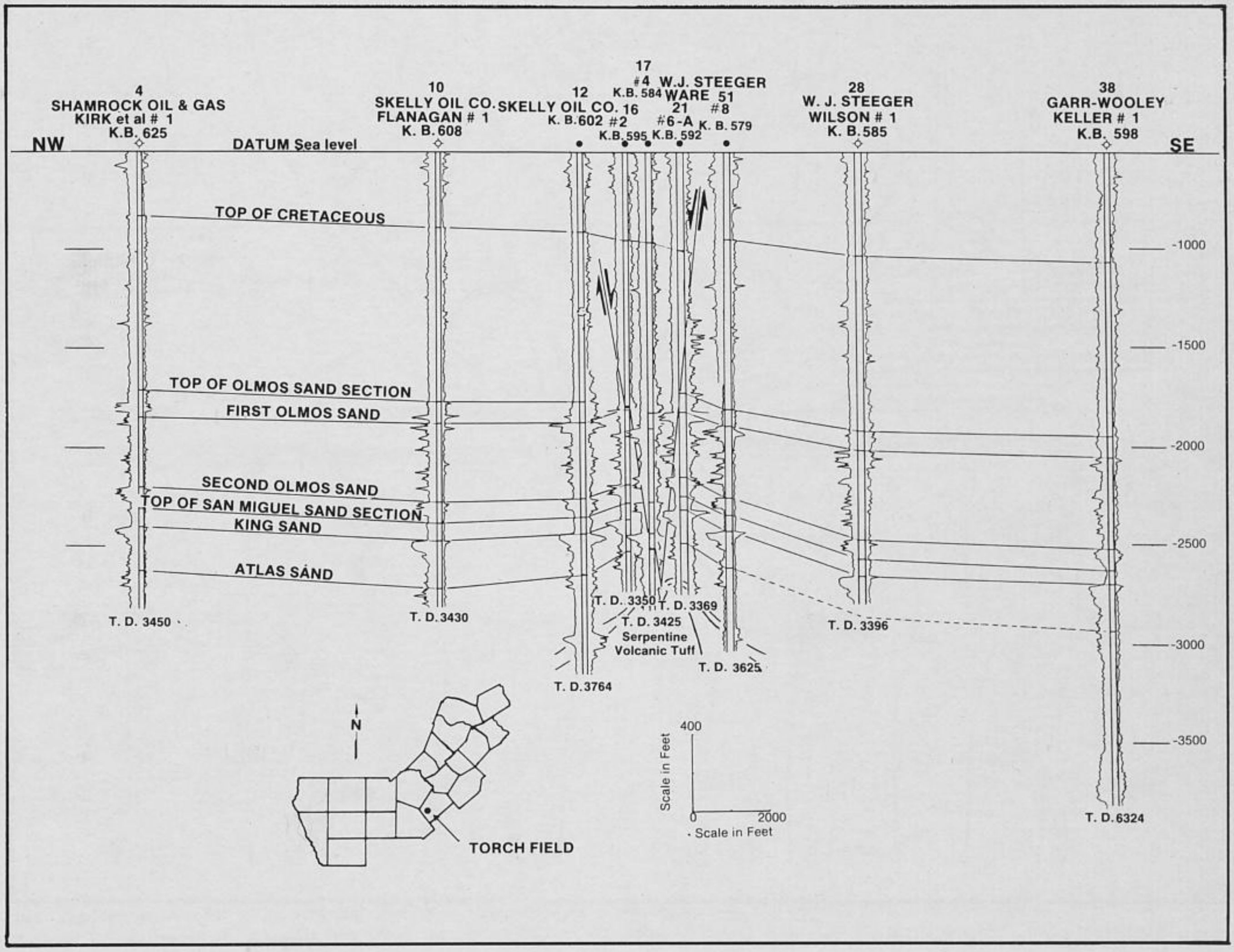


Fig. 23. NW-SE structure cross-section C-C', Torch field, Zavala County. Datum sea level. *Adapted from* Lewis, 1962.

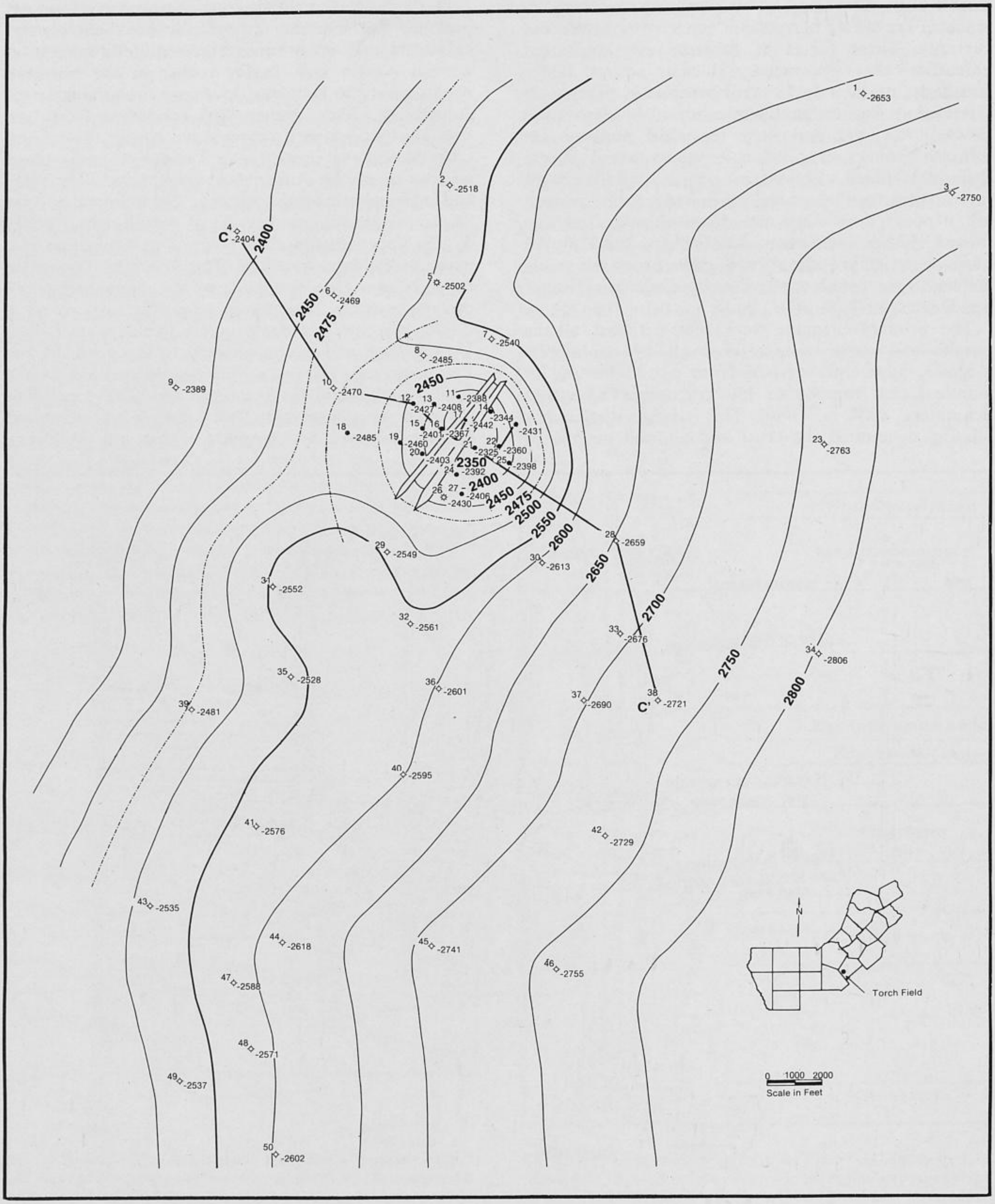


Fig. 24. Structure map, top of King sand, Torch field, Zavala County.

subprovince.

The absolute age of volcanic activity is not known. Most of the igneous activity associated with faulting, and hence with "plugs" of central and south Texas occurred between 63 and 86 million years ago (Baldwin and Adams, 1971, p. 228). Stratigraphically younger formations were affected by volcanic activity in the southern subprovince. The pronounced thinning of Late Cretaceous Austin and Eagle Ford Groups across the San Marcos arch (Adkins, 1932, p. 266) suggests that it affected sedimentation for some time, principally by subsiding at a slower rate than the basins it separated. Thus, subsidence and sedimentation occurred at different rates throughout the study area during Late Cretaceous time. Deposition of the Taylor Formation in the southern subprovince may have been contemporaneous with deposition of the Austin Formation in areas north of the San Marcos arch. If so, all "serpentine plugs" may have developed at roughly the same time.

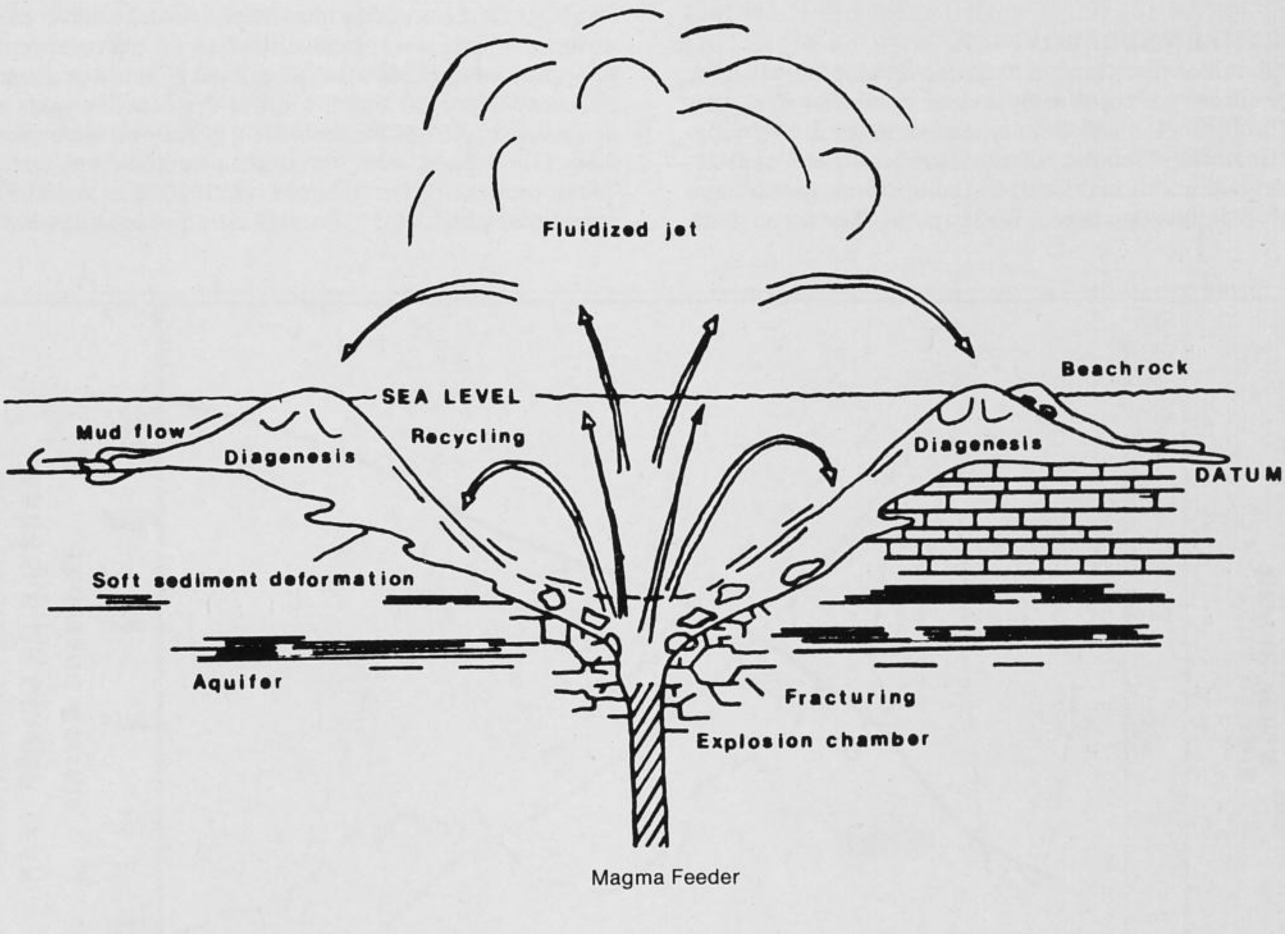


Fig. 25. Idealized model of an erupting submarine volcano. Note the fracturing of the country rock, the development of the tuff mound, and the accumulation of carbonate beachrock, analogous to the McKown, Dale and Anacacho Formations and to the biocalcarenite facies (*from* Ewing and Caran, 1982, p. 139).

PRODUCTION HISTORIES OF "SERPENTINE PLUGS"

One of the most unusual and profitable hydrocarbon plays in central and south Texas centers on these volcanic features and their associated deposits. Each "plug" has potential to produce from both volcanics and associated sediments. Since their discovery with the Thrall field in Williamson County in 1915, hydrocarbon traps in and around "serpentine plugs" have produced approximately 54 million barrels of oil and significant quantities of natural gas. In the section that follows, producing fields within each subprovince are described, together with production histories and the economics of development.

NORTHERN SUBPROVINCE

The initial discovery of "serpentine plug" fields took place in the northern subprovince 1 mi (1.6 km) east of Thrall, Williamson County, on February 2, 1915 (Fig. 2). Since the discovery of the Thrall oil field approximately 45 additional fields in the northern group have produced hydrocarbons. Wells in the Thrall oil field ranged in depth between 612 and 950 ft (≈ 186-289 m) and initially produced from 1000 to 5000 barrels of oil per day. During the first year of production approximately 1 million barrels of 39 gravity oil were taken from the Thrall field with little gas or water. The total production to the end of 1983 was 2,387,331 barrels. In 1983, 68 years after the initial discovery, 4,661 barrels of oil were produced from porous "serpentine" and porous shell breccia capping the structure to the east and northeast.

Hilbig oil field, 10 mi (16 km) southwest of Bastrop in Bastrop County, was discovered on February 3, 1933 (Fig. 2). Of 21 wells in the Hilbig field 16 have been producers. The wells were drilled to an average depth of approximately 2500 ft (762 m) and initially produced between 1000-2400 bbl/d. During the first six years of production 1,462,497 barrels of 37 gravity oil were taken from Hilbig field, with variable amounts of salt water. Total production to the end of 1983 was 6,120,575 barrels, of which 48,573 barrels were produced in 1983,

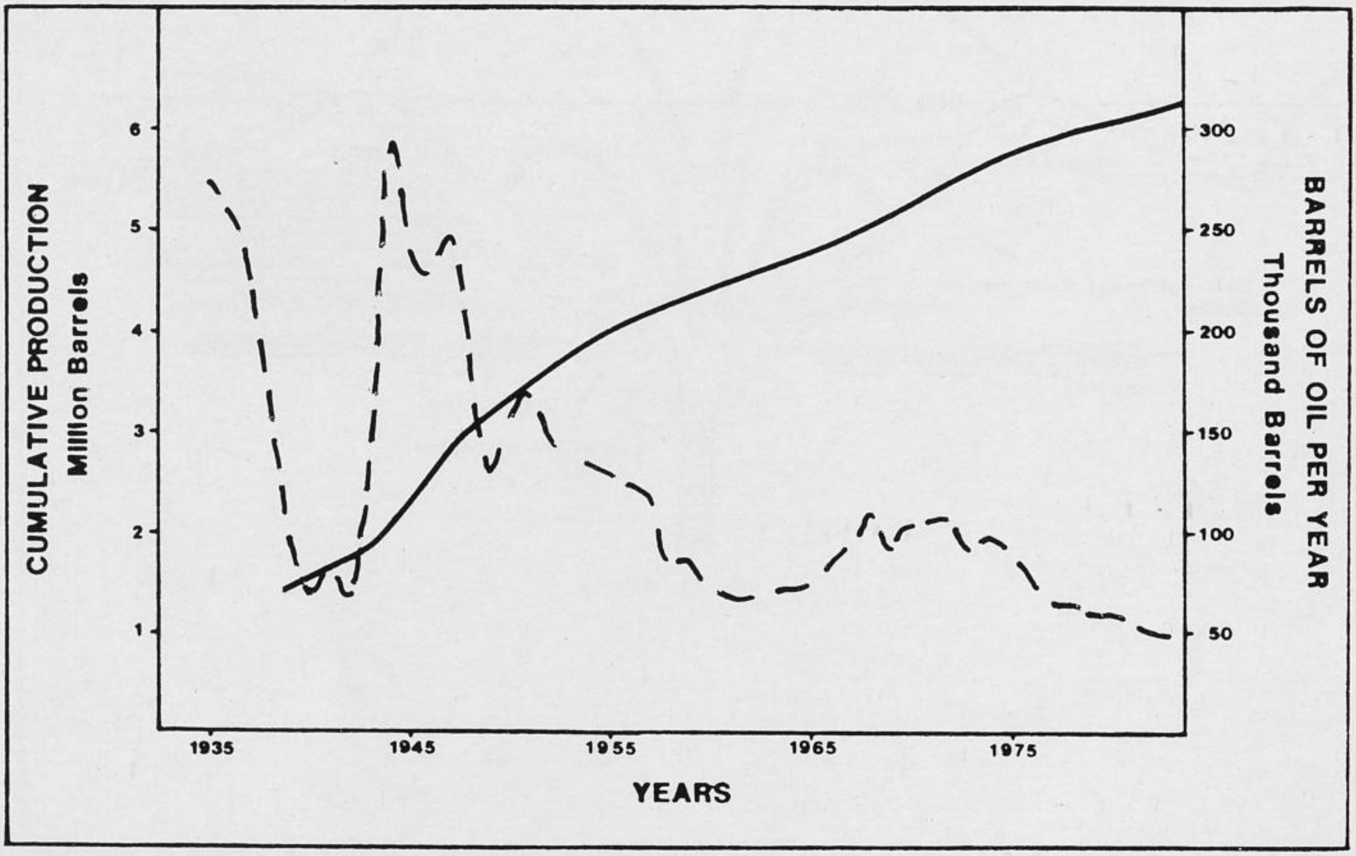


Fig. 26. Production graph showing relationship between years of field existence and (1) cumulative production (left, dashed line); and (2) barrels of oil per year (right, solid line). Hilbig field, Bastrop County, Texas. The fluctuation in the barrels of oil per year is not a characteristic of the reservoir, but perhaps could be due to demand, well and field conditions, and stages in field development.

52 years after discovery (Fig. 26).

The northern subprovince is the oldest and most productive area and is considered to be in a late mature stage of development. Advantages to exploration in this area are mainly shallow depth, between 500 and 3500 ft (≈ 152-1067 m), and longevity of production. The largest known field, Lytton Springs in northern Caldwell County, has produced approximately 11 million barrels of oil since 1925. Of that total 51,059 barrels were produced in 1983, 60 years after discovery. Total production for the northern subprovince to the end of 1983 was approximately 36 million barrels, and 17 of the fields have each produced over 100,000 barrels (Fig. 2).

MIDDLE SUBPROVINCE

The middle subprovince lies entirely within Wilson County. Approximately seven fields are related to the volcanic centers (Fig. 2). Hydrocarbons have been produced from the Buda and Austin Formations and from biocalcarenite facies within the Austin Formation. It is generally believed that discovery of the "serpentine plugs" in the subsurface of Wilson County occurred with the discovery of the North Poth field in November 1957. Production from the Buda and Austin Formations is related to fractures developed in response to the formation of "serpentine plugs"; these fractures are the principal producing sections. The biocalcarenite facies of the Austin Formation, surrounding the volcano, possesses good primary porosity and permeability and produces from two of the approximately 15 wells in the field. Total production of the North Poth field to the end of 1983 was 88,977 barrels of 34-42 gravity oil. Of this total 3,149 barrels were produced from all horizons in 1983.

The Sutil field in south-central Wilson County was discovered in October 1975 (Fig. 2). Two wells were drilled to an average depth of 6200 ft (≈ 1890 m) and produced 4,240 barrels the first year. The total production from the Austin and Buda Formations to the end of 1983 was 1,550,941 barrels of 25 gravity oil, of which total 227,534 barrels were produced in 1983.

The biocalcarenite facies of the Austin Formation was first discovered in Sutil field in July 1979. The first year's production from this facies was 12,108 barrels from approximately two wells. Total production to the end of 1983 was 285,747 barrels of 30 gravity oil. The total production for all horizons in Sutil field to the end of 1983 was 1,836,688 barrels, with 295,201 barrels being produced in 1983 (Fig. 27).

The middle subprovince is considered in a youthful stage of production and exploration. The higher cost of deeper drilling, in excess of 6000 ft (≈ 1829 m), is offset by the possibility of fracture-related reservoirs in the Austin and Buda Formations, in addition to reservoirs directly related to the "serpentine plug." Total

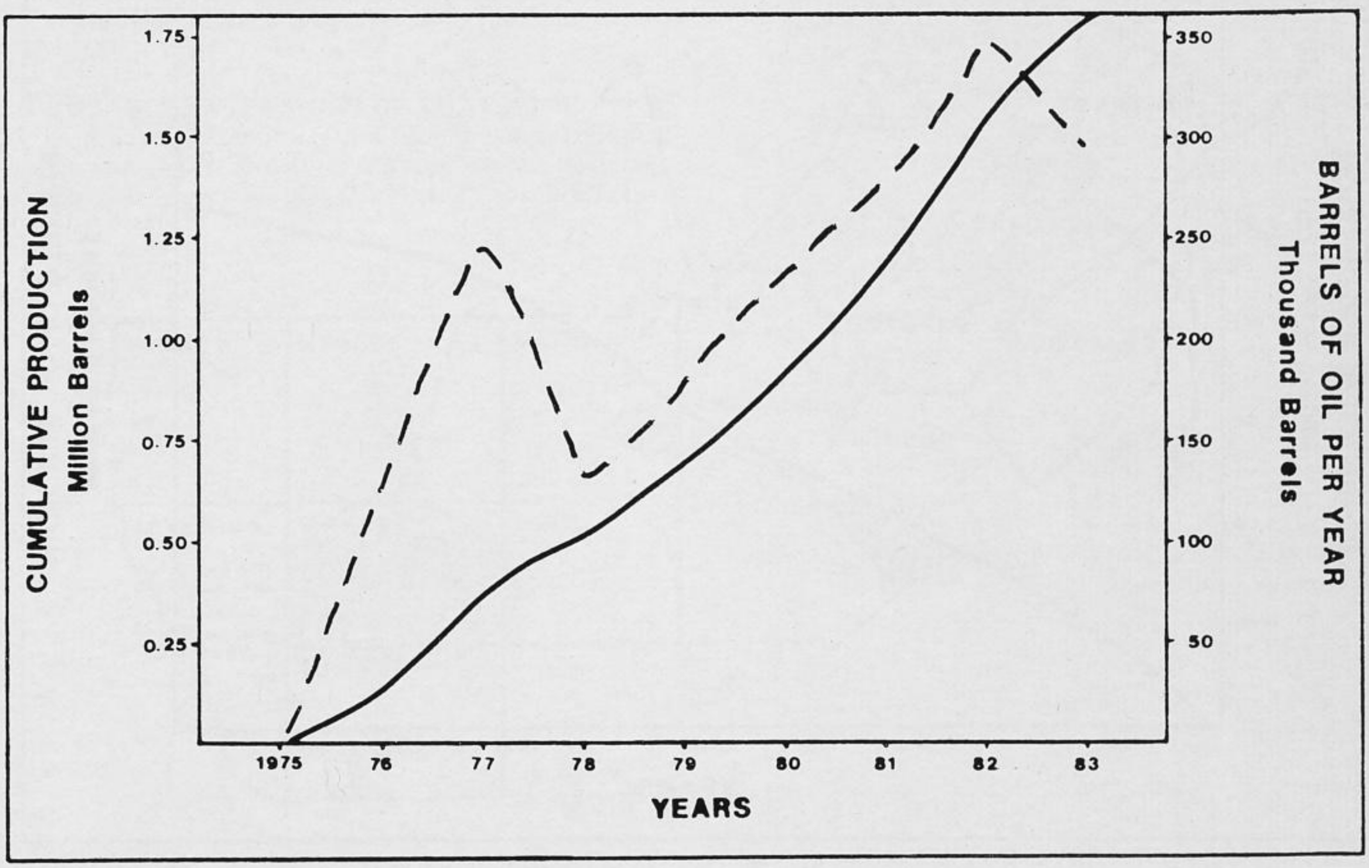


Fig. 27. Production graph showing relationship between years of field existence and (1) cumulative production (left, dashed line), and (2) barrels of oil per year (right, solid line). Sutil field, Wilson County, Texas. The fluctuation in the barrels of oil per year may be a characteristic of the fractured reservoirs such as the Austin and Buda Formations, but it is largely due to field expansion.

production for the middle subprovince to the end of 1983 was approximately 3,508,221 barrels, and four of the fields have each produced over 100,000 barrels (Fig. 2).

SOUTHERN SUBPROVINCE

The date and place of the initial discovery of production from a "serpentine plug" in the southern subprovince is not now known. However, in 1919 at the Chicon Reservoir in Medina County eight wells were drilled, four of which encountered "serpentine" that, upon investigation, seemed to be of the type found at Thrall field in Williamson County (Lonsdale, 1927, p. 118). Since that time Chicon Lake field has produced approximately 691,000 barrels from a depth of 900 ft (274 m). The next productive "serpentine" was discovered at Dunlay field, Medina County in 1938 at a depth of 550 ft (≈ 168 m). This field produced only 2,029 barrels (Fig. 2). Since the Dunlay field discovery, approximately 50 "serpentine plugs" have been recognized in the subsurface. Of these, approximately 35 have been found productive from "serpentine," shoal-water carbonates, and overlying or marginal sands associated with volcanic centers.

Torch field, in southwest Zavala County, was discovered on April 5, 1958 (Fig. 2). Torch field produces from six different reservoirs ranging in depth from 3006 to 3548 ft (≈ 916-1081 m). Five of these horizons are sands that overlie or are marginal to "serpentine plugs." During the first year of production 59,849 barrels of 32-38 gravity oil were produced. Total production to the end of 1983 was 2,536,174 barrels, with 33,305 barrels produced in 1983 (Fig. 28). In addition to oil, several sand units have produced significant quantities of natural gas. The San Miguel "King" sand, the major producing sand in the field, produced approximately 1,682,000 barrels to the end of 1983. The "serpentine" has itself been found productive, but it has produced only 697 barrels since 1978, with 249 barrels of that total produced in 1983. The Anacacho Formation, the major reservoir in other fields of the southern subprovince, has been found to be oil saturated (Lewis, 1977, p. 95), but as of 1983 it had not produced oil.

The southern subprovince is in an early mature stage of development. Advantages to exploration in this area are the shallow depths, between 500 and 4200 ft (≈ 152-1280 m), the potential for multiple reservoirs once a "serpentine plug" is located, and the possibility of encountering numerous additional untested "plugs."

Total production for the southern subprovince to the end of 1983 was approximately 14,780,095 barrels, and 11 fields have each produced over 100,000 barrels (Fig. 2).

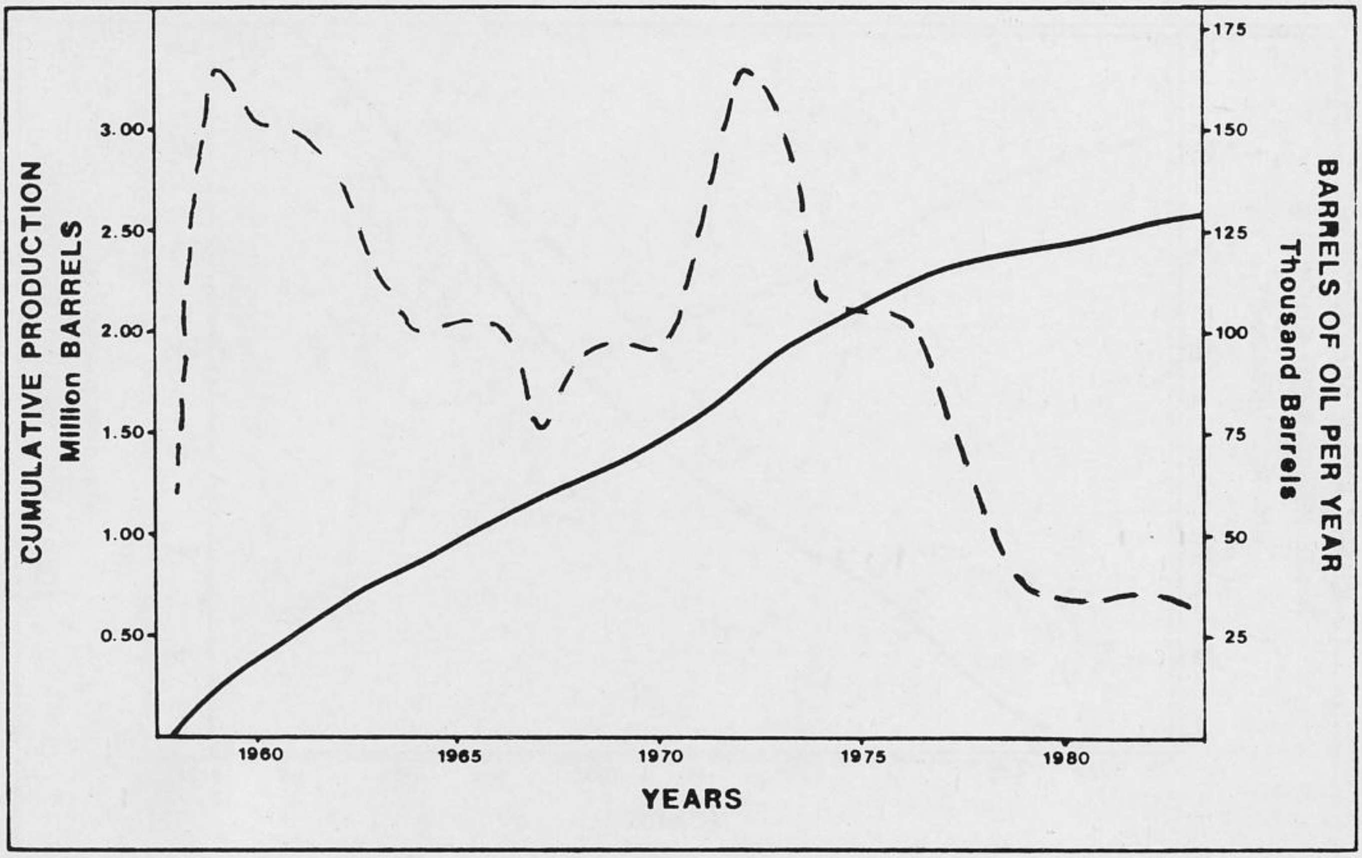


Fig. 28. Production graph showing relationship between years of field existence and (1) cumulative production (left, dashed line) and (2) barrels of oil per year (right, solid line). Torch field, Zavala County, Texas. The fluctuation in the barrels of oil per year is not a characteristic of the reservoir, but perhaps could be due to demand, well and field conditions, and stages in field development.

EXPLORATION FOR "SERPENTINE PLUGS"

Early discoveries of "serpentine plugs" were made accidentally by drilling in search of other objectives, such as water or oil in deeper formations. Several fields were discovered as a result of drilling to explore along mapped surface faults. However, no surface geologic method has to date been able to give positive indication of "plugs" in the subsurface.

To enhance discovery potential four factors are critical: (1) to define the zone of known "plug" occurrence, (2) to define probable extensions of this zone into untested areas, (3) to identify properties of "serpentine plugs" and associated rocks and structure important to the exploration program, and (4) to use exploration techniques appropriate to exploration for "plugs" in the areas of most probable discovery.

ZONE OF KNOWN "SERPENTINE PLUG" OCCURRENCE

Productive "serpentine plugs" are known to extend along a 250 mi (≈ 402 km) arcuate belt in central and south Texas. They occur in association with four major fault zones, roughly paralleling the Ouachita structural belt. The regional setting and descriptive geology of the known "serpentine plugs" has been described (Fig. 2). They occur as sporadic groupings along the major trends (Fig. 29).

PROBABLE EXTENSIONS OF THAT ZONE

A probable extension of this zone should exist in the area with similar structural features, which apparently controlled "serpentine plugs" in central and south Texas. Thus potential extensions may exist to the north, probably in the "gaps" in the present trend, and they almost certainly exist in the large untested area to the south (Fig. 30).

PROPERTIES OF THE "SERPENTINE PLUGS"

Properties of "serpentine plugs" make them unique among fields in central and south Texas: (1) all "serpentine plugs" originated with submarine igneous activity in the ancient Gulf of Mexico; (2) all apparently had a central vent that supplied extrusive material, forming a tuff mound overlying and surrounding the crater left after eruption; (3) the basaltic rocks originally

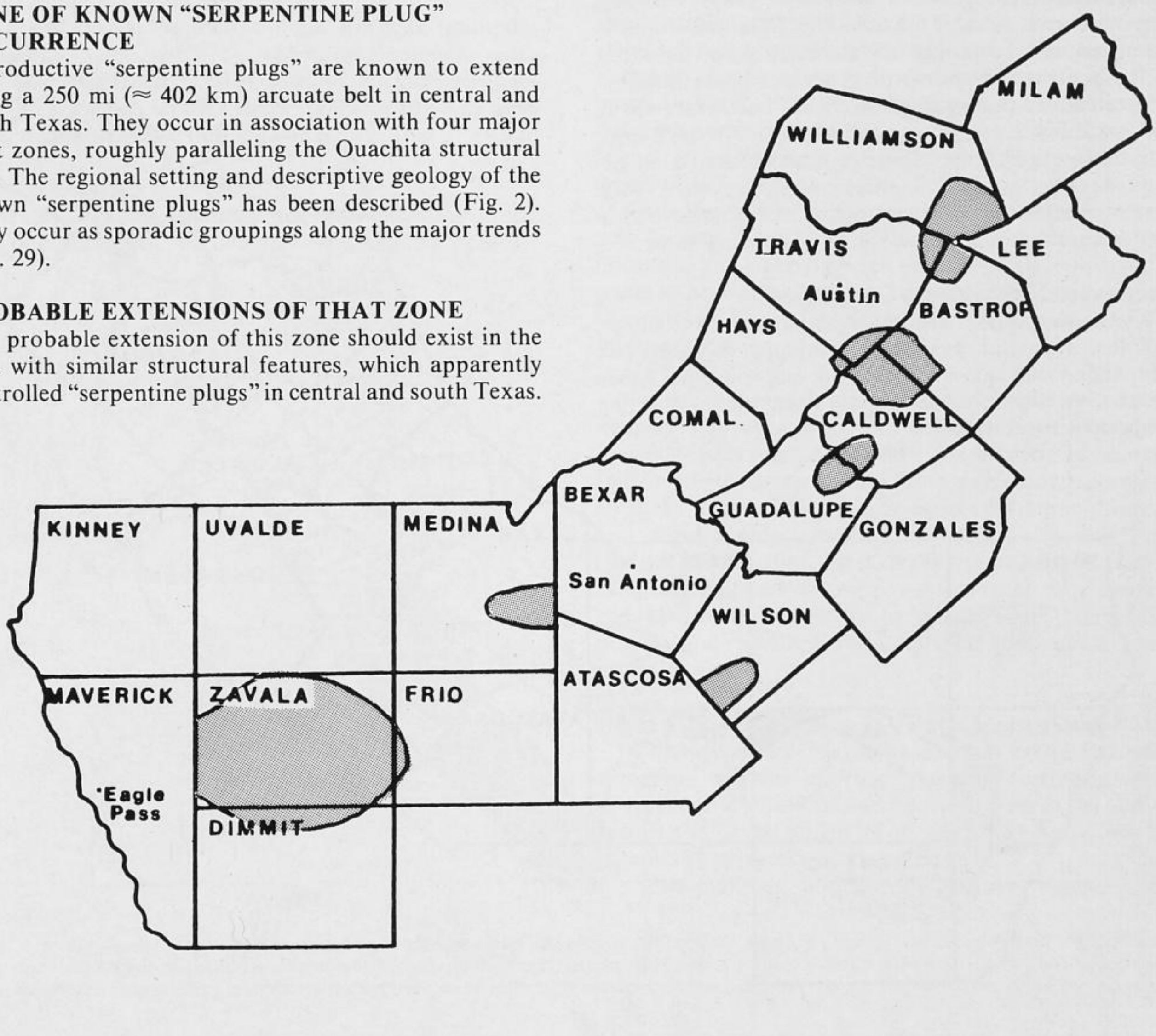


Fig. 29. The zone of known plug occurrence is confined to the area shown as shaded. Production along this trend is in various developmental stages, but all the areas have proven hydrocarbon production from "serpentine plugs" and their associated facies.

had characteristic high magnetic susceptibility and a portion of that should remain, particularly for those "plugs" with unaltered intrusive rocks; (4) "plugs" are small scale, but the rocks of which the "plug" is formed should in many cases have distinctive seismic velocities; (5) "plugs" are of relatively small size, between 1 and 2 mi (≈ 2.6-5.2 km^2) in area and 250-350 ft (≈ 76-107 m) thick, very different from other structures in the areas of their occurrence; and (6) initially the "plugs" were hot, and some portion of this heat may yet remain. In addition the chemistry of the "plugs" and associated hydrothermal waters should have left a distinctive signature on the land, at least early in their history.

PROPERTIES OF ASSOCIATED FEATURES

Associated features consist of shoal-water carbonates, thinning and draping of superjacent formations, and fracturing of deeper formations adjacent to pipes and vents.

The development of shoal-water carbonate facies, beach rock and reefy algal and coralline masses built on topographic highs of "serpentine plugs," formed limestone such as the McKown and Dale limestones in the northern subprovince and the Anacacho Limestone of the southern subprovince. This carbonate development occurred predominantly on the northeast, north, and northwest sides of "serpentine plugs." In the middle subprovince a thin limestone unit accumulated on the southwest sides of volcanic complexes with little development to the northeast, owing its existence to local shell accumulation and reworking of volcanic talus.

Draping of Superjacent Formations

Within the southern subprovince, "serpentine plugs" provided structure on which developed thinning and compactional draping of overlying and marginal sands of the San Miguel and Olmos Formations, forming domal structural traps.

Fracturing of Deeper Horizons

Fracture reservoirs such as the Austin Chalk and Buda Formation developed adjacent to the pipes and vents of "serpentine plugs," thus making the deeper horizon an attractive target for exploration.

OIL OCCURRENCE IN ASSOCIATION WITH "SERPENTINE PLUGS"

Not all "serpentine plugs" have associated hydrocarbons, and not all "serpentine plugs" that have had hydrocarbons produce all around the volcanic complex.

Within the northern subprovince the dominant hydrocarbon saturation occurs in stratigraphic traps in the porous, altered volcanic tuff. Secondary to this production is stratigraphic entrapment within porous zones of the McKown and Dale limestones, which occurs predominantly on the north and northeast sides of "serpentine plugs."

The dominant hydrocarbon saturation in the middle subprovince occurs in the high-energy biocalcarenite facies on gentle talus ramps on the southwest side of

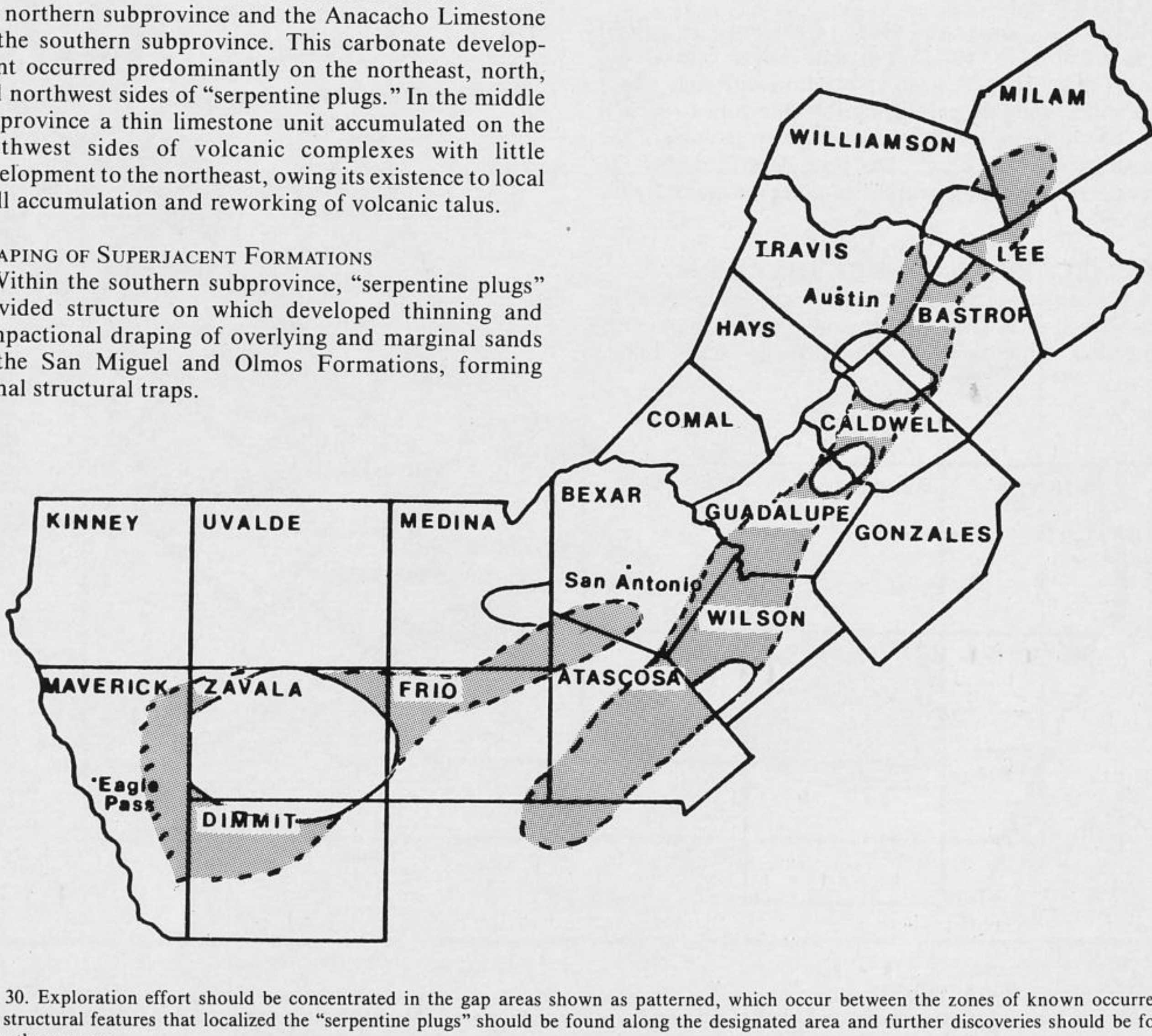


Fig. 30. Exploration effort should be concentrated in the gap areas shown as patterned, which occur between the zones of known occurrence. The structural features that localized the "serpentine plugs" should be found along the designated area and further discoveries should be found along these zones.

volcanoes. Production from the Austin and Buda Formations is related to fracturing. A higher density of fractures should be concentrated around a volcanic center, providing better reservoir potential in the underlying and adjacent units.

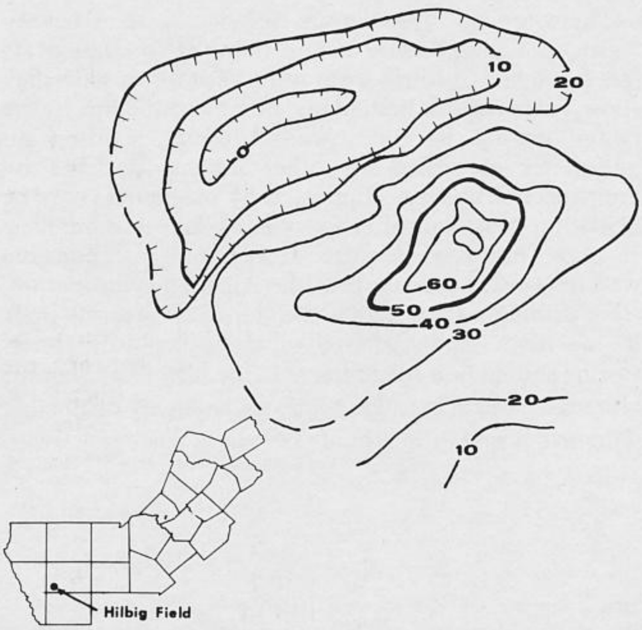
The dominant hydrocarbon saturation within the southern subprovince occurs in well-developed overlying and marginal sands of the San Miguel and Olmos Formations. Structural closure occurs over tops of the "serpentine plugs." Horst-and-graben relationships exist in many of the fields. "Serpentine plugs" also localized deposition of shallow-water, high-energy carbonate facies of the Anacacho Formation, predominantly to the north and northeast. Other carbonate reservoirs may exist to the southwest as they do in the middle zone, for wind, wave, and current directions should have been similar. Underlying and adjacent carbonate units may also exhibit higher intensities of fracturing around volcanic centers, as is the case in the middle subprovince.

EXPLORATION TECHNIQUES FOR "SERPENTINE PLUGS"

Exploration for "serpentine plugs" has been attempted in various ways, some of which have proven more profitable than others. The use of surface geology, magnetics, gravity, seismic, and exploratory drilling have all been used in the search for volcanic centers.

Surface Geology

The use of surface geology has been largely after the fact. In some cases, particularly with shallow "plugs," topographic expression may exist, but as an exploration tool this has not been notably successful, even though early discoveries occurred during the "golden age" of surface work. Surface work aided by high-altitude photos would enhance the success ratio of surface exploration, and no exploration technique is less expensive.



Remote Sensing

Recent advances in remote sensing have emphasized effects of connate water and hydrocarbon leakage on vegetation above oil fields. Microseepage of hydrocarbons and color variations resulting from chemical alteration have been recognized in several hydrocarbon producing areas (Patton and Manwaring, 1984, p. 441).

Stressed vegetation, visible on thematic mapper data, coincided with an area of marked leakage of hydrocarbons in the Patrick Draw field, Wyoming (Matthews et al., 1984, p. 663). The leakage was in part controlled by the presence of faults and fractures recognized as lineaments on remote sensing images. In Lost River field, Hardy County, West Virginia, gas is produced from a depth of 6000 ft (≈ 1829 m). The field was discovered as a seismic prospect, but later investigation using thematic mapper data indicated an anomolous population of maple trees in a climax oak forest apparently due to hydrocarbon leakage. Lost River field was also found to be coincident with an area of greater lineament density (ibid., p. 664).

Since the "plugs" were once sites of intense volcanic activity and later were hydrothermal centers of long duration, and since they are uniquely different than the sedimentary sequences that surround them, they appear to offer excellent targets for exploration using multispectral scanning techniques from space and from lower flying aircraft.

The use of thematic mapper and multispectral scanner imagery improves ability to detect surface expression of deeper structures, even where these are deeply buried. Improved spatial resolution from thematic mapper and airborne data enables the detection of minor drainage and topographic elements controlled by structures (Berger et al., 1984, p. 828). Surface "signatures" of "serpentine plugs," identified on remote sensing imagery should enable geologists to locate some "serpentine plugs" and perhaps to identify those most likely productive.

Geochemical

Multispectral imagery should aid in the geochemical detection of the microseepage of connate water, hydrothermal solutions and hydrocarbons at the surface and in the development of geochemical signatures for potentially productive "plugs."

These methods, applied judiciously, should show

Fig. 31. A total intensity magnetic map of a ground magnetometer survey over Hilbig field, Bastrop County, was completed during the course of this study. The distinct dipolar anomoly, which encircles the field, may be modeled as a squat cylinder (Gibson, 1985). This suggests that the volume of high susceptibility material on the sea floor was significantly greater than the volume represented by the feeder below the mound.

significant improvement over surface geology aided by high altitude photography but at a significant increase in cost.

Magnetics

Magnetic surveys have led to the discovery of several productive "serpentine plugs." Although aerial magnetic surveys have been credited with several discoveries, ground-level magnetics appears to give more conclusive response. "Serpentine plugs" mapped by ground-level magnetic surveys led directly to the discovery of Hilbig, Jim Smith, Yoast, and Cedar Creek fields in the northern subprovince (Fig. 2).

Mafic material of the volcanic center has a high initial magnetic susceptibility. Susceptibility was found to be represented by positive and negative anomalies (Liddle, 1930, p. 509). In marine sedimentary regimes of central and south Texas, where limestones, shales, and clean sands predominate, igneous bodies tend to be conspicuous on magnetic surveys.

During the progress of this study a ground-level magnetic survey was completed over the Hilbig field, Bastrop County. It clearly showed a 50-60 gamma anomaly (Gibson, 1985). Total field magnetic readings were taken along preexisting roads at a spacing of 264 ft (≈ 80 m). A distinct dipolar anomaly, such as that for a squat magnetic cylinder, existed over Hilbig field (Fig. 31). A single magnetometer line can yield evidence of an anomaly, but the actual magnetic geometry requires a survey with high station density. Aerial magnetometry flown at close-line spacings, 0.5 or 0.25 mi (0.8 or 0.4 km), can signal anomalies, but these data should be confirmed with ground magnetics.

Magnetics has been used with success predominantly in the northern and southern subprovinces where depths rarely exceed 3500 ft (1067 m). Magnetics used in conjunction with multispectral scanner imagery should yield higher resolution than either system alone. However, this increased probability of success is purchased at substantially higher cost.

Gravity

The use of gravity for the detection of "serpentine plugs" is uncertain. Since most of the igneous material was emplaced as ash or tuff and hydrothermally altered to clay, density contrasts should be minimal. The small size and relatively great depth of many of the "plugs" also increases the difficulty of detection by gravity. However, some "plugs" have included fairly large volumes of unaltered volcanic rock. These may be detectable by gravity.

Gravity, at a degree of precision necessary for explorations of the deeper "plug," is significantly more expensive than magnetometry and is probably of substantially less value in reconnaissance.

Seismic

Unaltered mafic and ultramafic igneous rocks produce strong positive reflections because of high compressional wave velocities, 18,000 to 24,000 ft/s (≈ 5486-7315 m/s). These are substantially higher than those of the Austin Formation, 12,000 to 15,000 ft/s (≈ 3700-4570 m/s), or the Taylor Formation, 10,000 to 13,000 ft/s (≈ 3050-4000 m/s). However, palagonite tuff mounds have low compressional wave velocities, averaging 9,500 ft/s (≈ 2900 m/s), lower than the surrounding sedimentary rocks.

Seismic lines over "serpentine plugs" have shown characteristic signatures, but because the "plugs" are small and superjacent structures are of very limited closure, they are most useful in refining details of "plugs" detected by other means. The placement of seismic lines is critical in the delineation of the "plug" structure, and spacings should not exceed 0.5 mi (0.8 km) (Lewis, 1983, p. 23).

Very high cost is a major limitation in use of reflection seismology.

Exploratory Drilling

There are no clues on an electric log to a nearby "serpentine plug," more distant than the compass of its igneous halo. Cuttings from wells within this halo may show volcaniclastic sediments, but the direction to the "plug" would be unknown. However, drilling on anomalies identified by other means, perhaps by multispectral imagery supported by magnetics, may be one of the most cost-effective of exploration techniques. It does, however, require exceptionally responsible wellsite work, particularly in the Austin-Taylor section, since drilling rates are high and returns frequently poor in the more highly altered of the pyroclastic facies. Coring should be a requirement in the section of interest, although electric log signatures can be highly distinctive if the well is well within the area of major igneous activity.

CONCLUSIONS

1. Volcanic features are rarely sites for petroleum exploration; however, one of the most unusual and profitable hydrocarbon plays in central and south Texas coincides exactly with these volcanic features. A study of the entire trend and mapping of selected example fields throughout the trend allowed for the proposal of future fairways of exploration.

2. Igneous activity occurred during the deposition of the Upper Cretaceous Austin and Taylor Formations (Coniacian/Campanian) along a 250 mi (400 km) arcuate belt extending from Milam County southwestward to Zavala County, Texas.

3. The approximately 225 surface and subsurface occurrences of "serpentine plugs" align themselves along four fault zones that roughly coincide with the buried Ouachita thrust belt.

4. Analyses of the plugs suggest that there are at least three distinctive groups: (1) a northern subprovince in which the dominant hydrocarbon saturation is in the altered volcanic tuff, (2) a middle subprovince characterized by hydrocarbon-saturated biocalcarenite, and (3) a southern subprovince characterized by well-developed and productive sands.

5. "Serpentine plugs" within the northern and middle subprovinces are associated principally with down-to-the-northwest faults associated with the Luling and Charlotte fault zones.

6. The alignment of "serpentine plugs" along the Luling fault zone and faults in various fields show that Luling faulting existed in central Texas during Austin/Taylor time.

7. Structural reversals in the northern and middle subprovinces provide evidence that tilting of the anticlines occurred after volcanic extrusion.

8. Subsidence of the Gulf Coast Basin occurred at different rates throughout the study area resulting in deposition of Taylor sediments in the southern subprovince contemporaneously with Austin facies in the northern subprovince north of the San Marcos arch.

9. Since 1915, approximately 54 million barrels of oil and significant quantities of natural gas have been discovered in association with "serpentine plugs."

10. Exploration for "serpentine plugs" should be concentrated along existing fault zones related to extension; thus, potential exploration targets may exist to the north, in the "gaps" in the present trend, and almost certainly in the large untested middle and southern subprovinces.

11. With the proper use of exploration tools such as enhanced remote-sensing techniques, magnetics, and seismic reflection, future exploration should be concentrated in the area of known "plug" occurrence extending into the gaps between the three described subprovinces.

APPENDIX I

CORE DESCRIPTIONS

Hilbig Field, Bastrop County, Texas

Humble Oil and Refining Company

Wolfenbarger #2, 2557-2863 ft
Goertz #1, 2530-2607 ft
Friske #2, 2469-2715 ft

These cores from Hilbig field were broken and only contained selected samples from the sections listed. The cored intervals were lithologically similar; therefore, a summary of the findings will follow.

Microscopically, the rock fragments are porphyritic, composed predominantly of plagioclase laths, skeletal olivine, and magnetite, which shows some alteration to hematite (Fig. 32). The olivine and plagioclase occur in cryptocrystalline or glassy groundmasses, which have been altered to palagonite, a hydrated basaltic glass that appears brown, orange, or yellow in thin section. This basaltic glass is commonly vesicular, and the vesicles are filled with chalcedony or calcite (Fig. 33). The rock fragments and basaltic glass are commonly associated with alteration products such as celadonite, which appears greenish in thin section (a hydrous Mg, Fe, Al silicate similar to illite and glauconite), and chlorite. Chlorite and zeolites form rims surrounding the grains. Shard fragments are typically rimmed by light-colored chlorite, which contrasts with the dark-green chlorite of the altered fragment interiors (Kuniyoshi and Liou, 1976, p. 1100). This contrast suggests that palagonitization of fragment rims occurred prior to chloritization. Locally, pore fillings and fractures are filled with calcite or chalcedony, and chlorite either rims the outside of grains or occurs as a pore filling (Figs. 34a, 34b).

A probable paragenetic sequence is: (1) the occurrence of chlorite as a pore filling or clay rim due to the alteration of biotite, pyroxene, or amphibole, (2) the introduction of silica in the form of chalcedony as pore and fracture fill, and (3) the advent of carbonate material as a result of partial dissolution of silica due to alkaline pore waters.

The primary magma for the Hilbig field volcanics was probably an alkali basalt, as is suggested by the abundance of plagioclase, more than is normally associated with nepheline basanite (Barker, 1985).

APPENDIX II

LOCALITIES

LOCALITY 1. McKown Formation underlain by nontronitic clays at McKinney Falls State Park, near Austin, Texas (from Young, Caran, and Ewing, 1982, p. 42).

LOCALITY 2. McKown Formation at J. K. Ross Quarry, entrance to McKinney Falls State Park, near Austin, Texas (from Young, Caran, and Ewing, 1982, p. 58).

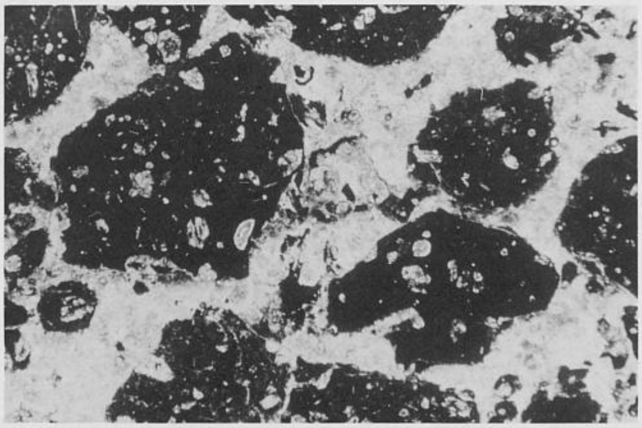


Fig. 32. Photograph of thin section from Humble Oil & Refining Co. Wolfenbarger #2 at 2575-2587 ft (≈ 785-788 m) (X40). Note the rounded, poorly sorted, porphyritic nature of the altered igneous rock fragments. The major constituents are plagioclase laths, skeletal olivine, palagonite, and magnetite. The magnetite is opaque in thin section and is partly altered to hematite.

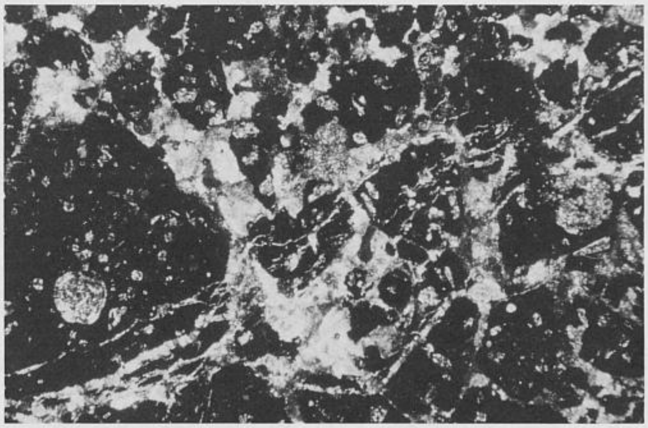


Fig. 33. Photograph of thin section from the Humble Oil & Refining Co. Friske #2 at 2460-2480 ft (≈ 750-756 m) (X40). The basaltic glass appears vesicular, with the vesicles and fractures filled with fibrous chalcedony or calcite.

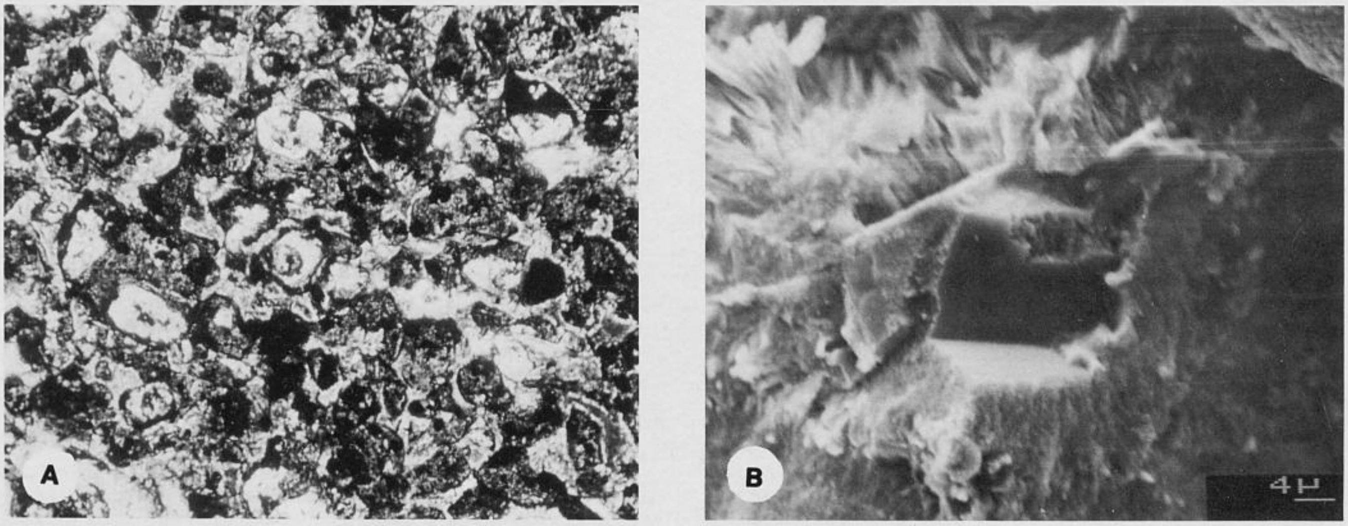


Fig. 34. (A) Photograph of thin section from the Humble Oil & Refining Co. Wolfenbarger #2 at 2656-2668 ft (≈ 809-813 m) (X40). Chlorite occurs as rims around pyroclastic rock fragments and is light in color. Dark chlorite occurs within fragment interiors. Silica and carbonate material are found as cement and fracture and void fill. (B) SEM photograph of sample from Wolfenbarger #2 well at 2656-2668 ft. The wavy, fibrous outline shows chlorite developing as a pore lining associated with calcite grains (4 micron).

APPENDIX III

LIST OF WELL LOGS

	Operator	Fee
Bastrop County		
Ba- 1	Roland K. Blumberg	#1 Brieger
Ba- 2	Wilcat Drlg. Co.	#1 Lilly T. Jett
Ba- 3	Cabbell Oil Co.	#1 Osborn
Ba- 4	Humble Oil & Refining	#1 Osborn
Ba- 5	Humble Oil & Refining	#2 Friske
Ba- 6	Humble Oil & Refining	#3 Wilhelm
Ba- 7	Humble Oil & Refining	#1 Wolfenbarger
Ba- 8	Humble Oil & Refining	#2 Wolfenbarger
Ba- 9	Humble Oil & Refining	#1 Goertz
Ba-10	Humble Oil & Refining	#5 Wilhelm
Ba-11	Humble Oil & Refining	#1 Friske
Ba-12	Humble Oil & Refining	#15 Hilbig Oil Unit
Ba-13	Humble Oil & Refining	#1 Wilhelm
Ba-14	Humble Oil & Refining	#6 Wilhelm
Ba-15	Humble Oil & Refining	#17 Hilbig Oil Unit
Ba-16	Humble Oil & Refining	#8 Wilhelm
Ba-17	Humble Oil & Refining	#7 Wilhelm
Ba-18	Humble Oil & Refining	#13 Hilbig Oil Unit
Ba-19	Humble Oil & Refining	#2 Wilhelm
Ba-20	Humble Oil & Refining	#16 Hilbig Oil Unit
Ba-21	Humble Oil & Refining	#2 Hasler
Ba-22	Humble Oil & Refining	#4 Wilhelm
Ba-23	Humble Oil & Refining	#1 Beck
Ba-24	Humble Oil & Refining	#2 Beck
Ba-25	Comstock Oil Co.	#1 A. A. Hoffman
Ba-26	M & G Operators	#1 Hendrix
Ba-27	Wilcat Inc.	#1 Harris Est.
Wilson County		
Wi- 1	Stringer Oil & Gas	#1 J. W. Pfeil
Wi- 2	M. D. McGregor	#1 H. H. Albert
Wi- 3	Buttes Resources	#1 Boenig
Wi- 4	Toiyabe Oil Co.	#1 Lashley
Wi- 5	Barker Expl. Co.	#2 Leonard Karnei
Wi- 6	Barker Expl. Co.	#1 Karnei
Wi- 7	Dorchester Expl. Inc.	#1 Norman
Wi- 8	Petrolia Drlg. Co.	#1 Arnold-Zaeske
Wi- 9	Petrolia Drlg. Co.	#2 Moy
Wi-10	M. D. McGregor	#1 Doege
Wi-11	Mark IV Energy	#1 Butler-Richter
Wi-12	Mark IV Energy	#1 Martinez
Wi-13	GAS Production Co.	#2 Geraci
Wi-14	Clayton W. Williams, Jr.	#2 Schiffer
Wi-15	Mark IV Energy	#1 Butler
Wi-16	Dorchester Expl. Inc.	#1 Beutnagel
Wi-17	Pro-Management	#1 Stewart
Wi-18	Petrolia Drlg. Co.	#1 Rodriquez
Wi-19	Tesoro & General Crude	#1 Bryan
Wi-20	Ramco Oil, Inc.	#2 Ruhnke
Wi-21	Petrolia Drlg. Co.	#3 Heirholaer
Wi-22	Petrolia Drlg. Co.	#3 Van Winkle
Wi-23	Petrolia Drlg. Co.	#2 Calvert
Wi-24	Clayton W. Williams, Jr.	#3 Schiffer
Wi-25	Dorchester Expl. Inc.	#1 Mills
Wi-26	Dorchester Expl. Inc.	#1 O'Neill Equip. Co.
Wi-27	Barker Expl.. Co.	#1 John Boenig
Wi-28	Dorchester Expl. Inc.	#1 Sanford
Wi-29	Tamarack Petr. Co., Inc.	#1 Heirholzer
Wi-30	Dorchester Expl. Inc.	#A-1 Coldeway
Wi-31	Barker Expl. Co.	#2 Victor Koenig
Wi-32	Barker Expl. Co.	#1 Katherine Bienck
Wi-33	GAS Production Co.	#1 A-1 Boenig
Wi-34	GAS Production Co.	#1 Isadore Jarzombek
Wi-35	GAS Production Co.	#1 Richter
Wi-36	Barker Expl. Co.	#1 Victor Koenig
Wi-37	M. D. McGregor	#1 A. W. Ritchie et al.
Wi-38	Petrex Operating Co.	#1 Hasse
Wi-39	Tesoro Petroleum Co.	#1 Valcher
Wi-40	Aegean Oil Corp.	#1 Stobbs
Zavala County		
Za- 1	Norton Oil et al.	#11 R. W. Norton Jr.
Za- 2	Norton Oil et al.	#1 Musteno
Za- 3	Colton & Colton et al.	#D-1 Cross S Ranch
Za- 4	Shamrock Oil & Gas	#1 W. O. Kirk et al.
Za- 5	Forest Oil Corp.	#1 B. Johnson et al.
Za- 6	Skelly Oil Co.	#1 Griffin Brand
Za- 7	W. J. Steeger	#1 R. W. Norton Jr.
Za- 8	Forest Oil Corp.	#A-1 B. K. Johnson
Za- 9	Taubert et al.	#1 Kirk Bros.
Za-10	Skelly Oil Co.	#1 J. C. Flanagan
Za-11	W. J. Steeger	#5 J. K. Ware
Za-12	Skelly Oil Co.	#1 J. K. Ware
Za-13	W. J. Steeger	#1 J. K. Ware
Za-14	W. J. Steeger	#7 J. K. Ware
Za-15	Skelly Oil Co.	#2 J. K. Ware
Za-16	W. J. Steeger	#2 J. K. Ware
Za-17	W. J. Steeger	#4 J. K. Ware
Za-18	Skelly Oil Co.	#6 J. K. Ware
Za-19	Skelly Oil Co.	#5 J. K. Ware
Za-20	Skelly Oil Co.	#3 J. K. Ware
Za-21	W. J. Steeger	#A-6 J. K. Ware
Za-22	W. J. Steeger	#11 J. K. Ware
Za-23	Colton & Colton et al.	#1 R. W. Keller, et al.
Za-24	W. J. Steeger	#10 J. K. Ware
Za-25	Forest Oil Corp.	#1-16 A. Ware
Za-26	Skelly Oii Co.	#4 J. K. Ware
Za-27	W. J. Steeger	#9 J. K. Ware
Za-28	W. J. Steeger	#1 Wilson
Za-29	H & J Drlg. Co.	#1 C. A. Maedgen
Za-30	I. W. Lovelady	#4 Stuart "B"
Za-31	C. C. Winn et al.	#1 C. A. Maedgen
Za-32	C. W. McCurdy et al.	#1 C. Maedgen
Za-33	J. P. Ross & G. Coats et al.	#2 Keller
Za-34	Roberts Petroleum	#1 Keller
Za-35	Buttes Oil & Gas et al.	#1 Maedgen
Za-36	McCurdy et al.	#1 Flanagan
Za-37	J. P. Ross & G. Coats et al.	#1 Keller
Za-38	Garr-Wooley Co.	#1 F. D. Keller
Za-39	C. W. McCurdy	#1 E. Van Rosenberg
Za-40	Dixon Drlg. Co. et al.	#1 W. Averhoff
Za-41	W. J. Steeger et al.	#1 R. R. Russell
Za-42	Equitable Petroleum	#1 F. Winston et ux.
Za-43	K. Strieber	#1 A. Ware
Za-44	Dixon Oil Co.	#1 C. C. Benham
Za-45	W. J. Steeger et al.	#A-1 R. Russell
Za-46	W. J. Steeger	#1 L. Stewart
Za-47	The Mecon Trust	#1 L. M. Trust et al.
Za-48	I. W. Lovelady	#1 J. W. Stuart
Za-49	Great Western Drlg. Co.	#1 Harris
Za-50	Great Western Drlg. Co.	#1 Stuart
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INDEX

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